

SUSTAINABLE DEVELOPMENT AND ENGINEERING SOLUTIONS FOR THE TOURISM, AGRICULTURE, AND FOOD SECTORS - II

EDITORS

Assoc. Prof. Dr. Alamettin BAYAV

Dr. Ayşe Vildan PEPE



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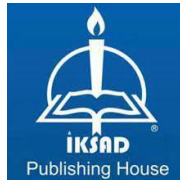
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PREFACE

The disciplines of agriculture, forestry, and aquaculture have long stood at the intersection of human progress and environmental stewardship. In a world where the demand for food, raw materials, and ecological balance grows ever more urgent, these fields provide the scientific foundation for ensuring sustainability, resilience, and innovation. The knowledge they generate not only safeguards natural resources but also strengthens economic and social well-being, making them central to addressing the grand challenges of our time.

This book, *Academic Studies in Agriculture, Forestry, and Aquaculture*, brings together a diverse collection of research that reflects both the depth and breadth of contemporary scholarship.

It is our sincere belief that the studies compiled here will serve as a valuable resource for researchers, practitioners, and policymakers alike. By fostering dialogue between science and practice, this book underscores the importance of collaborative knowledge in shaping a more sustainable future. We invite readers to engage with these works not only as academic contributions but also as guiding beacons for innovation and responsibility in agriculture, forestry, and aquaculture.

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CHAPTER 1

PLASTICS AND ADDITIVES USED IN GREENHOUSES: COMPOSITION AND FUNCTIONS

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INRODUCTION

Plants have various requirements for growth and development, including water, carbon dioxide, oxygen, nutrients, temperature, and light. Greenhouses are agricultural structures where the environmental conditions necessary for plant growth, such as solar radiation, temperature, humidity, and CO₂ concentration, can be controlled. Greenhouse cultivation is rapidly gaining popularity due to its ability to provide a controlled microclimate optimized for high product quality and yield, despite its high energy consumption and investment costs. Covering materials are a crucial structural element in creating the appropriate microclimate required for plant production in greenhouses. By separating the greenhouse's interior and exterior atmospheric conditions, the covering materials maintain this microclimate and protect plants from adverse external atmospheric conditions (wind, snow, rain, etc.). Plastic greenhouses worldwide occupy more space than glass greenhouses. Factors contributing to the increased footprint of plastic greenhouses include the larger dimensions of the plastic sheeting compared to glass panels, allowing for wider openings; the ability to construct plastic greenhouses with fewer structural elements, resulting in lower initial investment costs; advancements in technology have eliminated many of the negative characteristics of polyethylene greenhouse sheeting; and their affordability. Plastics used as greenhouse coverings function as effective electrical insulators, withstand exposure to acids and bases, and provide notable thermal stability along with resistance to mechanical stress. Despite these advantages, they also have certain limitations, including a relatively short operational lifespan, the accumulation of condensation on the interior surface that can drip onto crops, and a reduction of internal temperature below outdoor levels, particularly in the early morning hours after clear nights (Emekli & Büyüктаş, 2016; Shogren et al., 2019; Mishra et al., 2023).

1. PLASTICS USED AS GREENHOUSE COVERING MATERIALS AND THEIR PROPERTIES

The use of soft plastics (polyethylene, PE) as greenhouse covers is common. PE, classified as low-density polyethylene (LDPE), is still widely used today due to its excellent physical and mechanical properties and affordability. PE plastic covers have a resistance to sunlight of about one year. Furthermore, due to the intense solar radiation in our country, these plastics

must be replaced after a production season. Covering greenhouses in the fall ensures as much light transmission as possible during the winter. UV-Added PE plastic has a two-year durability due to the addition of UV additives. Due to the UV additive, it has a yellow color. When dry, plastic covers are permeable to infrared rays. Because IR additives are added during production, IR-Added PE plastic allows long-wavelength rays to pass through to a certain extent. (Briassoulis et al., 1997; Giacomelli, 1999; Dilara and Briassoulis, 2000). Antifog PE plastic, the antifog additive allows water vapour condensing on the inner surface of the plastic to spread out as a thin film, rather than as droplets, as on glass. This positively impacts light transmittance, allowing more radiation to reach the greenhouse compared to other plastics. In recent years, polyester film has also begun to be used as a greenhouse covering material. This material is known by trade names such as Mylar and Melinex, as provided by manufacturers. It is a covering material with high resistance to critical hot and cold weather conditions. It is also highly resistant to hail. Its lifespan on roof coverings is 4-5 years, and on side walls, 6-7 years. With a light transmittance of 85-95%, it is a plastic material that is similar to glass. (Öneş, 1990).

Polycarbonate (PC) is a greenhouse covering material manufactured as double- or multi-layered, transparent sheets with an air gap between them. Thicknesses range from 4-16 mm for double-layered and 10-16 mm for triple-layered. Solar radiation transmittance is less than that of glass, ranging from 70-80% depending on size. Double-layered PC is ten times lighter than glass, so a lower-density support structure is required. The light transmittance of PC covering material decreases by 1% per year due to factors such as moisture condensation and dust accumulation (Papadakis et al., 2000). Polycarbonate (PC) is a clear, rigid type of thermoplastic that can be manufactured in different thicknesses. It is often designed with two layers separated by air gaps and serves as a flexible covering material with high resistance to fire and impact. It is a long-lasting covering material widely used in greenhouses in recent years. Polycarbonate sheets are divided into two categories: solid polycarbonate and corrugated polycarbonate. Solid polycarbonate offers light transmittance comparable to glass, is suitable for thermoforming and cold bending, maintains its durability at very low and very high temperatures, provides protection against ultraviolet radiation from the sun, is unaffected by outdoor conditions, is fifty percent lighter than glass, and has an impact strength three hundred

times higher. PVC sheeting is defined as a material sensitive to cold, shrinking and wrinkling in cold weather, and even cracking and tearing. Because dust is captured electrically, it cannot be removed by washing. While light transmittance is 85-96% when first used, it can drop to 50-70% when dirty. Generally, 0.1-0.2 mm thick sheets are preferred. Softening begins after 50°C and melting begins after 70°C. Shrinkage and tearing occur when the temperature drops below -10°C. Compared to PE sheets, their heat transmission rate is lower. Their lifespan varies between 1 and 4 years. They are more expensive than PE (Filiz, 1988). Rigid (hard) plastics are sheeting materials that are marketed as flat or wavy laminated sheets or as curled balls (Yüksel, 1985).

Fiberglass sheeting has proven popular for several reasons. It's available in corrugated panels or flat rolls. Due to its ease of workmanship, a simple greenhouse can be covered with fiberglass panels in just one or two days. Additives must be used to prevent the material from expanding slightly and to prevent dust accumulation, which significantly reduces light transmission. Most greenhouse planners prefer corrugated fiberglass panels for the roof and flat fiberglass or glass for the side walls due to their durability and ease of application (Cartoğlu, 1990).

GRP (glass-reinforced polyester) is produced by reinforcing polyester with glass fibers. The GRP covering material consists of corrugated sheets coated with polyvinyl fluoride (PVF or Tedlar) or polyethene terephthalate (Melinex) to protect the surface from discolorations. Solar radiation transmittance is 80%. The thickness of the sheets varies between 0.8 and 1.5 mm, and is generally 1mm thick. The width of the sheets varies between 0.8 and 1.0 m, depending on the profile. They investigated the effects of glass, GRP (glass-reinforced polyester), and polyethylene covering materials commonly used in greenhouses on greenhouse interior temperature. The study compared temperatures measured outside with those of model greenhouses using glass, GRP, and PE mesh. The data obtained indicated that the glass covering material resulted in higher indoor temperatures. (Çolak and Şahin, 1995; Baytorun, 1995; Papadakis et al., 2000; Abdel-Ghany et al., 2012).

2. RELATIONSHIPS BETWEEN KEY PARAMETERS IN GREENHOUSE MICROCLIMATE AND PLASTIC GREENHOUSE COVERINGS

2.1. Effects of Plastic Covers on Greenhouse Cooling and Heating

As greenhouse construction and climate management expenses continue to grow, many aspects, from greenhouse construction to covering materials, heating techniques, and interior equipment, require reconsideration. It's important to remember that covering materials are not just for covering; their weight, resistance to various factors, and light and heat transmission properties significantly impact greenhouse costs and climate (Günay, 1993). The continuous increase in energy expenses for heating and cooling has raised the overall cost of greenhouse production. To counter this, covering materials are employed to regulate and sustain the greenhouse microclimate at conditions optimal for plant growth. Therefore, cooling and heating are considered crucial determinants of energy consumption. Baneshi et al. (2020). It has been reported that annual cooling and heating loads could significantly reduce by using appropriate greenhouse covering materials. According to Shin and Nam (2015), between 84.7% and 95.4% of the total heating load in greenhouses results from heat loss through the covering materials. For this reason, enhancing the thermal resistance of these coverings is essential. As noted by Kim et al. (2022), achieving cost-effective and consistent year-round agricultural production requires evaluating the overall thermal conditions of greenhouses in relation to the specific materials used for their coverings.

The additives used in the cover material also affect heat balance. Bartzanas et al. (2012) found that using an IR-added cover material in a greenhouse used for tomato cultivation during the winter months saved 10% of energy compared to a greenhouse with a standard cover material. During the summer, the internal temperature in the NIR-added greenhouse was 2°C lower than in a greenhouse with a standard cover material. It is possible to save heat in modern greenhouses using thermal curtains, polycarbonate, or double-layer PE cover materials. Monitoring greenhouse heating revealed that double-layer PE was the most suitable covering material (Çaylı and Temizkan, 2018). They also reported that thermal curtains should be used as a heat-saving measure. In

a study conducted to determine the effects of different greenhouse covering materials (normal PE, UV-modified PE, IR-modified PE, and double-layer PE) on eggplant growth, development, and yield, they determined that double-layer PE is the most suitable greenhouse covering material for earliness, considering parameters such as greenhouse temperature, saturation vapor pressure deficit, plant growth rate, and yield (Cemek et al., 2005).

2.2. Relationships Between the Solar Spectrum and the Greenhouse Cover Inside the Greenhouse

Most plants love the sun and require light for their growth. Light is also essential for forming enzymes and hormones that direct the basic physiological processes of all plants (photosynthesis, respiration, assimilation, and transpiration) and for creating many color pigments, especially chlorophyll. Light, a form of energy, affects plant growth and development through three important ecological characteristics. These effects can be expressed as the duration of illumination, light intensity, and light wavelength. There is a linear relationship between light intensity and photosynthetic rate (Ağaoğlu et al., 2001; Kevseroğlu, 2004).

Light quality is as important as its quantity for plant development, and plants require light of specific wavelengths for optimal growth. Solar energy reaching the earth from the sun consists of electromagnetic waves with wavelengths ranging from 290 to 5000 milli microns. Only those with wavelengths between 400 and 760 milli microns are visible to the naked eye. While blue-green light is adequate in photosynthesis, red light, with wavelengths between 600 and 760 milli microns, is absorbed by chlorophyll and has the highest physiological activity. When these rays are optimal, plants produce the highest levels of organic matter (Genç and Tükel 1992, Maddonni et al., 2001; Odabaş, 2003). While red light affects photosynthesis, it is generally necessary to use it in conjunction with blue light to ensure regular growth, prevent excessive stem extension, and minimize shade avoidance. In addition, blue light has significant effects on growth, photosynthesis, and the antioxidant system in green vegetables (Olle and Virsile, 2013; Snowden et al., 2016).

Plants primarily use the spectrum's infrared, red, and blue portions for photosynthesis and regulate numerous developmental and adaptive processes.

Chlorophyll's highest absorption occurs in the red (625–675 nm) and blue (425–475 nm) regions. Plants use these wavelengths most efficiently for the photochemical process of photosynthesis. In contrast, carotenoids function as auxiliary photoreceptors to chlorophyll, mainly capturing light within the blue spectrum. Photomorphogenic responses include a range of processes such as seed germination, directional growth toward light (phototropism), expansion of leaves, flowering, development of stomata, relocation of chloroplasts, and mechanisms that enable plants to reduce the effects of shading. These responses are regulated by three types of photoreceptors: phytochromes, cryptochromes, and phototropins. Green light (500–600 nm) is absorbed to a slightly lesser extent by these pigments, making leaves appear green (Smith, 1995; Sancar, 2003; Briggs and Christie, 2002; Gupta and Jatothu, 2013; Robson et al., 2022). While its role in photosynthesis is not as critical as that of red or blue wavelength bands, its ability to penetrate the vegetation much further than blue or red bands is essential for driving photosynthesis in the underlying leaves below (Smith et al., 2017). Increasing light intensity to a certain level linearly increases the rate of photosynthesis. However, it has been observed that photosynthesis rates decrease in some plants after light intensity exceeds a specific value. In particular, increased solar ultraviolet (UV) radiation intensity leads to the production of active oxygen species and the formation of free radicals in living organisms, DNA damage and partial inhibition of photosynthesis in plants, growth inhibition in plants, anatomical and morphological changes, and an increase in flavonoids (Caldwell and Flint, 1994; Kenar and Ketenoglu, 2009). Many fungi and bacteria are vulnerable to UV radiation during the spore formation and dispersal. According to Rothscild (1999), the primary effect of UV radiation on most microorganisms is DNA damage, which can lead to hereditary changes and genetic variation through mutations. However, UV radiation's harmful or beneficial effects on microorganisms vary depending on the wavelength (Paul and Gwynn-Jones, 2003).

To fully utilize the naturally available solar energy, greenhouse operators need to adjust the incoming solar radiation, as the amount and quality of this radiation play a key role in shaping the greenhouse microclimate. Only a small fraction of greenhouses worldwide is equipped with active climate control facilities (heating and cooling); most are "passive" greenhouses, relying on

incoming solar radiation and the energy transmitted through, and thus affected by, greenhouse covers and curtains. Sunlight varies geographically and seasonally. In this context, the materials and technologies used in greenhouse covers and curtains are gaining importance. These materials can passively manipulate incoming sunlight to transmit an ideal light spectrum for crop cultivation, thereby improving yields, managing the greenhouse microclimate, and reducing greenhouse energy use (Marcelis and Heuvelink, 2019; Mishra et al., 2023). In recent years, the increasing focus on sustainable development goals and energy conversion has led to the development of new materials and technologies that can further utilize sunlight in greenhouses, both in intensity and spectrum. Some spectrum manipulation techniques have long been applied to greenhouse coverings (Timmermans et al., 2020).

3. GREENHOUSE MICROCLIMATE MANAGEMENT AND GREENHOUSE COVERING MATERIALS WITH IMPROVED

3.1. Properties UV Stabilizers

Plastic covers are vulnerable to physical and chemical influences. However, it is possible to strengthen plastics and improve some of their properties by adding various additives. Among these additives, UV (ultra violet) is used to increase the greenhouse cover's resistance to sunlight and improve plant health. The lifespan of a greenhouse cover varies depending on the thickness of the cover and the quality and rate of UV radiation used. Different types and rates of UV additives are used depending on the cover's thickness, the desired lifespan of the greenhouse cover, and the region where the greenhouse will be used (Baytorun and Baştañçelik, 1993; Şentürk et al., 2021; İközler, 2019).

3.2. Ir-Blockers, Temperature and Solar Radiation Dynamics

Infrared (IR)-enhanced covers reflect infrared rays, slowing the greenhouse's heating and cooling and maintaining greenhouse temperature, saving energy. They minimize heat loss between day and night by reducing it by 2-5°C. They reduce the risk of frost within the greenhouse, preventing plant stress and accelerating plant growth. Infrared (IR)-enhanced cover materials used in greenhouses are designed to retain infrared rays reflected from the soil,

ensuring a much higher and more stable interior temperature than the outside environment. Cover materials with increased resistance, including IR stabilizers, protect the greenhouse from overheating during the day and cooling at night. Choosing infrared-enhanced covers is crucial for providing a consistently warm environment for greenhouse plants that face the risk of frost during long, dark winter days. Their opacity refracts light and prevents plant damage from excessive sunlight. Studies have shown that greenhouses using infrared-enhanced plastic covers increase production efficiency by 20% to 30%. Conversely, when these covers are not used, plants are directly exposed to sunlight, resulting in a significant decline in leaf and fruit quality (Öneş, 1990; Külcü and Özay, 2015; İkizler, 2019).

The use of plastic coating materials, which alter the spectral distribution of sunlight and thus affect plant growth, has the potential to replace the use of agricultural chemicals. Micro- and nano-additives in plastic determine the film's strength, ability to prevent heat loss, ability to prevent droplet formation, ability to transmit specific wavelengths of light, and ability to prevent dust from adhering to the film. UV stabilizers and absorbers (290 to 400 nm) can help extend the life of the materials. They can reduce the likelihood of affecting greenhouse biological systems and have even been found to control some plant diseases. Using infrared absorbers (700 to 2500 nm) reduces long-wave radiation and minimizes heat loss (Espejo et al. 2012; Allan et al. 2014). When absorbers of long-wave radiation (2500–40,000 nm) are used, greenhouse components and plants lose less heat (Li et al., 2021; Jimenez and Agudelo., 2015).

The EVA/EBA additive increases the greenhouse film's thermal properties and light transmittance. EVA (ethylene-vinyl acetate) increases the film's transparency and provides durability (impact resistance) and flexibility. LD (light diffuser) prevents plants from sunburn by refracting and diffusing sunlight within the greenhouse. Adding various additives with LD properties to the film materials reduces shadows caused by the film material, ensures a more even distribution of light within the greenhouse, and allows light to reach the lower parts of the plants, preventing burns and creating a stable cooling effect (Külcü and Özay, 2015; Şentürk et al., 2021).

The decrease in sunlight angle during the winter months, coupled with falling temperatures, necessitates heating greenhouses for frost protection. In

this case, the properties of greenhouse covering materials come to the fore. In this context, thanks to the advantages of developing technology, CO-EX technology has replaced greenhouse plastic produced with mono technology, allowing for more uniform distribution of film thickness and additives used in the production phase. In greenhouse plastic produced with CO-EX technology, many additives, such as UV additive (lifespan), IR additive (heat retention), EVA additive (flexibility), AF additive (drip), AT additive (electrostatic), and LD additive (light diffusion), can be applied to the plastic more uniformly during the production phase (Papadakis et al., 2000; Tezcan, 2022).

Plastic sheeting is one of the most important elements for increasing and maintaining temperature in greenhouse interiors. Hemming et al. (2014) reported that a 10% yield increase in tomato plants was achieved under Dutch conditions thanks to plastic sheeting materials that convert radiation entering the greenhouse into diffuse radiation. Al-Mahdouri et al. (2013) evaluated four different sheeting materials in terms of optical properties and reported that glass, polyvinylchloride (PVC), and polyolefin (PO) were the most effective for indoor greenhouse temperatures, from highest to lowest. Tantau et al. (2012) conducted a project to investigate the photosynthetic active radiation (PAR) transmittance of sheeting materials using twenty different sheeting materials. They reported that water droplets formed on the inner surface reduced PAR transmittance, while dust accumulation on the sheeting varied in permeability and increased during periods of rainfall. Furthermore, moisture condensation on the sheeting is a factor to consider when determining greenhouse heat requirements. The additives used in the cover material also affect heat balance. Bartzanas et al. (2012) evaluated the use of IR and NIR-added cover materials in three tomato-growing greenhouses regarding greenhouse energy consumption. Their findings indicated that the greenhouse with the IR-added cover material consumed 10% less energy in the winter than the greenhouse with the standard cover material, while the internal temperature in the NIR-added greenhouse was reported to be 2°C lower in the summer than the greenhouse with the standard cover material (Çaylı and Temizkan, 2018).

A fundamental technical requirement in greenhouses is maintaining appropriate air temperature and relative humidity for plant growth. Cooling greenhouses is crucial for providing a suitable environment for plant growth in arid regions. However, traditional cooling methods face numerous challenges.

Directing the heat load through the greenhouse canopy is believed to offer a promising solution to the problem of greenhouse air overheating during hot summers under these conditions. Filtering near-infrared (NIR) radiation in the greenhouse canopy can significantly reduce the heating load and address the problem of greenhouse air overheating. NIR-reflecting plastic films are the most suitable, low-cost, and simple films for greenhouses in arid conditions. Various additives must be added to the plastic film to improve its mechanical properties, durability, and ability to withstand extreme weather conditions. Near-infrared (NIR) reflective films can reduce greenhouse air temperature by a maximum of 50°C. This reduction is insufficient in regions where ambient temperatures exceed 45°C in summer. In this case, improved near-infrared (NIR) reflective plastic film covers are needed (Abdel-Ghany et al., 2012).

Morris et al. (1958) proposed using a 0.5 mm thick water film flowing onto the roof to reduce the maximum air temperature in greenhouses. This resulted in a 4-5 °C decrease in indoor greenhouse air temperature. However, the cooling effect of a water film flowing onto the greenhouse roof does not sufficiently reduce greenhouse air temperature in regions where summer temperatures reach 50°C. More selectively, instead of pure water, a CuSO₄ solution in water (called a liquid radiation filter, LRF) was used to selectively transmit most of the PAR and absorb most of the NIR. The concentration of the 1.5% to 2% CuSO₄-water solution flowing through the hollow-channel, rigid plastic (polycarbonate or acrylic) roof of semi-closed greenhouses has been investigated through simulation studies and practical tests (Van Bavel et al., 1981; Abdel-Ghany et al., 2001a). Based on these studies, fluid roof membranes can remove more than 50% of the solar energy incident on the greenhouse canopy through absorption, thus reducing the radiative heat load on the greenhouse (Abdel-Ghany et al., 2001b).

In a study conducted to determine the extent to which greenhouses covered with plastic materials retain heat energy, various experimental studies were conducted in greenhouses with side and gable walls covered with polycarbonate sheets and roofs covered with ethyl vinyl acetate-added plastic sheeting (Weimann, 1985). Thermal retention experiments were repeated with single-layer sheeting, single-layer sheeting and thermal curtains, double-layer inflated sheeting, and double-layer inflated sheeting and thermal curtains. The study determined that the single-layer sheeting, thermal curtain, and double-

layer inflated sheeting systems provided energy savings of 30% to 40% compared to the other alternatives. However, light transmittance measurements revealed no significant differences between the options.

3.3. Temperature, Humidity, And Radiation Dynamics

Temperature control is one of the most critical elements of greenhouse management. Tinted films can reduce solar heat load or help trap heat during cold months. For example, red or yellow films have been shown to increase internal temperatures, while blue or white diffusive films can reduce heat accumulation (Seginer, and Zlochin, 1997). Relative humidity and vapor pressure deficit (VPD) are closely linked to plant transpiration and disease development. Films with anti-drip or anti-condensation properties limit pathogen proliferation on leaf surfaces by reducing internal condensation (Tanny et al., 2003). Incoming solar radiation determines the total energy available for photosynthesis. Transparent films provide maximum PAR (photo synthetically active radiation), while tinted or UV-absorbing films selectively filter or scatter light. These spectral changes directly influence photomorphogenic processes.

3.4. Colored Greenhouse Covers and Their Impact On Plant Growth

It has been reported that different color plastic cover materials can change plant nutrient uptake and growth (Atilgan et al., 2020). The research results show that cover materials positively affect the nutrient content of Leaf K, Ca, Cu, Zn, Fe, and Fruit K, Ca, P, Mg. Researchers have reported that the application, which increases the nutrient content of tomato leaves the most, is a red color cover application. On the other hand, the highest fruit nutrition content is obtained from the blue color cover application. In addition, considering the yield values of the tomato plant, the highest yield values were obtained from blue, then red, transparent cover application, respectively. As a result, considering the effects of four different greenhouse applications on macro and micro nutrition and yield values, it has been reported that the most suitable application for tomato cultivation in the greenhouses is the blue color application, and the red color application should not be ignored. Using extra LED lighting with different color plastic cover materials and the development

parameters of the tomato plant in plastic greenhouses can change the yield values. The use of the cover material in tomato plants (compared to red and transparent cover material) was found to have a positive effect on yield, fruit mass, and plant green components. Furthermore, the covering material is red, as the tomato plant has been reported to reduce temperature and radiation energy values. (Çetin and Atılğan, 2020).

Applying photo elective and colorful greenhouse films represents a transformative strategy in controlled environment agriculture. Plastic covers that change the composition of incoming sunlight affect many physiological and morphological processes in plants. Light is more than an energy source for photosynthesis; it also serves as a signal that regulates plant behavior. Photo elective films can change the spectral balance by filtering the incoming sun radiation. Red films encourage leaf expansion by increasing the red-to-green ratio and delaying blooming. Blue films increase blue light by increasing stoma conductivity and leaf thickness. Green films reduce both red and blue light, leading to shadow reactions. UV blocking films reduce pigmentation and harmful visibility by eliminating UV-A and UV-B rays, but potentially limit compliance with stress. These spectral changes create different forms of growth and stress by changing plant hormonal ways (especially oksin, gibberellin and absisic acid) (Hernández and Kubota, 2012; Folta and Carvalho, 2015). It has been determined that red films (luminesan or pigment-added polyethylene) increased the fruit yield and sugar content in sweet pepper with tomato by increasing the speed of photosynthesis and increasing the photosynthesis rate (Oyaert et al., 1999; Shahak et al., 2004). These films improve the length and leaf area between nodes and improve the vegetation structure and shedding capacity. Blue films encourage compact growth, more chlorophyll content, and increased stomata intensity. It has been determined that the growth of ornamental plants such as Petunia, velvet flowers, and Coleus under blue plastic covers delays the flowering of plants. Still, the quality of the leaves increases (Rajapakse and Kelly, 1994). In the lettuce, blue light leaf thickness and anthocyanine and flavonoid content have been found to increase nutritional value. Green films suppress growth by reducing red and blue components and increasing the remote red ratio. Plants have longer stems and more pale leaves. This is an indication of shadow avoidance syndromes. For this reason, green

films are often not used in productivity-oriented greenhouses, but can be used in air conditioning or nursery operations (Johkan et al., 2012).

There are many experimental and commercial studies on greenhouse cover color. Red, blue, white, and transparent films for tomatoes, peppers, and cucumbers have given interesting results. For example, red and white films significantly increased yield, and white films provided better heat reduction (Shahak et al., 2008). Blue and UV-absorbent films improve lettuce texture and mineral intake (Johkan et al., 2012). In high radiation environments, widespread white films reduced leaf burning in cucumbers while increasing photosynthesis (Montero et al., 2011). Blue films increase the density in ornamental plants, while red films support early flowering in some vegetables and form a wider leaf area. Yield in tomatoes has increased visibly under red and green films, in terms of quality and biomass. These findings show how important the choice of film is, but it will be more accurate to consider all factors such as product type, climate, target market, and harmful pressure (Kittas et al., 2006; Rajapakse and Shahak, 2007). One of the applications made in recent years is the use of light-selective (photo-selective) colored networks for shading in greenhouse environments. These nets can be red, yellow, blue, green, and black. The effect of each color on plant development is different. For example, black and green light selective networks are usually used in hot periods. In particular, the nets mounted on or under the greenhouse cover are used to reduce the high temperatures in the greenhouse. Blue-colored networks absorb UV, red, and distant red wavelength rays, while the PAR blue-green band (400-540 nm) shows a wide permeability. Red nets pass 590 nm and up wavelength rays. Yellow Networks: They pass 500 nm and up wavelength rays. Gray colored networks show the lowest uniform permeability values in the Solar Infrared and PAR regions. (Briassoulis et. al., 2007b; Tezcan et.al., 2017).

In winter, when the amount of light is insufficient, the growth and development of the plant are adversely affected. Artificial lighting systems are used in greenhouses to support the growth and development of the vegetables (Dayıoğlu and Silleli, 2015). Additional lighting with red-orange LED light has increased the height of plants, leaves, and flowers, according to the greenhouse without illumination. The effect of the tomato plant on blue color (net photosynthesis rate, number of stomata, efficiency, and quality) was positive. (Hoshi et al., 2011; Liu et al., 2011; Brazaityte et al., 2010).

3.5. Greenhouse Cover and Pest and Disease Management

The AV (antivirus) additive used in the covering materials inhibits pest activity and the development of some harmful fungi on plants. Furthermore, it has absolutely no negative impact on bee activity. In recent years, most plastic films used to cover greenhouses are UV-absorbent. This reduces the impact of pests and diseases on crops and reduces pesticide load and costs. On the other hand, some insect species, such as whiteflies, use ultraviolet light to locate the food they need. Therefore, if ultraviolet light is blocked from entering the greenhouse, these pests will quickly abandon the greenhouse. Microorganisms found on the lower stems of plants, which need to reach the leaves for feeding, also experience blindness due to the lack of ultraviolet light. Consequently, they cannot get the leaves and flowers of the plants. Another study found that covers containing ultraviolet-blocking additives significantly inhibited the transmission of certain viruses (e.g., yellow leaf mosaic) carried by whiteflies and common in tomato cultivation. Additionally, black spots on leaves in red rose cultivation can be prevented with ultraviolet-blocking covers (Baytorun and Baştançelik, 1993; İkizler, 2019; Külcü and Özay, 2015). Fluorescence can increase red-light output, color pigments that change the ratio of specific wavelength ranges can support plant growth, and shiny surfaces can deter insects (Maraveas et al., 2023).

Films that block ultraviolet light (UVB or UVA+UVB) can have different effects. On the one hand, they reduce harmful solar radiation, which can damage DNA, proteins, and membrane lipids. On the other hand, they alter insect behavior and pathogen development. Many insects rely on UV signals for host location; therefore, UV-blocking films reduce the incidence of whiteflies, trips, aphids, and other leafhoppers (Ben-Yakir et al., 2008; Costa et al., 2002). Furthermore, UV-blocking films have been shown to delay or suppress the development of powdery mildew and Botrytis in cucurbits and strawberries. However, these films may suppress flavonoid biosynthesis and pigmentation in red-leafed cultivars. (Kasajima et al., 2008).

3.6. Anti-Fog and Anti-Drip agents, Anti dust

Condensation occurs when the inner surface of the film becomes cooler than the humid greenhouse air. Water droplets disrupt light transmission, encourage pathogen growth when drip onto the plant, and cause leaf burn due

to the lens effect. Greenhouse covers using Anti-Mist reduce the fogging that occurs during sunrise. Otherwise, light cannot penetrate the cover and is refracted and reflected. This prevents the plants from receiving sufficient light and heat needed for growth. To prevent this, cover materials containing antifog additives are used. Antifog agents are surface-active agents added or coated to the inner surface of the film. They reduce surface tension, allowing water to spread out in a uniform, thin layer rather than as individual droplets. Cover materials containing anti-drop additives increase light transmittance by 16% for a single-layer cover and 12% for a double-layer cover (Stanghellini et al., 2012). Anti-drip additives, usually based on ethoxylated fatty alcohols or silicones, help maintain this layer for extended periods. These additives also offer positive results, such as improving light penetration (up to 10-15% in humid climates), controlling diseases such as mold and Botrytis, and preventing mechanical damage to flowers and fruit. However, the effectiveness of these additives decreases over time due to washing or thermal degradation, and reapplication or reactivation may be necessary for multi-season covers. Dust and other debris accumulating on the outer surface of the cover gradually reduces the light transmittance of the plastic sheet. In such cases, choosing plastic sheets with anti-dust (AD) properties prevents dust from adhering to the plastic sheet and provides a solution to the light transmittance problem. Surfactants disperse condensation by reducing the surface tension of water, while antistatic compounds reduce the tendency for dust to accumulate on plastic sheets. (Papadakis et al., 2000; İkizler, 2019; Maraveas et al., 2023).

3.7. Nanocomposite Films and Functional Innovation

The incorporation of nanoparticles into greenhouse films has gained momentum in recent years. Examples include clay or silica nanoparticles for enhanced mechanical strength and barrier properties, zinc oxide (ZnO) or titanium dioxide (TiO₂) for dual UV protection and antimicrobial activity, and silver nanoparticles for antifungal and antibacterial effects. Nanocomposite films improve tear and puncture resistance. They also enhance UV properties and extend functional life without increasing cost. However, regulatory and environmental concerns regarding nanoparticle leaching and post-use recycling remain. Life cycle assessments (LCA) are necessary to assess true sustainability (Bumbudsanpharoke and Ko, 2015).

3.8. Biodegradable and Sustainable Additives

One of the measures that can be taken against increasing environmental concerns is the development of biologically fragmented greenhouse films. Starch-based polymers, polylactic acid (PLA) mixtures and additives supporting oxy-biological disintegration are used for this purpose. Although they are promising, these materials often face problems such as limited mechanical resistance and high production costs. Existing bioplastic covers are more suitable for seasonal low tunnels or mulches instead of permanent greenhouses. (Kyrikou and Briassoulis, 2007).

3.9. Environmental and Sustainability Challenges

Plastic pollution and disposal of agricultural films at the end of their use create serious sustainability concerns. Most commercial films are disposable, oil-based, and not biologically degraded. Recycling is limited due to contamination with soil, agricultural chemicals, and degradation by-products. The solutions to be developed are biologically disintegrated polymers (polylactic acid, polybutened adipate terephthalate), and re-processable thermoplastics, which are designed for clean separation and recycling. Oxo-portable additives catalyse the disintegration under UV and oxygen exposure. Certification systems such as EN 13432 and ASTM D6400 are used to confirm biologically degradable claims. However, cost and mechanical restrictions prevent the widespread adoption of large open greenhouse films. Recycling is vital because it reduces waste during the production of oil-based films and plates and during agricultural activities. One of the features that makes plastics popular is their recyclable properties. Recycling is still the best option, as there is no practical way to reduce PVC demand completely. Recycling has a significant carbon impact; Therefore, continuing to use plastic will adversely affect the environment. Here, while the paper has the highest emissions, low-density polyethylene has the lowest emissions. Recycling polyethylene terephthalate and low-density polyethylene is more advantageous in terms of the environment than recycling high-density polyethylene, paper, wood, and glass (Maraveas et al., 2023; Seren and Turhan, 2024).

3.10. Integration with digital agriculture and IoT

The rise of sensitive agriculture and the Internet of objects (IoT) also transforms greenhouse management. Perception technologies now make it possible to monitor quality, temperature gradients, humidity and disease markers. Integrates sensor -guided climate control systems with photo -selective films offers unprecedented control. Under blocking films under UV index-based ventilation, complementary LED lighting to compensate for spectral deficiencies, combining mobile applications with film data for maintenance planning, the fusion of material engineering and data science in greenhouse systems represents a limit of agricultural-technology innovation (Park et al., 2021).

CONCLUSION

This chapter has explored the complex interactions between colored greenhouse covers, plastic film additives, and the plant-environment system within protected cultivation structures. Colored and photo selective films alter the spectral quality of light and thus influence photosynthesis, flowering, morphology, and yield. Functional additives (UV stabilizers, anti-fog agents, IR modifiers, nanoparticles) enhance film longevity and microclimate control, reducing pathogen pressure and energy costs. Microclimatic dynamics such as temperature regulation, humidity balance, and radiation diffusion are directly influenced by film characteristics, making material selection a strategic decision in greenhouse design. Technological trends are moving toward smart, sensor-responsive, and biodegradable films, though economic and regulatory barriers persist. In the context of climate-smart agriculture and sustainable food systems, greenhouse covers are no longer passive structures.

Future research should focus on integrative solutions combining material innovation with real-time sensing, automated climate regulation, and environmental accountability.

With the right strategies, the next generation of greenhouse covers will not only boost productivity but also contribute meaningfully to resilience, sustainability, and global food security.

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CHAPTER 2

SOME DISEASE-RESISTANT CARE TIPS FOR SUSTAINABLE LAWN AREAS

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1. INTRODUCTION

1.1. Diseases and Control in Lawn Areas

The most important plant elements of our environment are green areas. Lawns are indispensable surface elements of green areas. Lawns, which perfectly cover their surroundings, effectively prevent erosion with their dense and deep root systems. Their homogeneous appearance and attractive green colors enhance the beauty and therefore the economic value of the landscape. In addition to their aesthetic benefits, lawns provide a natural, comfortable, safe, durable, and excellent playing surface for golf, football, and other sports fields (Avcioğlu, 2014).

Maintaining lawns requires significant effort and expense. The effort and expense can only be recouped through healthy plants and long-lasting lawns. Therefore, maintaining a healthy lawn is more important than simply growing it. Fungal diseases are a major problem in lawns. While it's often difficult to diagnose early on, they often manifest themselves through damage. Laboratory analysis is the most accurate and reliable method for diagnosis. Restoring diseased lawns often yields unsuccessful results. Therefore, eliminating the potential causes of the disease is the best course of action. (Beard, 1973; Açıkgoz, 1994; Avcioğlu, 2014).

Various pathogens emerge over time in turfgrass areas and can infect turfgrass plants and cause diseases. In general, three basic components must come together for any disease to occur. These are: a) the existing turfgrass species or variety is not resistant to the disease, b) the environmental conditions (temperature, humidity, etc.), and c) the pathogen that causes the disease is present in the environment, where the plant grows are suitable for the development and spread of the disease-causing pathogen (Figure 1.1a). In this respect, the most important factor to be followed in protecting against diseases is to choose the native turfgrass species and varieties that are best adapted to the region and as strong as possible, taking into account the purpose of use of the area. All components must be present for the disease to occur (Beard, 1973; Açıkgoz, 1994; Lamey and Arthur, 1996; Emmons, 2000; Vargas, 2005; Reynolds and Flint, 2009; Martinez et al., 2009; Kennelly, 2011; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Avcioğlu, 2014; Wilen, 2016; Sever Mutlu, 2017; Anonymous, 2025a).

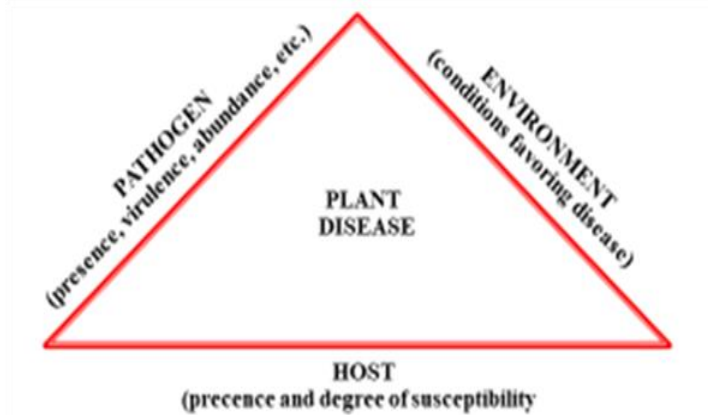


Figure 1.1a. The Disease Triangle (Wilén, 2016; Anonymous, 2025a).

In Türkiye, the amount of green spaces serving different purposes is increasing day by day, depending on the increase in the level of education and the development of people's environmental awareness. Developing local varieties is of great importance in order to maintain lawn areas in a healthy way and with minimum cost. Because native turfgrass species and varieties are better adapted to limited maintenance conditions (less water, less fertilizer, etc.), especially in semi-arid and arid climates, and experience fewer disease and pest problems, thanks to the natural genotypes that have existed in the region for centuries. Almost all of the turfgrasses varieties used in existing lawn areas in Türkiye are of foreign origin. However, in recent years, significant progress has been made in the development of our native turfgrasses varieties that can adapt to the conditions of our country, especially with the breeding studies carried out on warm climate grass species. It is hoped that with the use of developed native varieties, it will be possible in the near future to create sustainable and environmentally friendly green areas that are better adapted to the country's conditions and thus use fewer chemicals with minimum expense (Açıkgöz, 1994; Avcıoğlu, 2014; Sever Mutlu, 2017).

It is important to ensure that the turfgrass species and variety chosen for the adaptation zone are also suitable for the micro-ecological conditions of the area to be used, the intended use (football, golf course or home garden), the level of maintenance to be applied and the expected quality. For example, if the selected turfgrass type is suitable for the adaptation zone where the application will be made, but is not resistant to the intense shade conditions in the area, it

will become stressed and may be attacked by pathogens. An example of this situation is the use of Bermuda grass varieties in a home garden with shade conditions in the Mediterranean. Although Bermuda grass (*Cynodon dactylon* and its hybrids) is a suitable species for use in our coastal areas, it is not suitable for use in shaded areas because it requires at least 6 hours of full sun per day for good growth and development. Instead of Bermuda grass, other warm climate turfgrass species with better shade tolerance, such as Japanese ryegrass (*Zoysia japonica*) or crabgrass (*Stenotaphrum secundatum*), may be preferred. Similarly, if a species that is not well-suited to being stepped on or trampled is selected in a high-traffic area, or a species that is not drought-tolerant is selected in a turf area where irrigation will be limited, disease pressure will be greater (Beard, 1973; Açıkgöz, 1994; Avcıoğlu, 2014; Sever Mutlu, 2017).

Another important criterion that should be taken into consideration is whether the selected turfgrass species and varieties are resistant to the diseases commonly seen in that region. Because these resistant species or varieties can develop different mechanisms and continue their survival despite pathogen attack. Generally, cool-season turfgrass species (such as meadow grass "*Poa pratensis*", fescue species "*Festuca sp*", perennial ryegrass "*Lolium perenne*") are more susceptible to disease in summer, while warm-season grass species (such as Bermuda grass, Japanese ryegrass, coastal pseudosorghum "*Paspalum vaginatum*") are more susceptible to disease in late fall and early spring. Because pathogens always infect turfgrasses when they are not growing strongly and are under stress. In general, warm climate turfgrass species show the best growth and development at 27-30 °C, while cool climate varieties show the best growth and development at 16-24 °C (Vargas, 2005; Kennelly, 2008; Wong and Harivandi, 2009; Reynolds and Flint, 2009; Martinez et al., 2009; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Sever Mutlu, 2017).

1.2. Some Care Procedures to Prevent Disease Pressure

Diseases can be prevented or their progression can be significantly reduced by carefully implementing maintenance measures such as watering, fertilizing, mowing, preventing matting and soil aeration, which will allow the grass to grow healthy and strong and to renew itself. In this case, the important maintenance practices that should be considered can be briefly summarized as follows (Emmons, 2000; Wong and Harivandi, 2009; Hartin et al., 2011).

1.2.1. Irrigation time and amount

In general, too little or too much watering results in unhealthy, slow-growing turf surfaces that are susceptible to pathogen attack. In a good growing environment, the soil should be 50% solid, 25% water and 25% air. In over-irrigated lawns, almost all of the soil pores, which should be filled with 25% air, are filled with water and the soil air decreases to 0%. As a result, due to lack of oxygen, turfgrass roots become stressed, weakened and vulnerable to pathogen attack (Beard, 1973; Açıkgöz, 1994; Harivandi, 1999; Geisel and Unruh, 2001; Avcıoğlu, 2014; Sever Mutlu, 2017).

If there is no mandatory irrigation requirement, the best time to water to minimize disease pressure is at night, starting after midnight and ending a few hours before sunrise. In this way, water loss through evaporation will be minimized compared to watering in the middle of the day, and the period during which the turfgrass leaves remain wet will be shortened. In addition, early morning irrigation will help wash away the dew that forms on the leaves in the early morning, thus reducing disease pressure. Because dew drops are rich in sugars, they attract pathogens and increase the potential for disease development. Watering in the evening causes the leaves to remain wet for a long time (all night long), and the layer of water remaining on the leaves throughout the night creates an excellent habitat for the germination and development of fungal pathogens. Care should be taken to ensure that the water used for irrigation is clean groundwater. Unless absolutely necessary, chlorinated tap water and disease-contaminated canal and river water should be avoided (Beard, 1973; Harivandi, 1999).

1.2.2. Mowing time and height

Mowing errors are one of the most important factors causing disease problems in lawn areas. Especially the blades of lawn mowers must be sharp. Instead of making a clean cut, the blunt blades of the mower tear the tissue unnecessarily and cause excessive damage, and the resulting scar tissue creates a place where fungi can easily reach the plant tissue. Generally, lawns mowed too short are more susceptible to stressful conditions than lawns mowed longer, and their rate of regeneration in the face of disease pressure is considerably lower. For this reason, the recommended mowing heights for each turfgrass

type should be followed, taking into account the intended use and seasons (Beard, 1973; Harivandi and Gibeault, 1999; Emmons, 2000).

The optimum mowing height for Bermuda and Japanese ryegrass in a home garden may be 2.5-5 cm. However, the ideal cutting height for *Festuca arundinacea* (tall fescue) is 5-7.5 cm. Cool climate turfgrass species should be mowed slightly longer in the summer months to reduce the negative effects of high temperature stress and thus make them more resistant to diseases. Additionally, washing the blades of the equipment used after each mowing and collecting and removing turfgrass cutting residues from the area if there is a disease in the area is a good precaution (Harivandi and Gibeault, 1999; Emmons, 2000; Sever Mutlu, 2017).

1.2.3. Fertilization and plant nutrition

Fertilization and plant nutrition are among the most important issues for lawn areas. Macro elements; nitrogen (N), phosphorus (P) and potassium (K), meso elements; magnesium (Mg), calcium (Ca) and sulfur, micro elements; iron (Fe), zinc (Zn) and silicon (Si) are extremely important for turfgrass areas (Beard, 1973; Brohi and Aydeniz, 1991; Trenholm and Unruh, 2009).

The timing and quantity of all fertilizers used are also extremely important. In areas where excessive nitrogen is provided but insufficient potassium is provided, turfgrass plants develop a plant tissue with thinner cell walls. In these conditions, turfgrass plants become highly susceptible to pathogen attack. Potassium deficiency reduces the stress tolerance of turfgrasses and increases their potential for disease. Therefore, a balanced fertilization regimen containing approximately 50% potassium to the applied nitrogen is crucial for creating a more resistant tissue to fungal diseases. The use of slow-release fertilizers containing approximately 30% nitrogen and a balanced ratio of potassium and other elements is particularly recommended. Furthermore, instead of applying high doses only once or a few times a year, lower doses applied monthly or even weekly can create healthier and stronger turf. For a balanced fertilization regimen, a soil analysis must be performed, and the plant's essential nutrients should be applied to the turf based on the analysis results. The optimal fertilization time is when root growth and development are optimal. Therefore, the ideal time for fertilizing cool-climate turfgrasses is one month from the last frost date in spring to the first frost date

in autumn. For warm-climate turfgrasses, the recommended fertilizing time is summer (Beard, 1973; Brohi and Aydeniz, 1991; Trenholm and Unruh, 2009; Sever Mutlu, 2017).

1.2.4. Drainage and ventilation

Soils compacted by excessive use remain wet for extended periods after irrigation, leading to the development of soil-borne fungal diseases that thrive in damp and airless conditions. Therefore, lawns should be aerated at least once a year, preferably in the spring. This practice should be carried out with tools and machinery appropriate to the size and topography of the area, increasing the soil's drainage capacity and ensuring good air circulation between the soil pores and the atmosphere. The incidence of fungal diseases is higher in lawn areas with poor air circulation, particularly those surrounded by trees and shrubs. In such areas, crown removal and thinning pruning of trees is recommended to increase air circulation and allow additional sunlight to reach the lawn (Beard, 1973; Emmons, 2000; Sever Mutlu, 2017).

1.2.5. Thatching and its control

Thatch is an organic mixture of dead and living plant parts (stems, crowns, stolons, rhizomes, and roots) that accumulates beneath the green part of the lawn and on top of the soil. Microorganisms and soil insects gradually decompose this material. Excessive accumulation of this layer creates an ideal habitat for disease pathogens. Under favorable conditions, fungi living in this layer can rapidly develop and infect the plant. In most turfgrass fields, this layer should not be allowed to accumulate more than 1.3 cm, and on golf course greens, 0.75 cm. The incidence of many diseases can be reduced by promptly removing this excessively accumulated layer from the soil surface. The appropriate time for this process is autumn for cool-season turfgrass species and summer for warm-season turfgrass species. For this purpose, thatch layer is removed from the area using vertical blade verticut machines and/or core cultivation machines used for aeration. Following this process, sanding strengthens the turf and, in particular, increases its resistance to fungal root rot. In small home gardens, this layer can be reduced by using lawn rakes, spiked shoes and hand-made needles (Beard, 1973; Açıkgöz, 1994; Harivandi, 1999; Emmons, 2000; Avcioğlu, 2014; Sever Mutlu, 2017).

1.2.6. Weed control

Be sure to keep your lawn free of weeds, as they can spread disease and weaken the turfgrass roots. Apply a suitable herbicide regularly to control weeds and promote lawn health and vitality (Beard, 1973; Açıkgöz, 1994; Patterson, 1995; Le Strange and Reynolds, 2004).

1. 2.7. Other factors

Urine and feces from cats, dogs, and other animals that can cause disease in lawn areas must be removed from the area. Additionally, precautions should be taken to protect against disease agents that can be carried by pests such as moles, mice, and mole crickets (Beard, 1973; Açıkgöz, 1994; Avcıoğlu, 2014).

2. THE MOST COMMON DISEASES IN LAWNS

Almost all lawn diseases are caused by fungi. Bacterial wilt is the only known bacterial disease of lawns. Fungi prefer high temperatures and high humidity. Because they lack chlorophyll, fungi are microscopic organisms that cannot produce their own nutrients and therefore rely on other organisms. Most fungi obtain the nutrients they need from living or dead plant material. Because fungi lack roots to absorb water and conduction systems to transport it, they become inactive in dry, moisture-free conditions. Therefore, fungal disease problems occur particularly in humid, overcast, rainy, and hot conditions, where water can remain on the surface of turfgrass leaves as a film for hours. Some of the most common fungal diseases that can occur in lawns are summarized below (Beard, 1973; Lamey and Arthur, 1996; Emmons, 2000; Vargas, 2005; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Wilen, 2016; Sever Mutlu, 2017). The list is made in alphabetical order of the most common English names of the diseases for easy access.

2.1. Anthracnose

Disease agent: Anthracnose (*Colletotrichum cereale*) is a root and young leaf rot pathogen that can affect all grass species and varieties (McCain, 1983).

Species and varieties affected by the disease: Anthracnose can affect all turf species, but is most prevalent on *Poa* and *Fescue* turfgrasses.

Disease symptoms: In humid weather conditions below 20 °C, irregular yellowish spots 1-3 cm in diameter appear. Affected young leaves often turn

yellow to brick red. Root rot can also occur. The roots of diseased plants can easily be pulled from the soil, revealing a black root mat. In hot and humid weather conditions above 25 °C, irregular, yellow-brown spots appear. Plants become shriveled, and a weak and patchy turf develops. Anthracnose usually occurs in compacted, moist, and nutrient-poor soils. The disease usually occurs from early summer to winter, but can occur year-round (McCain, 1983).

Influencing factors: Anthracnose usually occurs in compacted, moist, and nutrient-poor soils.

Disease fighting: Fungicides can be used to treat anthracnose very effectively. An Integrated Turf Management (ITM) approach will help prevent anthracnose infections. Mowing height should be increased, soil compaction should be reduced, nitrogen fertilizer should be applied if fertility is low, soil moisture content should be maintained at a reasonable level, leaf wetness should be kept to a minimum using good irrigation practices and dew removal programs, overly dry soils should be avoided by applying infrequent and deep irrigation, and *Poa annua* weed should be reduced from entering *Agrostis/Festuca* lawns (McCain, 1983; Patterson, 1995; Anonymous, 2025b;c).



Figure 2.1a. Disease on the turf area
(Anonymous, 2025b;c)

Figure 2.1 b. Disease on the leaves

2.2. Bacterial Wilt

Disease agent: Bacterial wilt and rot disease is the only bacterial disease seen in turfgrass and is caused by the bacterium *Xanthomonas translucens* pv. *graminis* (John and Roch. 2010; Anonymous, 2025d;e;f).

Species and varieties affected by the disease: *Lolium perenne*, *Agrostis stolonifera* and *Poa annua* species typically make up the structure of turfgrass. These are the species most favored by this pathogen (Mitkowski, 2005; Anonymous, 2025d;e;f).

Disease symptoms: Leaves begin to wilt from the tip down. Within a few days, the entire leaf wilts, turns blue-green, shrivels, and curls. At this early stage, the root and crown tissues appear white and healthy. The leaves soon turn reddish-brown. This is soon followed by death and decay of the entire plant. Symptoms of bacterial wilt and decay can be confused with anthracnose, red leaf spot, and leaf smut. (Mitkowski, 2005; John and Roch. 2010).

Influencing factors: The bacteria overwinter in infected grass. They are transmitted by splashing rain or running water, lawn mowers and other lawn equipment, or shoes. The bacteria enter healthy grass plants through wounds created by the mowers. Clusters of bacteria in the veins block the normal flow of water through infected plants, causing them to wilt and die. (Mitkowski, 2005; John and Roch. 2010; Anonymous, 2025d).

Disease fighting: Using one or more resistant varieties can eliminate the need for repeated antibiotic applications in susceptible turfgrass areas. The best long-term solution is to use resistant turfgrass varieties. Chemical control has reduced disease incidence in turfgrass areas using the antibiotic oxytetracycline. Preventive control is possible by wetting the turfgrass with an antibiotic and at least 50 gallons of water per 1,000 square meters. Applications should be made at 3-4 week intervals during the spring and fall months when the disease is active. (John and Roch. 2010; Anonymous, 2025d;e;f).



Figure 2.2a.b. Bacterial wilt disease on the turf areas (Anonymous, 2025f)

2.3. Dollar Spot (Mummy or Sclerotinia)

Disease agent: It is a turf fungal disease caused by four species in the genus *Clarireedia* in the family *Rutstroemiaceae* (Salgado-Salazar et al., 2018).

Species and varieties affected by the disease: This fairly common disease causes significant damage to numerous turfgrass species, particularly the delicate peacock grass (*Agrostis tenuis*), *Festuca* sp., and Bermuda grass (Salgado-Salazar et al., 2018).

Disease symptoms: The causative pathogen reaches its optimum development between 21-27 °C. It first appears as small (2.5-12.5 cm in diameter) brown, straw-colored to reddish circular spots, especially in closely mowed lawns. These spots later coalesce and spread into larger, irregular areas. In the early morning, when the turfgrass surface is still moist, fungal mycelia resembling white spiderweb threads can be seen in the diseased areas. A yellowish-brown band across the leaf width, compressed at both edges, is highly characteristic of this disease in leaf samples taken from diseased areas (Hartin et al., 2011; Landschoot, 2012; Laura, 2012).

Influencing factors: The main factors are inadequate fertilization, drainage, excessive grass buildup and night irrigation (Laura, 2012).

Disease fighting: Irrigation to remove dew from leaves in the early morning is recommended to reduce disease pressure, especially on golf and football fields. If the disease has been seen in the same location in previous years, preventative use of fungicides is recommended. Fungicides containing chlorhalonil, propiconazole, thiophanate-methyl, and iprodione are particularly effective in preventing the spread of the disease (Landschoot, 2012).



Figure 2.3a. Disease in the field **Figure 2.3b.** Lesion on the leaf (Kaminski, 2013).

2.4. Fairy Ring

Disease agent: This disease, which can occur in all grass species, can be caused by several species of fungi in the basidiomycetes class (*Agrocybe* spp., *Lepiota* spp., *Marasmius oreades*) (Anonymous, 2025g).

Species and varieties affected by the disease: Can be seen in all grass species and varieties (Anonymous, 2025g).

Disease symptoms: This disease, which can occur in all grass species, can be caused by several species of fungi in the basidiomycetes class (*Agrocybe* spp., *Lepiota* spp., *Marasmius oreades*). It appears as circular rings of turfgrass on the lawn, darker green than the surrounding turfgrass. The fungus breaks down organic material on the soil surface to release nitrogen for nutrition. The turfgrass plants in these areas, where the fungal mycelia are present, absorb this released nitrogen, resulting in a darker green color and rapid growth. These fungi do not directly harm the turfgrass. However, if the fungi release toxic compounds and/or if the mycelial layer they form on the soil surface forms a layer thick enough to prevent water from reaching the turfgrass's root zone, the turfgrass on the rings may die (Anonymous, (2025g).

Influencing factors: Fungi appear during rainy and humid weather.

Disease fighting: Direct fungicide application may not always yield positive results. Therefore, the area should first be well aerated to allow water to reach the root zone, and the accumulated thatch layer should be removed. Afterward, a sufficient amount of nitrogen application is recommended. If desired, fungicides containing azoxystrobin, flutolanil, metconazole, pyraclostrobin, and triticonazole can be used. (Vargas, 2005; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Anonymous, 2025g).



Figure 2.4a. Witch ring and **b.** Drying caused by disease (Anonymous, 2025g).

2.5. Grey Snow Mold

Disease agent: This disease is caused by the fungus *Typhula incarnata*. It is a less harmful form of pink snow mold. While its damage may appear widespread, it generally only damages the leaves and not the grass itself (Landschoot, 2012; Laura, 2012; Anonymous, 2025h).

Species and varieties affected by the disease: Disease affects all cool-season turf species (Anonymous, 2025h).

Disease symptoms: Symptoms are first noticed in late winter or early spring when the snow cover melts. The most distinctive symptoms are dead, matted leaf blades with white or brown crust that resembles paper pulp. The spots can range from a few centimeters to several meters in diameter and often coalesce to cover large areas of turf (Vargas, 2005; Anonymous, 2025h).

Influencing factors: It is common in years when a thick snow cover remains for a long time, from mid to late winter.

Disease fighting: Precautions include thoroughly mowing the lawn in the fall, removing and piling snow from sidewalks and driveways to avoid long-term snowdrifts on the lawn, and applying only moderate amounts of nitrogen fertilizer to the lawn in the fall. When symptoms appear with the spring snowmelt, diseased areas can be raked to break up crusted, matted leaves, and nitrogen fertilizer can be applied to encourage lawn recovery. For successful control, fungicides should be applied before the first permanent snow cover in the fall, typically in late November. There is no benefit to applying fungicides after symptoms of gray snow mold appear in the spring (Hartin et al., 2011; Anonymous, 2025h).



Figure 2.5a. Disease on lawn **Figure 2.5b.** Disease on leaves (Anonymous, 2025h).

2.6. Grey Leaf Spot or Helminthosporium

Disease agent: It is a disease caused by *Drechslera* and *Bipolaris spp.* Species (Anonymous, 2025₁).

Species and varieties affected by the disease: Although it generally damages cool climate turfgrass species, Bermuda and *Zoysia* turfgrass species are also quite susceptible to this disease (Elliott and Harmon, 2011; Anonymous, 2025₁).

Disease symptoms: Infected turfgrass develops circular or irregularly longitudinal spots on the leaves, leaf sheaths, and stems, with grayish-tan centers and dark brown-purple edges. The pathogens also cause dark brown rot on the roots and root crown, as well as on the leaves. Plants with infected root crowns die, especially in hot and windy weather. This causes the turf to thin and lose quality (Elliott and Harmon, 2011; Anonymous, 2025₁).

Influencing factors: Overwatering, poor drainage, low mowing height, excessive nitrogen fertilization, or nitrogen deficiency all contribute to the development and progression of this disease (Elliott and Harmon, 2011; Anonymous, 2025₁).

Disease fighting: First, the disease should be controlled by correcting the aforementioned poor growing conditions and improper maintenance practices, and if necessary, fungicides should be applied. Fungicides containing azoxystrobin, chlorothalonil, fludioxonil, iprodione, mancozeb, myclobutanil, propiconazole, pyraclostrobin, trifloxystrobin, triticonazole, and vinclozolin can be used (Elliott and Harmon, 2011; Anonymous, 2025₁).



Figure 2.6a. Disease on lawn **Figure 2.6b.** Disease on leaves (Anonymous, 2025₁).

2.7. Melting Out

Leaf spot and melting out actually are different diseases with similar symptoms and pathogen characteristics. Both pathogens can affect all parts of the plant (leaves, shoots, and roots). The major apparent difference between the two is that the melting out pathogen is active during cool, wet weather, while the leaf spot pathogen infects during the heat of the summer (Elliott and Harmon, 2011; Latin, 2024; Anonymous, 2025j).

Disease agent: Melting out (caused by *Bipolaris sorokiniana*) typically appears in April and May during cold, rainy weather (Anonymous, 2025j).

Species and varieties affected by the disease: The symptoms of leaf spot closely resemble gray leaf spot disease on perennial ryegrass (Latin, 2024).

Disease symptoms: Symptoms and disease characteristics from a distance, the symptoms of both diseases resemble a diffuse pattern of off-color turf. Close inspection of leaves from affected plants reveals decaying leaf blades with purple/brown lesions. These diseases can damage large areas of turf if favorable conditions persist (Latin, 2024; Anonymous, 2025j).

Influencing factors: Overwatering, poor drainage, low mowing height, excessive nitrogen fertilization, or nitrogen deficiency all contribute to the development and progression of this disease (Elliott and Harmon, 2011).

Disease fighting: Avoiding excess nitrogen fertility in early spring and midsummer will limit the severity of disease outbreaks. Raising the mowing height and relieving other stresses (like redirecting traffic away from affected turf) also will reduce disease severity and help hasten turf recovery. Also, avoiding irrigation during the late afternoon and early evening during the heat of the summer helps restrict the development and spread of leaf spot (Elliott and Harmon, 2011; Landschoot, 2012; Laura, 2012; Latin, 2024).



Figure 2.7a. Disease on lawn

Figure 2.7b. Disease on leaves (Latin, 2024)

2.8. Necrotic Ring Spot

Disease agent: It is caused by a root-infecting fungus (*Leptosphaeria korrae*) (Anonymous, 2025d;f;j).

Species and varieties affected by the disease: Fungus affects Kentucky bluegrass and annual bluegrass on golf courses, sports turf, professional landscapes, and home lawns (Landschoot, 2012; Anonymous, 2025d;f;j).

Disease symptoms: Symptoms first appear as small clustered patches of gray-tan colored turf. Because it is a root disease, initial above ground symptoms include die-back from the leaf tips followed by collapse of the leaf and decline of the entire plant. Infected roots appear stunted and necrotic when compared to healthy roots (Landschoot, 2012; Anonymous, 2025d;f;j).

Influencing factors: Initial outbreaks of the disease normally occur during cool wet weather in spring or fall months (Landschoot, 2012; Anonymous, 2025d;f;j).

Disease fighting: It is advised to locate those varieties or use another turfgrass species, such as perennial ryegrass for over-seeding damaged areas in the fall. A balanced nitrogen fertilizer program should be implemented, and irrigation should be deep and infrequent. Systemic fungicides containing active ingredients such as thiophanate-methyl and propiconazole should be applied in the spring (Hartin et al., 2011; Laura, 2012; Landschoot, 2012 Anonymous, 2025d;f;j).



Figure 2.8a. Disease on lawn **Figure 2.8b.** Disease on leaves (Anonymous, 2025f).

2.9. Pink Snow Mold (*Fusarium* or *Microdochium* Patch)

Disease agent: The disease is caused by a fungal pathogen, *Microdochium nivale*, that blights leaves but is not reported to affect roots and crowns (Anonymous, 2025b;f).

Species and varieties affected by the disease: The disease affects all grass species, particularly *Agrostis* species, *Poa annua*, and *Lolium perenne*.

Disease symptoms: The disease can appear not only after snowfall but also in cold, damp weather. Gray, wet spots, 4-6 cm in diameter, appear on the lawn. The spots then spread and coalesce. The outermost areas of the spots in the infected area become dark brown. Under ideal temperature and humidity conditions, a gray-pink cottony mycelium can be seen in lawns. This resembles a papery film after snowfall. After a while, the turfgrass plants begin to regenerate, starting from the center of the spots (Anonymous, 2025b;f).

Influencing factors: Overwatering, poor drainage, low mowing height, excessive nitrogen fertilization, or nitrogen deficiency all contribute to the development of this disease.

Disease fighting: Mow height should be adjusted to the recommended level. Diseased plant residue should be removed. Excessive nitrogen fertilizer should be avoided. Irrigation should be regulated to ensure adequate moisture levels without creating drought stress. At the first signs of the disease and in cases of mild disease, a solution of 6-7 g of iron sulfate per m² in 2 liters of water can be used. Autumn is the most suitable season for application, and the application should be repeated monthly depending on disease activity. For chemical control, 360 g/l of Hymexazol is used (Vargas, 2005; Latin, 2024;).



Figure 2.9a. Disease on lawn **Figure 2.9b.** Disease on leaves (Anonymous, 2025b).

2.10. Pythium Blight or Damping-Off

Disease agent: This disease, caused by *Pythium spp.* species, is the most rapidly developing and most damaging among turfgrass diseases (Kennelly, 2008; Anonymous, 2025j)

Species and varieties affected by the disease: It can infect all cool-weather turfgrass species and Bermudagrass species, but *Lolium perenne* is particularly susceptible to this disease.

Disease symptoms: The fungus can infect and kill all the grass in an area within a day if the weather is humid, rainy, overcast, and the average temperature is 26-35 °C. Circular or irregular straw-yellow spots appear in infected grass areas. In very high humidity conditions, the fungus's gray-white mycelium can be seen. Infected leaves are darker greenish-blackish, oily, and stick together. Infected leaves dry, turn reddish-brown, and eventually turn straw-yellow. In addition to leaves, *Pythium* species also cause rot in plant roots and crowns (Kennelly, 2008; Anonymous, 2025j).

Influencing factors: The disease is particularly severe and causes significant damage on turf surfaces subject to excessive nitrogen application, poor drainage, and poor air circulation. Often requires re-seeding the area (Kennelly, 2008 Anonymous, 2025j).

Disease fighting: To reduce disease pressure, it is essential to ensure good surface and soil drainage, avoid overwatering, and avoid high nitrogen applications, especially during hot and humid weather. Chemicals containing metalaxyl, propamocarb, mefenoxam, and mancozeb are effective against this disease (Kennelly, 2008; Anonymous, 2025j).



Figure 2.10a. Damage on turf. **Figure 2.10b.** Lesions on leaves (Kaminski, 2013).

2.11. Powdery Mildew

Disease agent: Powdery mildew disease in lawns is caused by the fungus *Blumeria graminis* (Latin, 2024; Anonymous, 2025a;b).

Species and varieties affected by the disease: It can be effective in all turfgrass areas (Latin, 2024; Anonymous, 2025a;b).

Disease symptoms: This disease causes the lawn to appear as if it's been dusted with flour. Small, white spore masses develop in circles on infected leaves. The white masses begin to grow and cover the entire blade. Small black dots, known as fruiting bodies, develop within the powdery spots. Severely infected grass begins to turn yellow (Latin, 2024; Anonymous, 2025a;b).

Influencing factors: This lawn disease develops on the surface of your lawn and is caused by many factors, including poor air circulation, ample shade, and high humidity (Latin, 2024; Anonymous, 2025a;b).

Disease fighting: Cut back or prune any plants that block sunlight from reaching your lawn. Remove or thin out thick vegetation that impairs air circulation around infected areas. Water early in the morning to allow excess moisture to drain quickly and keep shaded areas from becoming unnecessarily wet. Reduce fertilization to avoid heavy nitrogen applications, which can promote fungal growth. Fertilizing and weed control should always be performed to prevent this disease from recurring in the future. You can also use fungicides for faster control (Kerns, 2011; Hartin et al., 2011; Laura, 2012; Landschoot, 2012; Latin, 2024; Anonymous, 2025a;b).

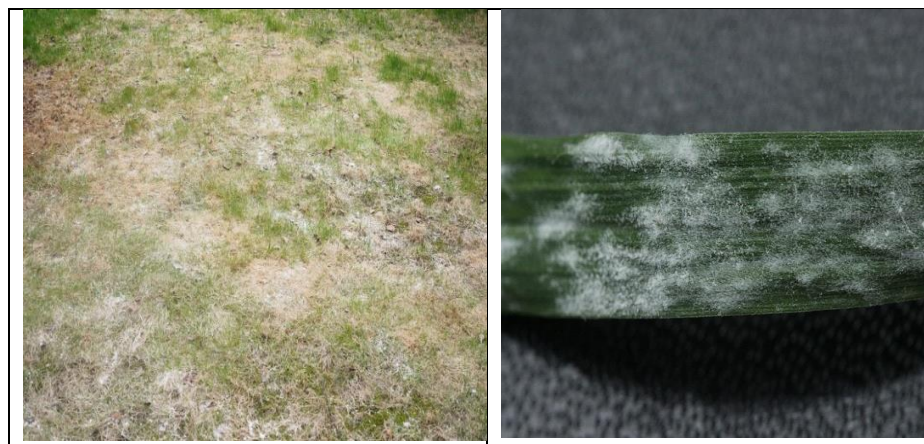


Figure 2.11a. Damage on turf.

Figure 2.11b. Lesions on leaves (Kaminski, 2013).

2.12. Red Thread

Disease agent: This disease is caused by the fungus *Laetisaria fuciformis* and is one of the most common diseases of turf during the rainy periods of late spring and early summer. (Anonymous, 2025a;b;c).

Species and varieties affected by the disease: This disease and pathogen are only seen in turfgrasses. It is seen in turfgrasses such as annual ryegrass, creeping fescue, Kentucky fescue, perennial ryegrass, fine fescue, and Bermudagrass that do not receive adequate nitrogen fertilization (Kerns, 2011; Hartin et al., 2011).

Disease symptoms: The disease is characterized by distinct signs and symptoms. Affected lawns appear as circular, water-soaked spots ranging from 5 to 60 cm in diameter. Dead leaves initially turn straw brown. Necrosis generally progresses from the leaf tip to the base. (Anonymous, 2025b).

Influencing factors: This disease is common when there is both heat and high humidity (Anonymous, 2025a;b;c).

Disease fighting: The best results against against the disease are achieved with regular application of conventional fungicides (Triadimefon and propiconazole). It can also be controlled with hexaconazole, myclobutanil, and penconazole (Kerns, 2011; Hartin et al., 2011; Anonymous, 2025a;b;c).



Figure 2.12a. Damage on turf. **Figure 2.12b.** Lesions on lawn (Anonymous, 2025b).

2.13. Rhizoctonia Blight (Brown, Large and Yellow Patch)

Disease agent: It is a fungal disease caused by the species *Rhizoctonia solani* (Beard, 1973).

Species and varieties affected by the disease: Although it damages many turfgrass species, *Agrostis sp.*, *Lolium perenne*, *Stenotaphrum secundatum* and *Poa pratensis* are the most damaged species (Beard, 1973; Vargas, 2005; Hartin et al., 2011; Anonymous, 2025a;b;c.).

Disease symptoms: It appears as small (5-10 cm) or sometimes much larger (meters in diameter) circular patches of light brown dead across the turf. Disease activity begins at an average of 15.5 °C and develops rapidly at 27-32 °C. Grayish-black mycelia formed by the fungus can be seen along the edges of the patches, especially in the early morning when the surface is moist. Infected turfgrass initially appears scalded, then wilts, turns light brown, and dies (Landschoot, 2012; Anonymous, 2025a;b;c).

Influencing factors: Extremely humid weather, particularly when accompanied by high temperatures, excessive nitrogen fertilization, thick felt layers (more than 1.5 cm), poor drainage, and shaded conditions increase disease pressure and damage (Hartin et al., 2011).

Disease fighting: When excessive nitrogen is applied, the severity of diseases caused by *Rhizoctonia* species increases. It is recommended that fertilizers contain adequate amounts of phosphorus and potassium to increase plant tolerance to disease. Good surface and subsurface drainage is essential to reduce moisture in turf areas. Fungicides containing azoxystrobin, fenorimol, propiconazole, thiophanate-methyl, iprodione, chlorothalonil, thiram and mancozeb can be used. In Türkiye, fungicides containing 26.7% Boscalid + 6.7% Pyraclostrobin are used (Vargas, 2005; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Anonymous, 2025a;b;c).



Figure 2.13.a. Disease spots on lawn **b.** Disease lesions on leaves (Kaminski, 2013).

2.14. Rust

Disease agent: Rust disease is caused by different types of *Puccinia spp* (McCain, 1983; Anonymous, 2025a;b;c).

Species and varieties affected by the disease: It is especially effective on *Lolium perenne*, *Cynodon sp.*, *Poa pratensis*, *Zoysia japonica* and *Festuca* turfgrass species (Anonymous, 2025a;b;c).

Disease symptoms: The causative agent, the fungus, infects the leaves, stems, and root crowns of turfgrass plants, causing rust. Pale yellow spots initially appear on infected leaves. Later, rust-colored, spore-bearing pustules begin to spread from the plant's cuticle. While the disease reduces turf quality, it doesn't kill the plants, so fungicides may not be necessary except in areas where high turf quality is desired (Beard, 1973; Emmons, 2000).

Influencing factors: Turfgrass plants grown in nutrient-poor soils and in shade and arid conditions are more susceptible to this disease (Landschoot, 2012; Laura, 2012; Anonymous, 2025a;b;c).

Disease fighting: To reduce disease progression, appropriate fertilization and irrigation should be applied to the type of turf used. Spore populations in infected areas should be reduced by regularly mowing the lawn and removing mowing debris. To reduce the damage caused by Pythium root rot, methods that increase mowing height and promote root development should be used. If desired, fungicides containing azoxystrobin, mancozeb, mancozeb plus copper hydroxide, metconazole, myclobutanil, propiconazole, pyraclostrobin, triadimefon, trifloxystrobin, and triticonazole can be used (Kennelly, 2008; Wilen, 2016; Sever Mutlu, 2017; Anonymous, 2025a;b;c).



Figure 2.14a.b. Rust disease on leaves (Landschoot, 2012)

2.15. Slime Molt

Disease agent: These fungi (*Mucilago*, *Physarum*, and *Fuligo* species) differ from most turf pathogens in that they do not directly infect the plant (Emmons, 2000; Landschoot, 2012; Anonymous, 2025a;b;c).

Species and varieties affected by the disease: It can affect all grasses, especially *Poa pratensis* (Anonymous, 2025a;b;c).

Disease symptoms: Turfgrass leaves can become covered with a slimy, creamy-white growth. This slime develops into gray or blue, pinhead-sized spore masses within a few days. Affected areas can range from a few centimeters to several meters wide and vary in shape from rings to lines or patches. If slime molds persist in the grass for an extended period, grass leaves may become deprived of sunlight and begin to turn pale green or yellow (Landschoot, 2012; Anonymous, 2025a;b;c).

Influencing factors: During warm, wet weather periods, slime molds migrate onto turfgrass leaf surfaces, producing massive amounts of spore-like structures of varying colors, often forming white, yellow, orange, blue, or gray patches in turf (Landschoot, 2012; Laura, 2012).

Disease fighting: Slimy molds, which don't harm grass, can be removed by sprinkling leaves with water. Removing dry spore masses by mowing, raking, brushing, or sweeping will help restore the lawn to its normal appearance. Chemical control measures are not necessary (Beard, 1973; Emmons, 2000; Landschoot, 2012; Laura, 2012; Anonymous. (2025a;b;c).



Figure 2.15a. Spore-like structures on leaves **b.** Growing on mulch (Landschoot, 2012)

2.16. Southern (Athelia) Blight

Disease agent: Gray rot, also known as southern blight, is a disease caused by the fungus *Sclerotium (Athelia) roffsii* (Ünal, 2019).

Species and varieties affected by the disease: It can be found in all turfgrass species worldwide (Anonymous, 2025a).

Disease symptoms: This fungus can cause damping-off, root and crown rot. The first symptom on seedlings is a dark brown lesion at or below the soil line. Complete infestation of the stem tissue quickly leads to plant collapse and death. In older plants, the lesions girdle the stems, causing the plants to wilt without leaf discoloration. Severely infected plants may eventually die. The lesion continues to expand, causing a root rot that extends below the soil line and up to several centimeters above the soil line (Ünal, 2019).

Influencing factors: This fungus is an efficient saprophyte and can survive in soil and plant debris for several years. It can be spread by surface water and by transport of infected soil on agricultural equipment. High temperatures (30-35 °C) and high humidity levels favor disease development. The fungus is particularly prevalent in tropical and subtropical regions characterized by high humidity and temperature, followed by periods of drought (Ünal, 2019; Anonymous, 2025a).

Disease fighting: A good hygiene program, including the uprooting and burning of all infected plants, combined with agricultural practices such as careful management of soil moisture and deep plowing of debris, can help reduce losses from this disease. Fungicides and fumigation can also help reduce losses from this disease (Ünal, 2019; Anonymous, 2025a).



Figure 2.16a. Disease on lawn



Figure 2.16b. Disease on plant (Ünal, 2019)

2.17. Summer Patch

Disease agent: This hot-weather disease is caused by the fungus *Magnaporthiopsis poae* (Anonymous, 2025b).

Species and varieties affected by the disease: The disease occurs in annual fescue, Kentucky fescue, and fine fescue (Landschoot, 2012).

Disease symptoms: Symptoms of summer patch in lawns, grounds, and athletic fields typically begin as circular areas of wilting Kentucky bluegrass or fine fescue turf, progressing to reddish-brown or light brown sunken patches, often with a tuft of healthy grass in patch centers. Patches range from a few inches to over 3 feet in diameter and can appear as a mix of rings, crescents, or spots of various sizes. In severe cases, patches of diseased turf can coalesce, making field diagnosis difficult (Landschoot, 2012; Anonymous, 2025b).

Influencing factors: Hyphal threads of *M. poae* on infected plant debris can be spread to other areas by aeration teeth, vertical cutting blades, excavation equipment, or soil movement.

Disease fighting: Cultural measures such as aerating the soil and improving drainage, increasing mowing height, and fertilizing with ammonium sulfate to lower soil pH in spring and fall should be implemented. Furthermore, on golf courses, summer spot can be controlled with penetrating fungicides, provided preventative applications (3-4 weeks before symptoms develop) are applied at the highest recommended label doses (Landschoot, 2012; Anonymous, 2025b).



Figure 2.17a.b. Summer patch symptoms on a lawn in central Pennsylvania (Landschoot, 2012)

2.18. Take All Patch

Disease agent: This disease is caused by the fungus *Gaeumannomyces graminis* var. *Avenae* (Landschoot, 2012; Anonymous, 2025b).

Species and varieties affected by the disease: The disease affects all turfgrasses (Landschoot, 2012; Anonymous, 2025b).

Disease symptoms: Typically appear as rings, crescents, or large patches with centers covered with annual bluegrass, fine fescue, or weeds. These patches range in diameter from a few centimeters to 90 cm diameter, and older patches are often slightly sunken relative to the surrounding turfgrass. Symptoms become most pronounced after the turf is stressed by hot, dry weather. The roots and crowns of affected plants are often brown or black.

Influencing factors: This disease is most frequently seen between June and October on newly established sloped turfgrass fields in sandy soils, on recently fumigated soils, or on new golf courses constructed in previously forested or wetland areas (Landschoot, 2012; Anonymous, 2025b).

Disease fighting: Control measures should be taken before patches appear. In high pH soils, use an acidifying fertilizer such as ammonium sulfate to lower the soil pH to between 5.5 and 6.0. However, high ammonium sulfate levels can cause leaf burn in turfgrass during hot weather; therefore, low rates of ammonium sulfate should be applied and watered into the turf in spring and fall. Manganese sulfate should be applied in spring with sufficient water to penetrate the root zone. Some penetrant fungicides can control entire patches if applications are timed to inhibit *G. graminis* growth and infection before visible patch symptoms appear in the turf (Landschoot, 2012; Anonymous, 2025b).



Figure 2.18a.b. Take-all patch symptoms on lawn (Landschoot, 2012)

2.19. Typhula Blight

Disease agent: This disease is often called gray snow mold or spotted snow mold. The cause of this disease is the fungi *Typhula incarnata* or *T. ishkariensis*. *Typhula incarnata* is the causative agent of gray snow mold, and *T. ishkariensis* causes spotted snow mold (Dale, 201).

Species and varieties affected by the disease: This disease is a significant problem in cool-season turfgrass during the winter months (Dale, 2010).

Disease symptoms: This disease is often called gray snow mold because of the gray patches that appear after the snow melts. After the snow melts, patches of gray to grayish-white mycelium can be found, measuring 15 to 30 cm in diameter. Within the patches, infected grass leaves develop rusty or reddish-brown sclerotia, often up to five millimeters in diameter. Gray snow mold can cause the infected host to thin and even die (Dale, 2010; Stackhouse et al., 2020; Anonymous, 2025j).

Influencing factors: The disease occurs at temperatures around 0°C and high humidity (Dale, 2010; Stackhouse et al., 2020).

Disease fighting: If left uncontrolled, it can cause serious turf loss. It is usually controlled with fungicide applications and other cultural practices in late autumn (Dale, 2010). This chemical application should be made in late autumn, before the first snowfall. Possible chemical applications include a chlorothalonil product with a demethylation inhibitor or DMI, a thiophanate-methyl product with a DMI, or a chlorothalonil product with an iprodione. Finally, mowing the grass until it is dormant may be beneficial to keep the turfgrass short (Dale, 2010; Stackhouse et al., 2020; Anonymous, 2025j).



Figure 2.19a. Disease on lawn



Figure 2.19b. Disease on plant (Dale, 201).)

2.20. Yellow Tuft or Down Mildew

Disease agent: Yellow tuft, or downy mildew, is caused by the water mold fungus *Sclerophthora macrospora* (Anonymous, 2025k).

Species and varieties affected by the disease: The disease occurs on most cultivated turfgrass species, cereals, and many weedy grasses (e.g., crabgrass), but seldom causes extensive losses, except on turfs maintained at shorter mowing heights, such as golf greens (Emmons, 2000; Vargas, 2005; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Anonymous, 2025c;d;f;k).

Disease symptoms: Early symptoms of yellow spot disease include the appearance of small clusters of slightly stunted, light green, or yellow grass plants, slightly thickened or enlarged leaf blades, and poor leaf development. When the disease is severe, small yellow spots (yellow spot) may be present in the turf, ranging from 4-60 cm in diameter (Emmons, 2000; Vargas, 2005; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Anonymous, 2025c;d;f;k).

Influencing factors: Downy mildew are most noticeable in late spring and fall and appear first in poorly drained areas.

Disease fighting: Drainage should be good, overwatering should be avoided, lawns should not be mowed when wet, excessive fertilization should be avoided and balanced fertilization should be implemented, weed control should be implemented. Spring applications of Metalaxyl fungicide before infection occurs are most effective in controlling yellow tuft (Emmons, 2000; Vargas, 2005; Kennelly, 2011; Hartin et al., 2011; Landschoot, 2012; Laura, 2012; Anonymous, 2025c;d;f;k).



Figure 2.20a. Disease on lawn **Figure 2.20b.** Disease on plant (Kaminski, 2013).

3. CONCLUSION AND SUGGESTION

Various pathogens emerge over time in turfgrass fields and can infect grass plants, causing diseases (Beard, 1973; Açıkgöz, 1994; Lamey, and Arthur, 1996; Le Strange and Reynolds, 2004;. Martinez et al., 2009; Kerns, 2011; Landschoot, 2012; Laura, 2012; Avcioğlu, 2014; Sever Mutlu, 2017).

Disease control always requires extensive labor, effort, and expense. Therefore, measures must be taken to prevent disease transmission.

Generally, for any disease to develop, a disease-resistant plant, a warm and humid environment, and the presence of a pathogen are necessary (Wilen, 2016). These three factors must coexist to prevent diseases. Therefore, selecting the most suitable, and if possible, native, turfgrass species and varieties, considering the intended use and best adaptation to the region, is the most important step in disease prevention. Because native turfgrass species and varieties were developed using natural genotypes that have existed in the region for centuries, they are better adapted to limited maintenance conditions (less water, fertilizer, etc.), especially in semi-arid and arid climates, and experience fewer disease and pest problems (Lamey, and Arthur, 1996; Le Strange and Reynolds, 2004;. Martinez et al., 2009; Kerns, 2011; Landschoot, 2012; Laura, 2012; Avcioğlu, 2014; Sever Mutlu, 2017).

Among the selected species, genetically disease-resistant species and varieties should be preferred. The optimal time for seed sowing should be determined. Care should be taken to ensure that the grass species and variety selected for the adaptation zone are appropriate for the microecological conditions of the area, the intended use (football, golf course, or home garden), the required level of maintenance, and the expected quality. Species with good shade tolerance in shaded areas, good resistance to trampling and crushing in heavily used areas, and drought-tolerant species should be preferred in areas with limited irrigation (Lamey, and Arthur, 1996; Le Strange and Reynolds, 2004;. Martinez et al., 2009; Avcioğlu, 2014; Sever Mutlu, 2017).

Proper fertilization, watering, mowing, aeration, matting prevention, sanding, rolling, raking, weed control, cleaning up pet and wild animal feces, and removing all potentially disease-causing waste are crucial for healthy and strong turf growth and renewal. Taking all these precautions will help keep your lawn healthier.

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CHAPTER 3

GUAR (*Cyamopsis tetragonobla* L. Taub.): PROMISING PLANT OF FUTURE

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1. INTRODUCTION

Guar (*Cyamopsis tetragonoloba*), an annual species of legume, has been cultivated since ancient times in the fringes of South Asia for this drought-tolerant plant food (the soft pods are used as a vegetable), fodder, and symbiotic nitrogen fixation (Ravelombola et al., 2021). It has become one of the most valuable cultivated plants, especially thanks to the galactomannan found in its seeds in the 1950s. Guar gum, a galactomannan polysaccharide that constitutes approximately 80-90% of the seed endosperm, is economically important (Verma et al., 2025). Hydrocolloid guar gum acts as a thickener, stabilizer and emulsifier in food, pharmaceuticals, textiles and oil drilling (Pal et al., 2025).

To meet the demand of oil fields, India produces 1-1.25 million tonnes of guar seed annually, which accounts for 80% of the world supply. Most of the seed is grown in Rajasthan, Gujarat and Haryana in northern India. In addition, it is grown for guar gum in Pakistan, Texas, Australia and Africa. Today's cultivated guar was developed and cultivated from the wild relatives of Africa, *C. senegalensis* and *C. serrata* (Krishnan et al., 2011). It has been cultivated with rainwater for years in South Asia, especially during monsoon rains. Breeding studies on cluster bean have improved pod production, grain yield, gum quality and drought resistance traits (Patel et al., 2022).

Guar is generally a tall plant, depending on the variety. Clusters containing a number of pods, the number of which varies depending on the genotype and growing conditions, emerge from the axils of the leaves, which consist of three leaflets in the compound leaf form located on the stem (Gautam et al., 2024). The number of seeds in a guar pod varies between 5 and 12, while the weight of a thousand seeds is 25-40 g (Santonoceto et al., 2019). Its seed is rich in galactomannan gum (35-40%) and protein (43-46%) (Benakanahalli et al., 2021). The most valuable part of the guar plant is guar gum, a polysaccharide with a galactomannan structure obtained from the endosperm of its seeds.

Although seed content and vegetative traits are controlled by genetic makeup, seed gum content, first pod height, branching pattern and pod size are highly affected by plant growing conditions. Unlike most field crops, guar can be grown under conditions of high temperature and low rainfall (Gautam et al., 2024). Its deep taproots and efficient stomatal management enable it to resist moisture stress, but prolonged drought during flowering or seed formation

reduces yield. Prolonged waterlogging suffocates guar roots and prevents nodulation (Zhang et al., 2025). Guar grows best in sandy loam soils with neutral to slightly alkaline pH (7.0-8.5) and can withstand moderate salinity, but severe salinity reduces growth and yield (Acharya et al., 2022). Legumes such as guar fix atmospheric nitrogen in their root nodules, increasing soil fertility and reducing the use of synthetic nitrogen fertilizers. Guar plant is tolerant to drought and salinity.

Guar's biotic problems limit yield despite its resistance. The biotic problems such as bacterial blight, Alternaria leaf spot, anthracnose and powdery mildew in guar plant negatively affect the photosynthetic areas of plants, causing leaf shedding (Manley et al., 2023). The most important pests of guar are plant and pod pests. The most important pests are aphids, jassids, whiteflies, pod borers and *Contarinia texana* (Saad et al., 2017). Disease-free seeds, resistant varieties, crop rotation and timely fungicide/insecticide applications are important in growing a quality product. Integrated pest management, including genetic resistance, cultural habits and biological controls, is becoming increasingly common in countries with extensive cultivation. Breeders are promoting disease and pest tolerance in new guar varieties. In this context, researches continue on *Rhizobium* and arbuscular mycorrhizal fungi to reduce pesticide use by increasing plant vitality and disease resistance.

One of the most important issues in cultivation is drying the pods and reducing the moisture content of the seed to safe levels before processing. Mechanized harvesting and storage, which have become widespread in recent years, have reduced losses in India's small-farm-dominated guar sector and increased export quality criteria (Reis et al., 2021). Today, one of the most important uses of guar gum outside of industry is its use directly for human health, especially in medical gels and biodegradable polymers. Guar, a legume that is tolerant to adverse conditions compared to many legume plants, has a great agro-industrial potential. In this book chapter, the vegetative properties of the guar plant and its adaptation to different conditions are evaluated.

2. CLASSIFICATION, ORIGIN AND DOMESTICATION

Cyamopsis is a genus of which wild species *C. serrata* and *C. Senegalensis* form the cluster bean or sometimes called guar is a developed variety of these two species (Krishnan et al., 2011). In the field of guar breeding,

due to the presence of stress resistance and diseases, research has greatly benefited due to the genetic material these wild species offer (Rani et al., 2025). Belonging to the family *Fabaceae*, the subfamily *Faboideae*, with an estimated genome size of around 580 Mb and a diploid chromosome number of $2n = 14$ (Priyadarshini & Madhanakumari, 2023; Li & Deve et al. 2024), guar is a plant species.

Guar is an annual legume with indeterminate growth habit and is single stemmed or branching depending on the genotype. Its three-leafed compound leaves that are arranged alternately are complemented by flowers of pale white to violet hues in small clusters on the branches in the axils (Deepashree et al., 2022). The plant gets its name from the characteristic clusters of flat and narrow pods between 4 and 10 cm long. In genotypes produced for seed thousand grain weight is only between 25-40 g.

Guar (*Cyamopsis tetragonoloba*) is an African native plant and has been domesticated in South Asia, especially India and Pakistan for thousands of years (Rani et al., 2025). Archaeological and ethnobotanical evidence indicates that guar has been exploited in these regions since prehistory because of its principal edible fresh pods and as a fodder (Gautam et al., 2024). It is being reported that characteristics such as drought resistance, high gum content and adaptation to semi-arid ecosystems have been enhanced as a result of selection pressures exerted during the domestication process (Li et al., 2024; Rani et al., 2025). Today, India accounts for the majority of the world's guar seed production (Ravelombola et al., 2021). Apart from Pakistan, the Texas High Plains of the United States, Australia and some parts of Africa are among the important production areas. In India, particularly the state of Rajasthan is the primary production centre of the country as stated by Rani et al. (2025).

In recent years, advances in genomic technologies have provided important findings regarding the domestication, taxonomy and molecular biology of guar. Genome assembly studies at the chromosome level have enabled the assembly of approximately 99.8% of the genome into seven pseudomolecules, yielding approximately 34,700 gene models (Li et al., 2024). With the availability of these high-resolution genomic tools, guar-specific photoperiodic adaptation mechanisms, gene family expansions and contractions and differentiation events compared to other legume species can be investigated in great detail (Li et al., 2023). In addition, molecular evidence

for the development of high-quality seed endosperm was obtained. In particular, upregulation of genes involved in fruit-specific galactomannan biosynthesis was found to be critical to the abundance and industrial value of guar gum (Li et al., 2024).

Current genomic data suggest that guar has experienced a bottleneck in the domestication process and as such has less genetic diversity than its wild relatives. However, it is reported that there is still great allelic variation in cultivated germplasm, especially of stress tolerance, and gum quality (Rani et al., 2025). This clearly shows the value of the wild relatives in widening the genetic base (Makino et al., 2018). Indeed, the mapping of domestication-associated loci and the development of molecular markers, as well as the implementation of genome wide association studies (GWAS) have been greatly helped by the availability of high-quality reference genomes (Li et al., 2024).

Although studies on the taxonomy, domestication, and genomic characterization of guar have made significant progress in recent years, some fundamental research gaps still remain. In particular, a detailed reconstruction of the domestication process is needed, gene flow between wild populations and cultivated varieties must be clearly demonstrated, and the socio-economic impacts of guar must be comprehensively assessed under different agro-ecological conditions and cultural production systems (Sheteiwy et al., 2023; Rani et al., 2025).

3. A GENERAL OVERVIEW OF BOTANY

Cluster bean has a wide phenotypic diversity encompassing both quantitative and qualitative traits. While quantitative diversity includes agronomic traits such as plant height, pod length, number of pods per plant and seed yield (Jukanti et al., 2015; Priyadarshini & Madhanakumari, 2023; Khatoon et al., 2024), qualitative diversity includes plant type, leaf morphology, degree of hairiness, flower color and pigmentation, and seed shape and surface characteristics. Principal component and cluster analyses on collections of germplasm indicated genotypes that had excellent production potential and long pod structure and high gum content (Boghara et al. 2016). Because the traits, particularly the length of pods and the number of pods per plant, are highly heritable, they are suitable selection criteria in breeding programmes (Lavanya et al., 2021).

Mature cluster bean seeds consist of three basic parts: outer protective seed coat, 35-42% endosperm and 43-47% embryo. The endosperm, which is the most economically valuable part, consists of 80-90% galactomannan and is known to have a mannose/galactose ratio of about 2:1 by Manivannan et al. (2016), Priyadarshini & Madhanakumari (2023). This structure of galactomannan is related to the high rheological properties of guar gum, which can be used so diversely in the food, pharmaceutical, textile and petroleum industries (Jukanti et al., 2015; Manivannan et al., 2016).

Extensive anatomical studies indicate that inflorescences and flower buds possess different morphological changes at different developmental stages (Sharma et al., 2021). In addition, structural adaptations, such as the accumulation of lignin and the changes in the cell wall, have been found to restrict water loss through mechanical strength (Narayan et al., 2023; 2025). Trichome density and adaptation in stomata has increased water use efficiency under drought stress conditions and contributes to successful growth of the species in marginal and semi-arid ecosystems (Narayan et al., 2025).

This great structural and phenotypic diversity makes cluster bean a useful genetic resource for both conventional and molecular approaches to the breeding approach. High variation and heritability in yield and quality are offering tremendous scope for selection-based improvement studies (Lavanya et al., 2021). In particular, parameters such as the galactomannan content and viscosity related to the economic importance of guar gum, the stability of the yield in arid conditions and the quality of seeds are among the target parameters in the breeding programs (Manivannan et al., 2016; Sharma et al., 2021).

As a result, botanists define the cluster bean as a tall, indeterminate type of growing plant, with clustered pods and rich seeds that are high in galactomannan. The wide phenotypic diversity, drought resistance and high industrial value of the species is a strong basis for genetic improvement studies as well as increasing use in the food, pharmaceutical and non-food sectors.

4. AGRICULTURAL TRAITS AND CULTIVATION

In such areas where cultivation of some other plants is not economical, cluster bean is grown because of its resistance to drought and low requirement of water (Pathak & Roy, 2015). It is reported that the cluster bean is not only drought resistant but salt tolerant (Francois et al., 1984). The most important

vegetative feature of the bean in its adaptation to arid conditions is its deep root system. It is one of the rare plants able to be grown in high temperatures and water deficiency, due to its deep root system, its ability to use water in the lower profile of soil and to its thick epidermis of the leaves, which allows less transpiration (Alexander et al., 1988).

Cluster bean is grown without irrigation after monsoon rains (Kharif season) in India and Pakistan (Ali et al., 2004), whereas in most other countries it is grown with irrigation. Some of the studies on water consumption of cluster beans was done in the USA. In one of these studies, it was determined that irrigation was appropriate three times at different development stages in grain cultivation (Alexander et al., 1988). According to the research results, it was recommended that the first irrigation be done approximately 20–35 days after emergence before flowering, the second irrigation be done approximately 60 days after emergence (while the first pods begin to form and flowering continues in other plant parts), and the third irrigation be done 80 days after emergence (while grain filling continues in the middle pods). The same researchers determined that the third irrigation period (midpot period) was the most critical period for high grain yield (Alexander et al., 1988). In the USA of Texas, it has been reported that the bean should be grown in dry conditions or under limited irrigation conditions, and that it is not suitable for cultivation under full irrigation conditions (as it is a plant adapted to dry conditions) (Trostle, 2013). Conducted researches in different regions of Turkey has shown that irrigation should be done at least three times, and that approximately 400 mm of water is needed in one growing season (Akçura et al., 2021).

While the lowest temperature for cluster bean for grain purposes is 8 °C, the most suitable temperature is between 24 - 30 °C (Baligar & Fageria, 2007). In addition, it has been stated that the basic temperature requirement of the bean is 14.6 °C and the cultivation temperature limits are in the range of 10–45 °C (Daisy, 1979; Angus et al., 1980; Ecocrop-FAO, 2007). Although cluster bean is a plant that can be grown in all types of soil conditions, it gives high yields in fertile soil conditions with good drainage. Only in heavy clay soils should caution be exercised when cultivating (Fageria, 1992). Although there is not much information about the appropriate soil reaction, it has been reported that it can be grown at pH levels of 5.5 – 8.5, as with other plants (Singh, 2014).

In the preliminary studies carried out in Çanakkale of Türkiye between 2011 and 2014, a planting time trial was also established, with the first planting date being March 15 and the last planting date being June 15. Ideal plant emergence was not achieved in plantings before May 15 (Unreleased data). For this reason, it is appropriate to plant it in May and June, as in other warm climate plants grown in our country. The potential of growing early types as second crops in our regions where second crop farming is carried out can also be evaluated in future studies. In cluster bean, the distance between rows and within rows varies depending on the plant type (Singh, 2014). In grain types, those that grow upright and form fewer side branches are grown at 30–60 cm between rows and 8–20 cm between rows (Undersande et al., 1991; Gresta et al., 2013; Anonymous, 2014; Kelby, 2015). In crop cultivation, since it is aimed to obtain more herbage from the unit area and types that form more side branches are preferred, 20–30 cm between rows and 8–15 cm between rows is used (Singh, 2014). In trials conducted in different locations in India, 60 cm x 10 cm, 45 cm x 10 cm and 30 cm x 10 cm row spacings were used, while ideal grain yields were obtained from the 45 cm x 10 cm planting norm, while in late planting locations, the 30 cm x 10 cm planting norm had higher grain yields (Yadav et al., 2014). In another study conducted in India, combinations of 45 cm x 30 cm, 60 cm x 30 cm and 45 cm x 45 cm inter-row and intra-row distances were evaluated at four different planting times, and it was determined that the 45 cm x 30 cm combination had the highest grain yield at the planting time on July 1 (Deka et al., 2015).



Figure 1. A genotype with an upright growth nature at day 90 (original)



Figure 2. A genotype that forms extensive side branches at day 90 (original)



Figure 3. Genotype that does not form side branches on the 90th day (original)

Cluster bean is a plant that can be used in sustainable agriculture and has the ability to improve soil structure (Kumar, 2005). Under normal growing conditions, there is no need for fertilizer when the pre-plant is fertilized (Fageria, 1992). In Rajasthan, the most cultivated part of India, cluster bean is commonly grown without fertilization in fields that are left fallow for two or three years and used as pasture (Fageria, 1992). Approximately 15% increase in grain yield was observed in plants planted after the cluster bean in the crop rotation. Because of this feature, it is sufficient to apply 2 kg da⁻¹ pure nitrogen and 4 kg da⁻¹ pure phosphorus fertilizer in a growing season in the fields where it is first grown (there is also a need for studies on symbiotic bacterial strains in our country) (Singh, 2014). Depending on the nature of the development of the cluster bean, the plant height varies between 50 cm and 300 cm (Fageria, 1992; Baligar & Fageria, 2007). Generally, plant height is the longest in upright growing types and the shortest in horizontally growing branching types (Pathak, 2015). Images of different plant types of cluster bean in Çanakkale conditions are given in Figures 1, 2 and 3. The cluster bean is a genetically indeterminate plant that flowers only as long as it photosynthesizes. It is fertilized entirely with its own pollen (Stafford & Hymowitz, 1980). The flowers are in the form of a stem, mostly white, although there are also types with purple colors (Pathak, 2015). In some types, a flower cluster emerges from each leaf axil (Figure 4). In some types, a cluster of flowers emerges from a distance of about 3 cm on the entire stem (Figures 4 and 5).



Figure 4. Flower of cluster bean in Çanakkale conditions (Original)



Figure 5. General appearance of cluster bean pods in Çanakkale conditions (Original)

Cluster bean has a short vegetation period. It reaches harvest maturity in 90–120 days, depending on the genotype. The pods are angular and covered with dense hairs (Figure 6). The first pods begin to form 3–6 weeks after emergence (Stafford & Hymowitz, 1980). Pod length varies between 5-10 cm (Ganal, 1998). The types consumed as vegetables have long pods, while the types consumed as grains have short pods (Pathak, 2015). The number of seeds in a pod is between 6 and 10 (Fageria, 1992; Ganal, 1998). The number of pods in an axil varies between 3 and 30 (Figure 7). Girish et al. (2012) examined 20 traits, including the number of pods per plant, of 45 genotypes collected from different geographical regions, and reported that 7 different genotype groups were formed based on the traits examined, and that a hybridization program could be created with certain genotypes between the groups.



Figure 6. (a) Green pods of cluster bean in Çanakkale **(b)** Mature pods of cluster bean (Original)

In the selection studies carried out on bean, it was determined that the traits that have a high correlation with grain yield are the number of pods per plant, single plant grain yield and the number of grains per plant (Raghuprakash et al., 2009; Pathak et al., 2011; Sultan et al., 2012). In the preliminary trials and selection studies we conducted in Çanakkale conditions, the number of pods per plant varied between 70 and 300 depending on the genotype (Figure 6a). One of the most important features of the cluster bean is that it does not have the pod cracking problem that is a problem in many legume plants (Figure 5, 6b). In other words, there is no grain loss in cultivation due to the

development nature of the plant. It is a plant suitable for mechanical harvesting. However, in some types, the first pods are close to the soil surface, so it would be useful to focus on the types whose first pods are above the ground in grain cultivation (Figure 7).



Figure 7. Genotypes with different first pod heights in Çanakkale conditions (Original)

In a study conducted to characterize 140 cluster bean genetic resources in terms of morphology, agronomy and grain yield under Indian conditions, it was found that single plant grain yields varied between 7.4 g plant^{-1} and 134 g plant^{-1} (Jukanti et al., 2015). The average grain yield of cluster bean was determined as $150\text{-}250 \text{ kg da}^{-1}$ in India, $70\text{-}100 \text{ kg da}^{-1}$ in Pakistan, $45\text{-}224 \text{ kg da}^{-1}$ in dry conditions in Texas, USA (average $135\text{-}300 \text{ kg da}^{-1}$ under irrigated conditions), and $200\text{-}300 \text{ kg da}^{-1}$ in trials conducted in Italy (Zahoor, 2007; Gresta et al., 2013; Trostle, 2013; Anonymous, 2014). In Australia, which has established a national breeding program for cluster bean, it has been reported that the average grain yield of cluster bean is 400 kg da^{-1} under rainy conditions (Anonymous, 2014). In a study conducted to select cluster bean types with different numbers of side branches at different plant densities, it was determined that the grain yield in the low-branching genotypes in row planting was 25% higher than the high-branching genotypes (Beech et al., 1989).

Cluster bean is a plant that adapts well to the coastal regions of our country and the Southeastern Anatolia region. It is inevitable that the cultivation of cluster bean will become widespread in Turkey due to its high economic return, the use of all vegetative parts and seeds, and its potential to be a good crop rotation plant with other plants in irrigated agricultural areas. The most

important limiting factor in the prevalence of cluster bean cultivation is the lack of an industry in our country, especially for processing the cluster beans.



Figure 8. Plant grain yield and grain appearance of some lines of cluster bean (Original)

5. SEED STRUCTURE AND CHEMICAL PROPERTIES

Its seeds are in different shades of yellowish green, red and black. When seed morphology was examined, it was determined that the shell constituted 14–17% of the total seed mass, the endosperm 35–42% and the embryo 43–47% (Benakanahalli et al., 2021). The endosperm, the most economically valuable part, is rich in galactomannan and is the main source of guar gum, which is widely used in industry (Rani et al., 2025).

Table 1. Chemical content of Cluster bean (*Cyamopsis tetragonoloba*) seeds

Seed Part	Weight ratio (%)	Chemical Composition					
		Protein (%)	Lipid (%)	Ash (%)	Moisture (%)	Fiber (%)	Form
Coat	% 14 – 17	5	0.3	4	10	36	D-Glycose
Cotyledon	% 35 – 42	5	0.6	0.6	10	1.5	Galactomannan
Embryo	% 43 – 47	55.3	5.2	4.6	10	18	Glycose

(Anonymous, 2014)

As seen in the table, unlike many field crops, a significant portion of the cluster bean seed consists of the embryo (43–47%). In addition, the protein content of the embryo (55.3%) is quite high (Table 1). The most valuable part of the seed is the cotyledons from which galactomannan is obtained (Anonymous, 2014). While the cotyledon ratio in the seed varies between 35–42% (Manivannan et al., 2016), the gum ratio of the grain is between 16.8% and 30.9% under common cultivation conditions (Anonymous, 2014; Pathak & Roy 2015). However, in a study conducted in India with 40 genotypes, it was reported that the gum rate varied between 20.2% and 37.2%, and the cotyledon rate varied between 27.2% and 50.9% (Pathak & Roy, 2015). However, in a study conducted in India with 40 genotypes, it was reported that the gum rate varied between 20.2% and 37.2%, and the cotyledon rate varied between 27.2% and 50.9% (Pathak et al., 2011). A study conducted in Australia for one year found that the rate of chewing gum varied between 23.9% and 28.0% (Douglas, 2005). Another study conducted under Italian conditions reported that the galactomannan content of the cluster bean varied between 27.1% and 32.5%, while the protein content varied between 24.9% and 31.5% (Greta et al., 2013). According to the results of this research, the values in gum content in the Mediterranean environment are similar to those in India. In their research conducted with 40 cluster bean genotypes, Pathak et al. (2011) determined positive and significant relationships between carbohydrate content and cotyledon ratio and gum ratio, while negative and significant relationships were found between gum ratio and protein ratio. The remaining part of the cluster bean grain after gum is obtained is an important animal feed due to its high protein content (Rodge, 2008). While the remaining part after processing produces substances used in animal feeding called guar korma (32%) and guar churi (34.5%), the remaining part becomes waste (Anonymous, 2014). It is reported that waste rate can be reduced further with new processing technologies (Anonymous, 2014).

Although there is a lot of literature on the use of white cluster beans in animal nutrition, not much research has been done on their nutritional quality. In a study conducted by Kays et al. (2006), it was determined that the TDF (Total Diameter Fiber) and SDF (Soluble Diameter Fiber) contents in 9 guar genotypes varied between 52–58% and 26–32%, respectively. It has also been reported that the protein content of the remaining part after the gum is obtained

varies between 28.9% and 46% (Pathak et al., 2011). The green parts of the cluster bean can be used as green manure and also as roughage (Arora & Pahuja, 2008).

6. DROUGHT STRESS

Guar is a species that stands out with its ability to adapt to arid and semi-arid ecosystems. This feature enables it to thrive in conditions. Less dependence on synthetic fertilizers, resistance to high temperatures and drought, low water requirements, and nitrogen fixation capacity through symbiotic relationships with *Rhizobium* bacteria are the main factors that increase the fertility of the soils where guar is grown (Upreti et al., 2021; Sokol et al., 2022). These properties directly contribute to guar's ecological success and its importance in sustainable agriculture. The optimum temperature for germination is 25–35 °C, but the plant can withstand intermittent temperatures up to 45 °C. However, low humidity conditions can negatively affect flowering and seed formation processes, leading to yield losses (Alshameri et al., 2020a; Pabuayon et al., 2022; Garcia et al., 2023). In contrast, guar is highly sensitive to waterlogging; excessive soil moisture inhibits root development and the nodulation process. In terms of soil properties, guar grows best in well-drained, sandy-loam texture and conditions ranging from neutral to slightly alkaline.

Drought, one of the most important consequences of global climate change, is one of the most important abiotic stress factors that threaten agricultural production. Water scarcity has a negative impact on the growth and development of plants and causes serious declines in the yield and quality (Ozturk et al., 2021). The sustainability of agriculture in the semi-arid regions is dependent upon the cultivating of drought resistant and water use efficient plant species. In this context, the guar plant is an outstanding plant with the extraordinary capacity of adaption to arid and hot climatic conditions. Thanks to its deep root system, it can reap the benefits of water in the lower layers of soil; therefore, it can be considered as an ideal alternative product for water constrained regions (MacMillan et al., 2021; Pabuayon et al., 2022). In addition, it enriches the soil by fixing nitrogen in the atmosphere and so can play an important role in rotational cropping systems. This remarkable tolerance of the guar plant to drought stress is a result of complex mechanisms

developed by the plant at the morphological, physiological, biochemical and molecular level.

In the next subheading the response of guar plants to drought stress will be discussed in detail in the light of the prevailing academic studies. The effects of drought on physiology, molecular mechanisms, osmotic regulation, yield and quality traits of the guar plant will be discussed and adaptation and compensation strategies used by the plant to cope with drought will be discussed. It is aimed that this information will contribute to the development of new ways for the guar plant breeding programs and sustainable agricultural practices, in the water-limited regions.

6.1. Physiological Effects of Drought Stress

Drought stress causes a decline in water potential in plants and arouses a cascade of physiological responses. These reactions are indicative of the attempts of the plant to reduce the loss of water as well as to use the water optimally. Guar plants have impressive physiological ability to cope with drought stress. The trick behind the drought resistance of the guar plant is that it can efficiently use water and utilize the water present deep in the soil. Assimilation of water and tolerance to drought is dependent on root density of the plant in the soil profile. The water withdrawal pattern of guar plants under various water restriction was studied in a study by Pabuayon et al. (2022). It was found that guar plants absorbed a large fraction of the water in deeper soil layers, that is, 50-100 cm, particularly in the cases of extreme and severe drought (51 mm and 127 mm irrigation, respectively). This scenario arises as a benefit of the taproot of the guar plant and the plant is not susceptible to the surface drought. According to MacMillan et al. (2021) the guar plant has also been reported to possess deep roots that are involved in the uptake of water particularly during the drought seasons. This helps the plant to endure and go on developing even at times of severe water stress. Surprisingly, Pabuayon et al. (2022) established that irrigation amount reduced with the increase in irrigation water use efficiency (IWUE). It demonstrates that guar plant is able to transform scarce water resources into more seeds. However, no significant difference was found between different irrigation levels in terms of agronomic water use efficiency (AWUE) based on total water (rainfall + irrigation) use.

This suggests that the plant establishes a balance by adjusting yield components according to water availability.

Water stress causes undesirable effects on the development of plants and retards cell division and plant growth. Guar plants have also been reported to be under stress by drought with a reducing effect on the guar plant height, the leaf area index (LAI) and biomass production. Pabuayon et al. (2022) have discovered that the shorter the water restriction, the lower was the height of plants and the leaf area index in both trial years. It is one of the precautions that the plant will take to minimize the loss of water into the atmosphere by transpiration by decreasing the extent of leaf surface. A reduced canopy minimizes water loss as well as the photosynthetic capacity that results in a decrease in biomass accumulation.

Among the earliest and fastest adaptations of plants to drought stress is the process of closing of the pores on the leaf surface in order to minimize the loss of water (transpiration) (Mukarram et al., 2021). Stomata closure assists the plant to sustain its water potential through minimized transpiration. However, stomata close inhibit the uptake of carbon dioxide (CO₂) that is significant in photosynthesis. The basic tradeoff between plant growth and drought survival is brought about by this dilemma. Drought resistance of the guar plant is also directly linked to the potential to form an optimal ratio between water loss and CO₂ uptake through the optimal control of the stomata movements. When stomatal conductance is low due to the drought stress, there is low rate of gas exchange hence the rate of net photosynthesis reduces. Although such physiological reaction is useful in the short run to safeguard the plant against water stress, in the long run it constrained growth and yield potential. Drought stress triggers a multidimensional network of signaling, which causes extensive alteration of gene expression, protein synthesis and plant metabolic pathways. Guar plant has developed various forms of defense and adaptation to this stress at both the molecular and biochemical front. These processes are appraised in below.

6.2. Molecular Mechanisms of Drought Stress

Guar is a legume crop of great economic significance, whose agricultural sustainability potential is also enormous in the arid and semi-arid areas (Vishnyakova et al., 2023). Yet, the increase in the risk of drought caused by

climate change has an adverse effect on guar crops and productivity (Soltani-Gerdefaramarzi et al., 2024). Hence, it is extremely important to study the mechanisms of molecular defense of the guar plants to drought stresses to develop more resistant cultivars. In this subheading, the multifaceted molecular reactions of guar plants to drought stress are outlined in a holistic viewpoint, the perception of the signal up to the expression of genes, the reorganization of metabolism to the physiological changes.

6.2.1. Detecting and activation of signal transduction of stress.

The plant experiences the first stress due to drought manifested in depleting water potential in the roots. This physical signal triggers a cascade of chemical reactions which initiate a cascade of biochemical and molecular reactions. A plant hormone Absciscic Acid (ABA) is at the centre of this process (Alshameri et al., 2020a). In drought, the genes of the major enzymes participating in the biosynthesis of ABA (e.g. 9-cis epoxycarotenoid dioxygenase - NCED) become expressed, and ABA levels surged quickly. The mechanism enables plants to establish quick and successful adaptation to drought (Hussain et al., 2021). Intracellular receptors of the Pyrobactin Resistance 1(PYR1), Pyrobactin Resistance 1-Like (PYL), Regulatory Component of Absciscic Acid Receptor (RCAR) family of proteins are bound by rising ABA (Soma et al., 2021). In this respect, it inhibits Type 2C Protein Phosphatases (PP2C). Protein kinases of the SnRK2 (Sucrose non-fermenting Related Kinase 2) family are activated by inhibition of PP2Cs which they normally suppress. The SnRK2 kinases activated phosphorylate the target proteins and transcription factors and transmit the information to the cell nucleus initiating the expression of the drought response genes (Shen et al., 2022). At the same time, the signal transduction can also be activated by mechanosensitive channels and receptor kinases on the cell wall that identifies the physical tension between the cell wall and the plasma membrane (Cox et al., 2019).

Cellular signaling and the control of most physiological processes are caused by rapid and brief increases in intracellular calcium (Ca^{2+}) concentrations (Lin et al., 2024). Calcium sensors that sense this calcium signals include Calcium Dependent Protein Kinases (CDPK) and CBL-interacting protein kinases (CIPK) which interacts with Calcineurin B-like

proteins (CBL) (Cheong et al., 2007). Activation of kinases in an ABA-independent way phosphorylates target proteins permitting fast and various responses to stress by the plants. This mechanism forms a subset of the adaptability and efficiency of the plant in response to varying conditions of the environment (Danquah et al., 2014).

The guar plants respond to heat and drought stresses through the actions of hormone signaling (particularly ABA), protein kinases, transcription factors (WRKY and F-box) and heat shock proteins (HSP20, HSP70, HSP90) (Alshameri et al., 2020). Known to be increased under stress conditions, these genes were shown to be triggered by ABA-mediated signaling especially in stimulating quick responses to adaptation, including stomatal closure and osmoregulation (Vishnyakova et al., 2023).

6.2.2. Transcriptional reprogramming: Gene expression network control

Transcription factors are significant proteins, which regulate the expression processes of the target genes binding to their promoter regions (Weidemüller et al., 2021). These transcription factors are involved in the coordinated regulation of the activation of a large number of genes in reaction to drought stress. Alshameri et al. (2020b) indicated that transcription factors of the Myeloblastosis (MYB), MYB-related and Ethylene response factor (ERF) were found to have been upregulated in the guar plants subjected to drought stress. These transcription factors have been reported to be significant in the plant abiotic stress responses, particularly in ABA (abscisic acid) - dependent and ABA-independent signaling (Xie et al., 2019). All these factors improve plant resistance to stress by controlling gene networks that promote the synthesis of protective proteins, osmolytes and antioxidant enzymes (Dvorak et al., 2021). The hub of the response to drought stress is a multifaceted transcriptional network resulting in the upregulation of the expression of thousands of genes. The main organizers of this reprogramming are transcription factors (TFs) that are activated by ABA-dependent and - independent signaling pathways (Soma et al., 2021). The study of the transcriptome of the guar plants has shown that the expression of genes of numerous TF families, including Myeloblastosis (MYB), Myelocytomatosis oncogene (MYC), (NAM, CuC2, ATAF1/2 gene domain (NAC), WRKY,

Basic-Leucine zipper (bZIP) and ERF, change under the stress of drought significantly (Reddy et al., 2022).

The expression of genes is manifested in two significant pathways. The ABF/AREB (ABA-responsive element binding factor) are phosphorylated by SnRK2 kinases, and ABA-dependent regulation of the transcription factors bind to ABRE in promoter regions of the target genes and activate their transcription in the first one (Ndathe et al., 2022). Such target genes consist of Late Embryogenesis Abundant (LEA) protein genes, dehydrin and other protective protein genes (Nagaraju et al., 2019). In the second, DREB/CBF (Dehydration responsive element binding protein/C repeat-binding factor) family transcription factors bind dehydration-responsive elements (DRE/CRT) in promoters of the target genes with ABA-independent regulation. The pathway is a typical reaction mechanism to osmotic stress-specifically, cold and drought (Mizoi et al., 2012).

Research in guar plants has provided evidence on the presence of some graft-specific transcription factors such as CtMYC induced by drought stress and expressed in the tissues (Sharma et al., 2023). The existence of such specialized regulators indicates that adaptive mechanism of guar plant to drought is species based. These transcription factors do not only interact with each other, but they proceed in a hierarchical manner, coordination of the stress response. This network allows the plant to install a dynamic and flexible response based on the degree and the intensity of stress. A stress RNA-seq experiment by Alshameri et al., (2020b) demonstrated that hundreds of genes were changed in their expression in response to stress in a drought-tolerant genotype of guar. A total of 499 genes were detected to be upregulated (expressing highly) and 191 genes were detected to be downregulated (expressing lowly). Twenty-one of these genes, 28 up-regulated and six down-regulated, were found to be novel and previously unknown guar- specific genes. The upregulated genes include protein families that play a decisive role in protecting, transduction, and metabolism of the cell. These are aquaporins (water channels), protein kinases and phosphatases (signal transduction), LEA proteins (cellular protection) and enzymes of different signaling pathways (Shahzad et al., 2023). Multidimensionality across these genes suggests that the plant has developed a multidimensional defense against stress. The result of

this discovery is that guar plants could have their own peculiarities in terms of drought tolerance mechanisms.

6.2.3. Metabolic adaptation: Management of energy and protective compounds

Drought stress changes plant metabolism fundamentally. As photosynthesis slows down, carbon assimilation slows down and energy and resources are directed to survival mechanisms. In the case of carbohydrate metabolism, storage polysaccharides such as starch are degraded to soluble sugars (sucrose, fructose, trehalose) that are osmotically active. These sugars are involved in osmotic adjustment, cell turgor, and energy sources and signaling molecules. In the case of guar plants, higher levels of transcripts for starch and sucrose metabolism-related genes were found in the drought-tolerant genotypes (Pandey et al., 2022a). Additionally, enhanced expression of sugar transporters such as SWEET is to ensure that these sugars are distributed effectively between cells and tissues. In addition, carotenoid biosynthesis (10 genes) minimizes cellular damage by establishing an effective antioxidant defense system as well as photosynthetic pigment production.

Drought stress leads to osmotic imbalance, which leads to water loss and cell shrinkage. To deal with this situation, the guar plant has a sophisticated mechanism called "osmotic adjustment". In this process, "compatible solutes" such as amino acids such as proline, glycine betaine and soluble sugars (sucrose, trehalose) accumulate inside the cell (Ozturk et al., 2021). These molecules help to hold water inside the cell (by lowering the water potential of the cytoplasm) and also prevent dehydration damage (by stabilizing the structure of proteins and membranes). Proline accumulation is a multifunctional protective mechanism in addition to osmotic balance. This amino acid helps maintain membrane integrity, helps in protein folding and has antioxidant properties. Similarly, the synthesis of special protein groups such as LEA proteins is increased, which form "molecular shields" and protect the structural integrity of other proteins and membranes in the case of water deficiency.

Plants develop antioxidant defense mechanisms when stressed by drought. Drought causes the production of Reactive Oxygen Species (ROS) because of reasons such as disruption of the photosynthetic electron transport chain. ROS are toxic molecules that damage cells at high concentrations.

However, they also function as signaling molecules at low concentrations. To cope with this oxidative stress, the guar plant has developed a strong defense system consisting of both enzymatic (superoxide dismutase - SOD, catalase - CAT, peroxidase - POD, ascorbate peroxidase - APX) and non-enzymatic (ascorbate, glutathione, tocopherols, carotenoids) antioxidants. It has been demonstrated that the activity of these antioxidant enzymes and the expression of the genes encoding them are significantly increased in drought-tolerant guar genotypes (Kumari et al., 2024).

6.2.4. Cellular protection and repair mechanisms

A number of protective proteins and mechanisms are activated to minimize and repair cellular damage caused by stress in plants. One of these mechanisms is heat shock proteins (HSPs). HSPs (HSP70, HSP90, sHSPs), which function as molecular chaperones, help proteins that have been misfolded or denatured due to stress to regain their correct structures (Alshameri et al., 2020a). HSPs maintain protein homeostasis (proteostasis) by preventing protein aggregation and directing damaged proteins to proteasomal degradation (Hu et al., 2022). Hydrophilic proteins belonging to the group of LEA and Dehydrins accumulate during dehydration, displacing water and maintaining the integrity of membranes, proteins and other cellular structures (Goyal et al., 2005). It is thought to act as a kind of "molecular shield."

Drought stress also causes changes in the structure of the cell wall. KEGG (Metabolic Processes Primarily Activated in Drought Stress) pathway analysis shows which metabolic processes are primarily activated in drought stress (Kumar et al., 2021). The phenylpropanoid biosynthesis pathway (12 genes) is responsible for the production of structural and protective compounds such as lignin and flavonoids (Yao et al., 2021; Zhang et al., 2021). Increased lignin biosynthesis of the cell wall makes the cell wall tough and the cell cannot collapse and lose water in uncontrollable situations (Zhang et al., 2021). Modifications in cellulose and hemicellulose metabolism also play a role in adapting the plant to the alterations in water potential through the process of changing the cell wall flexibility (Jardim-Messeder et al., 2020). The multilayered network of molecular mechanisms that the plant response of guar to drought stress is comprised of makes it a multilayered network. ABA-dependent and -independent signaling pathways activate a multifaceted

transcriptional reprogramming, starting with the perception of stress (Vishnyakova, et al., 2023). These programs instruct the plant to use less energy and produce defense chemicals. Meanwhile, cellular cleaning and defense mechanisms are turned on, which guarantees cell survival.

Proline, soluble carbohydrates, and other osmolytes play an important role in osmotic balancing, maintaining cellular turgor and metabolic activity (Upreti et al., 2021; Narayan et al., 2023). Under moderate stress conditions, the plant can maintain photosynthetic activity by regulating transpiration. Genetic diversity in drought tolerance is well documented; for example, genotypes such as RGC-1002, RGC-986 and HG-563 exhibit higher relative water content, chlorophyll stability and photosynthetic efficiency than RGC-936 and Varsha. These features contribute to biological yield stability under variable rainfall conditions. Anatomical and biochemical adaptations also support resilience. Accumulation of lignin and phenolic compounds in cell walls reduces oxidative stress while delaying wilting (Narayan et al., 2023). ROS, which increase with drought stress, are suppressed by the antioxidant defense system of guar, consisting of enzymes such as SOD, CAT and APX (Upreti et al., 2021; Kumari et al., 2024). Drought tolerant genotypes provide yield stability by showing higher activity in these defense mechanisms (Pandey et al., 2022b; Vishnyakova et al., 2023).

Stress experienced during the generative period limits production performance by reducing pod numbers and seed formation (Avola et al., 2020; Vishnyakova, 2023). However, some genotypes can maintain the number of seeds per pod even under stress conditions. Recovery of nodulation and biological nitrogen fixation (BNF) capacity after rewatering demonstrates the durability of the *guar-rhizobium* symbiosis (Shrestha & Adams, 2022). Different agronomic practices are effective in reducing drought and heat stress. Foliar application of antistress agents (e.g., salicylic acid, potassium, thiourea) increases photosynthetic efficiency, osmolyte accumulation, and yield (Narayan et al., 2023). Nanoparticle-based seed applications and biochar additives strengthen root development, soil water retention capacity and osmotic compatibility (Vishnyakova et al., 2023). Additionally, beneficial microorganisms such as *Bacillus spp.* and arbuscular mycorrhizal fungi (AMF) provide biological protection by increasing nutrient uptake, proline accumulation and antioxidant activity (Umrao et al., 2024).

Genomic and transcriptomic studies shed light on the biological basis of stress tolerance in guar. Transcription factors such as WRKY, MYC and F-box proteins, which regulate ABA-mediated responses, osmotic adjustment and lignin synthesis, have been shown to be upregulated under stress. It has also been reported that the expression of genes related to carbon and nitrogen metabolism, antioxidant defense, sugar metabolism and cell wall strengthening is increased in drought-tolerant genotypes (Narayan et al., 2023). While significant progress has been made at the level of individual mechanisms, research on the interaction of drought and high temperature stresses remains limited. High temperatures aggravate drought stress by exacerbating water loss, oxidative stress, and reproductive failure. Therefore, integrated studies to be conducted at physiological, biochemical and molecular scales are an urgent need (Pandey et al., 2022a).

Generally, deep root structure, osmotic adaptation capacity and strong antioxidant defenses confer drought tolerance to guar. Targeted breeding is possible by evaluating genetic variation and using physiological/molecular markers. However, the main obstacle to production stability is the sensitivity of generative periods to water scarcity. Leaf surface spray treatments, seed preparation, microbial inoculants and soil amendments stand out as viable adaptation strategies against drought and heat stress. Genomic and transcriptomic analyses of stress signaling networks identify promising genes for marker-assisted breeding and biotechnological improvement. Future research should focus on the interaction of drought and temperature effects, the sustainability of management practices, and the integration of molecular and agronomic breeding processes.

7. PRINCIPAL DISEASES AND MANAGEMENT

The yield and quality of guar can be significantly reduced, especially due to fungal and bacterial factors. The most common and damaging diseases include bacterial blight, *Alternaria* leaf spot, anthracnose and powdery mildew. These diseases spread rapidly under suitable climatic conditions and can cause regional epidemics. Bacterial blight, caused by *Xanthomonas cyamopsidis* or *X. axonopodis* pv. *cyamopsidis*, is one of the most devastating guar diseases. Waterlogged intravascular lesions rapidly develop into necrosis, which can spread to the petiole and stem, causing plant death. Use of healthy seeds,

development of resistant varieties and appropriate bactericide applications are critical in controlling seed-borne infections (Mahmoud, 2021; Makhoul et al., 2024).

Alternaria leaf spot and anthracnose cause necrotic lesions on leaves, pods and stems, while powdery mildew causes yield reduction through leaf fall and loss of photosynthesis. Zineb (for leaf spot and anthracnose) as well as sulfur and dinocap (for powdery mildew) are widely recommended for the management of these diseases. However, fungicide resistance and the emergence of new pathogen races make chemical control alone insufficient (Jaiswal et al., 2022; Al-Khayri et al., 2023). Another cause of yield losses in guar production is insect pests. Aphids (*Aphis craccivora*), jassids and whiteflies are the main sap-sucking pests and reduce photosynthetic efficiency as well as mediate the transmission of viral diseases (Kaur, 2022; Makhoul et al., 2024). Additionally, pod borers, hairy caterpillars and stem flies can cause serious losses on a local scale.

The guar mosquito (*Contarinia texana*) causes significant economic damage, particularly in the Southwest United States and certain parts of India. Consumption of flowers and pods by larvae seriously reduces seed setting success. While cultural practices such as adjusting planting times, field cleaning and removing residues constitute the first line of defense against this pest, insecticide applications may be inevitable in severe infestations (Kaur, 2022). Effective IPM strategies for guar include regular monitoring, insecticide application according to the economic damage threshold, and practices that support the natural biological balance, such as protecting ladybugs, lacewings, and parasitoids (Makhoul et al., 2024). Essential oils, pheromone traps and biological control agents are gaining increasing attention as environmentally friendly alternatives (Jaiswal et al., 2022; Al-Khayri et al., 2023).

The biofertilizers and bio stimulants also make guar disease and pest resistant. Nodulation and nutrient uptake are improved with *Bradyrhizobium*, *Bacillus subtilis* and arbuscular mycorrhizal fungi (AMF) inoculation, and disease resistance are also improved (Hashem et al., 2019; Al-Khayri et al., 2023). Regarding this, biostimulants like chitosan, selenium nanoparticles and methyl jasmonate enhance the defense capacity of the plant through strengthening the antioxidant systems (Olowe et al., 2020). It is reported that the plant microbiome, the rhizosphere and endophytic bacteria, competitively

exclude the pathogens, produce antibiotics and induce the immune system (Enebe & Babalola, 2018). These are the natural interactions on which long-term sustainable biotic stress management is based.

Nowadays, with the help of omics technologies, disease and pest resistance mechanisms have begun to be more clearly understood in recent years (Murmu et al., 2024). QTLs, regulatory networks and resistance genes identified with the help of transcriptomic, genomic and proteomic methods (Al-Khayri et al., 2023; Varadharajan et al., 2025). Gene pyramiding, marker-assisted selection and genome editing techniques allow the development of new varieties with multiple resistance genes (Jaiswal et al., 2022). Research shows that biologically and ecologically based practices in guar biotic stress management are more sustainable and effective, both environmentally and economically, than chemical methods (El-Sawah et al., 2021; Golestani et al., 2025). Although the use of healthy seeds, the development of resistant varieties and fungicide applications are still among the basic strategies, the importance of biofertilizers, bio stimulants, microbiome-based applications and omics technologies is increasing. However, the development of integrated strategies to adapt to regional differences is a need that must be constantly updated against the evolutionary dynamics of diseases and pests.

8. CULTIVATION, POST-HARVEST MANAGEMENT, AND QUALITY ASSURANCE

Guar is a versatile annual legume with high economic value on a global scale due to the galactomannan content in its endosperm. Guar gum functions as a stabilizer, thickener, emulsifier, and gelling agent thanks to its hydrocolloid properties and is widely used in many industries, including food processing, pharmaceuticals, oilfield operations, textiles, and cosmetics. The increasing global demand for guar gum has accelerated research initiatives to improve gum quality, increase stress tolerance, diversify its uses, and increase the productivity and competitiveness of post-harvest systems (Jain et al., 2023; Gautam et al., 2024). The resulted high-quality reference genome has provided valuable advances to the research of guar breeding.

Genomic materials can be used to determine gum-related alleles, such as galactose-mannose ratio, viscosity stability, gum production capacity and branching frequency (Sharma et al., 2020; Gautam et al., 2024; Verma et al.,

2025). Besides, multi-trait selection indices (Multi-Trait Stability Index (MTSI), Multi-Trait Genotype-Ideotype Distance Index (MGIDI)) are useful in selecting better genotypes that yield both high and stable gum quality in various environmental conditions (Benakanahalli et al., 2021).

Nonetheless, despite all this, genetic makeup of guar has certain constraints in the sense that natural cross-pollination cannot occur in cleistogamous flowering, this constrains genetic recombination, and restriction in the domestication process which has in turn narrowed the germplasm diversity. Researchers suggest using wild relatives, pre-breeding strategies, and method of combining modern molecular techniques such as the application of the gene-editing tool (CRS/CAS) with the marker-assisted selection as an option to widen the genetic base (Gautam et al., 2024; Verma et al., 2025).

Even though the Guar has a high degree of adaptation to arid and semi-arid environment, it is vulnerable to heat, drought and salinity stresses throughout the growth period. Recent breeding programs are specifically targeted to early vigor, late drought resistance, heat and moderate salinity tolerance. It is shown by physiological research that resistant genotypes grow vigorous root systems, manage osmotic pressure by the accretion of proline and soluble carbohydrates, and enhance stress reaction by the antioxidant activities of enzymes (Meftahizadeh et al., 2019; Boote et al., 2023). Transcriptomic studies are increasingly revealing the stress-responsive genes and transcription factors (e.g., WRKY, MYB, bHLH) that play a role in regulating these adaptive responses (Umrao et al., 2024).

Agricultural practices are important tools to promote genetic resistance of guar. Optimized planting times, in particular, enable the plant to better adapt to environmental stresses and maintain yield stability. Balanced fertilization practices increase growth and gum yield by ensuring the effective use of both macro and micro nutrients. In addition, inoculation with biofertilizers – for example, promoting symbiosis with *Bradyrhizobium* species and applying AMF – strengthens soil biological activity, facilitates nutrient and water uptake, and mitigates the negative effects of environmental stresses. Such precision agricultural interventions not only improve soil health but also contribute to sustainable production of guar by reducing environmental variability (El-Sawah et al., 2021; Sheteiwy et al., 2023).

Bio stresses are a threat to the production of guar. Such diseases as bacterial blight, *Alternaria* leaf spot, anthracnose, powdery mildew, and such pests as aphids and guar fly lead to massive losses in yield in various regions (Jain et al., 2023; Gautam et al., 2024). More recently, through marker-assisted selection, field screening and molecular breeding studies, it is now possible to identify resistant genotypes. Nevertheless, the ever-changing nature of the pathogen races and pest biotypes to produce new forms indicates the need to constantly invent new forms of resistance management. Integrated Pest Management (IPM) is particularly the most sustainable solution in this case. Resistant varieties are important to ensure the maintenance of productivity; the application of biological control strategies, biofertilizer and bio stimulants, and strategic chemical interventions when needed (Kumar & et al. 2018; Sheteiwiy et al., 2023; Manley et al., 2023). The holistic strategy enables to reduce the short-term yield losses and is added to environmental sustainability in the long-term.

As much as guar gum remains the most critical commercial product, new studies have highlighted the need to diversify and venture into bio-based and green chemistry uses. Guar gum derivatives, which have been chemically or physically modified, e.g., to create hydroxypropyl, cationic, and carboxymethyl derivatives, are also proving useful in bioplastics, hydrogels, biodegradable packaging material, or controlled-release drug delivery systems (Prabaharan, 2011; Pandit, 2017; Sharahi et al., 2025). Moreover, new technologies guar gum processing with ultrasonication, radiation and high pressure help to enhance the solubility, viscosity and stability of the guar gum and to expand the range of its possible applications in industry and biomedical settings (Sharma et al., 2020; Kian-Pour et al., 2023).

Research on digestibility, amino acid balance and functional processes of protein fractions, specifically, reveals guar as a source of not only gum, but also a beneficial source of protein (Kotnala et al., 2024; Kheto et al., 2024). Simultaneously, the chemically and physically modified guar gum is also applied to new functional foods, biobased materials and pharmaceutical products (Ghosh & Katiyar, 2022; Tahmouzi et al., 2023).

These innovative techniques are compatible with ecological goals, support the circular bioeconomy approach, and contribute to guar becoming a more sustainable and high-value-added product, moving beyond traditional

markets. Gum quality, seed viability and market value depend largely on timely harvesting. Guar pod should be harvested when it turns brown and the seeds harden. Delay in harvesting not only results in serious crop losses but also negatively impacts the quality of guar gum. While small-scale producers in guar-growing countries still harvest by hand due to inadequate mechanization (Meftahizadeh et al., 2019), large-scale production systems are adopting mechanical harvesting.

After harvest, the seeds are processed by threshing, dried to 8–10% moisture level and stored free from pests to prevent spoilage caused by fungi or insects. Strict quality and traceability standards are required for export markets, especially food grade guar gum (Jain et al., 2023). Therefore, the adoption of modern blending, effective drying and contemporary storage technologies reduces post-harvest losses, ensures gum quality and increases competitiveness in the global market.

9. RESULTS AND RECOMMENDATIONS

Guar is a strategic legume for both food and non-food sectors due to its durability and industrial value. The interrelated priorities shaping guar's development in the coming period are:

1. Quality-based breeding: Genetic improvement of quality parameters such as gum yield, viscosity and purity.
2. Climate resilience: Integration of physiological, molecular and agronomic approaches to develop varieties tolerant to drought, high temperature and salinity stress.
3. Biotic stress tolerance: Use of marker-assisted selection and genomic tools for resistance to major diseases and pests
4. New uses: Evaluation of guar in bio-based products, green chemistry applications, and seed protein
5. Seed systems and mechanization: Expanding the production of certified seeds, developing mechanized harvesting methods and ensuring traceability standards for export markets.

Despite significant advances in genetics and agronomy, limited genetic diversity, rapid evolution of diseases and pests, and inadequate access to mechanization for smallholder farmers remain key challenges. Therefore, sustainable development of guar-based production systems requires the

development of recommendations appropriate for regional ecological and socio-economic conditions, long-term soil health research and optimization of value chains. In conclusion, strengthening genomic resources, multi-trait breeding approaches and integrated agricultural practices provide the basis for both higher quality gum production and climate adaptation of guar. The future of guar cultivation depends on overcoming genetic bottlenecks, improving seed and post-harvest systems, and integrating sustainability and climate resilience goals.

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Authors' contributions

İrem Poyraz: Methodology, Writing-original draft, Writing- review and editing.

Mevlüt Akçura: Supervision, Funding acquisition, Methodology, Writing-original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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CHAPTER 4

WALNUT CULTIVATION IN TÜRKİYE AND REGIONAL CONCENTRATION COEFFICIENT IN GLOBAL WALNUT FOREIGN TRADE

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1. Introduction

The agricultural sector holds strategic importance due to its direct connection with human nutrition. Within this sector, fruit cultivation is gaining increasing value in terms of domestic consumption, export potential, and nutritional benefits. In particular, nuts hold a strategic position in global agriculture due to their high nutritional content and commercial returns. Among this group, the walnut stands out as a significant species with its nutritional properties and economic value. Walnuts are a valuable food source for human health due to their high levels of fatty acids, protein, and minerals. Additionally, the growing demand for processed walnut products in recent years has drawn considerable attention. The health benefits of walnuts are largely attributed to their nutritional content, especially their omega-3 fatty acids. Experts note that walnut consumption has positive effects on numerous health issues such as cardiovascular diseases, inflammatory disorders, and cognitive impairments (Şimşek & Gülsoy, 2016; Salar & Kuruüzüm-Uz, 2021). Furthermore, walnuts contain compounds with antioxidant activities, which add to their appeal in the health sector (Gülsoy et al., 2021).

Globally, walnut production has gained significant momentum in recent years, with countries such as China, the United States, Iran, and Türkiye becoming key producers in this field. Türkiye, with its ecological diversity, favorable climatic conditions, and soil structure, is among the countries with high potential for walnut cultivation. However, the interaction between walnut cultivation and climate change poses significant challenges. Walnuts are vulnerable to environmental stresses such as drought and frost, which may worsen with climate change, potentially affecting their growth and yield even in traditionally suitable areas (Gauthier & Jacobs, 2011).

In Türkiye, walnut cultivation has historically been an integral part of rural life and has traditionally been maintained by small-scale family farms using conventional methods. However, since the 2000s, with the increase in government subsidies for agriculture and the spread of modern farming practices, walnut production has taken on a more systematic and commercial dimension. During this transformation, the rise in the number of specialized walnut orchards has contributed significantly to the increase in total production volume and the enhancement of Türkiye's competitiveness in walnut foreign trade (Kadakoğlu et al., 2022). Nevertheless, walnut cultivation in Türkiye is

not evenly distributed, with production concentrated in specific geographic regions. Parts of Central Anatolia, the Aegean, Marmara, and Eastern Anatolia regions are among the leading walnut-producing areas, a pattern directly influenced by ecological conditions, investment preferences, infrastructure availability, and regional agricultural policies.

In recent years, globalization has led to a significant increase in the trade of agricultural products. In this context, the trade of fresh fruits and vegetables has expanded both in volume and geographical coverage. Key drivers of this trend include the rising purchasing power in developed countries, the accelerated integration of developing countries into global markets, and structural changes in consumer preferences. Within this framework, Türkiye has emerged as a significant actor in global fresh fruit and vegetable trade due to its agro-ecological diversity, high production capacity, and logistical advantages (Bayav et al., 2025).

Türkiye's potential in walnut production also has significant implications for foreign trade and presents opportunities that could contribute to the national economy. Walnuts are a product with rising demand in global agricultural trade. This rise is driven by factors such as the growing trend toward healthy eating, increased interest in plant-based protein sources, and the expanded use of walnuts in the processed food industry. These trends are among the primary factors that contribute to the increased export value of walnuts. For Türkiye, the walnut sector is not only a field of agricultural production but also a strategic product in terms of rural development, trade balance, and international competitiveness. Moreover, the walnut industry has broad applications beyond direct consumption and is used as a key ingredient in various food and beverage products, thereby increasing its market value (Ding et al., 2020).

When evaluating Türkiye's current position in walnut foreign trade, it is observed that, despite high production capacity, the country sometimes becomes a net importer. Key reasons include high domestic demand, issues related to product quality and standardization, and limited competitiveness in international markets. Although Türkiye holds a comparative advantage in walnut exports in global markets, the sustainability of this advantage is occasionally in question. Factors such as low-cost production by competitor countries, issues of quality and standards, and tariff and non-tariff barriers can limit Türkiye's competitiveness. Nevertheless, the expansion of modern

plantations, the development of high-quality varieties, and the diversification of export markets offer significant opportunities to strengthen Türkiye's position in walnut foreign trade.

When evaluating foreign trade, not only volume and income levels but also market diversity and the country groups in which trade is concentrated should be taken into consideration. In this regard, one frequently used method in foreign trade literature is the regional concentration coefficient, which allows for the measurement of whether a country's trade relations in specific markets are above or below expected levels. This method serves as a significant tool in analyzing the level of trade integration between Türkiye and the countries to which it exports. In fact, there has been a noticeable increase in studies using the regional concentration coefficient in recent years (Arisoy et al., 2014; Arisoy et al., 2019; Arisoy & Kaplan, 2022; Arslan et al., 2022; Bayav et al., 2025).

To effectively utilize Türkiye's potential in walnut cultivation and walnut foreign trade, it is of great importance to properly analyze the regional concentration in production and trade. This study aims to examine Türkiye's walnut foreign trade structure over the past five years using the regional concentration coefficient method, thereby assessing its position in current markets and providing guiding data regarding potential new markets.

2. Materials and Methods

The data used in this study were obtained from the databases of the International Trade Centre (Trade Map) and the Food and Agriculture Organization of the United Nations (FAO). Additionally, relevant literature was used to support the analysis.

In the literature, various similar methods have been employed to analyze international trade relations. In this study, the Trade Concentration Coefficient was calculated to interpret the level and direction of bilateral trade. The trade concentration analysis approach not only reveals changes in an exporting country's share in trade with a specific importing country but also provides a quantitative assessment of the intensity of trade relations between countries.

The formula used to calculate the Regional Concentration Coefficient is presented below (Froment & Zighera, 1964):

$$\text{Concentration Coefficient} = \frac{X_{ik}^j * X_k}{X_{jk} * X_{ik}} \tag{1}$$

In Equation (1):

X_{ik}^j : Export value of product k from country j to country i

X_k : Global export value of product k

X_{jk} : Export value of product k from country j

X_{ik} : Import value of product k by country i

The Concentration Coefficient reveals the level of trade interaction between two countries. The trend of this coefficient over time reflects the evolution of bilateral trade relations. A coefficient value above 1 indicates that the importing country's demand for a specific exporting country exceeds the expected level, suggesting a concentration trend in imports from that country. In other words, it implies that trade between the relevant countries is developing at a rate above the global average.

3. Results and Discussion

Global walnut production increased from 2.8 million tons in 2014 to approximately 4 million tons in 2023, marking a 42% growth over the period. This upward trend corresponds to an average annual increase of 4.1%. While production followed a rising trend between 2014 and 2016, it experienced a slight decline in 2017 and 2018, only to resume its upward trajectory from 2019 onward. Notably, there has been a significant acceleration in production since 2020, with output surpassing 3.9 million tons in both 2022 and 2023. The expansion in productivity and production capacity has been the primary driver of this growth. Overall, the period following 2019 has exhibited stronger and more stable growth compared to previous years (Figure 1).

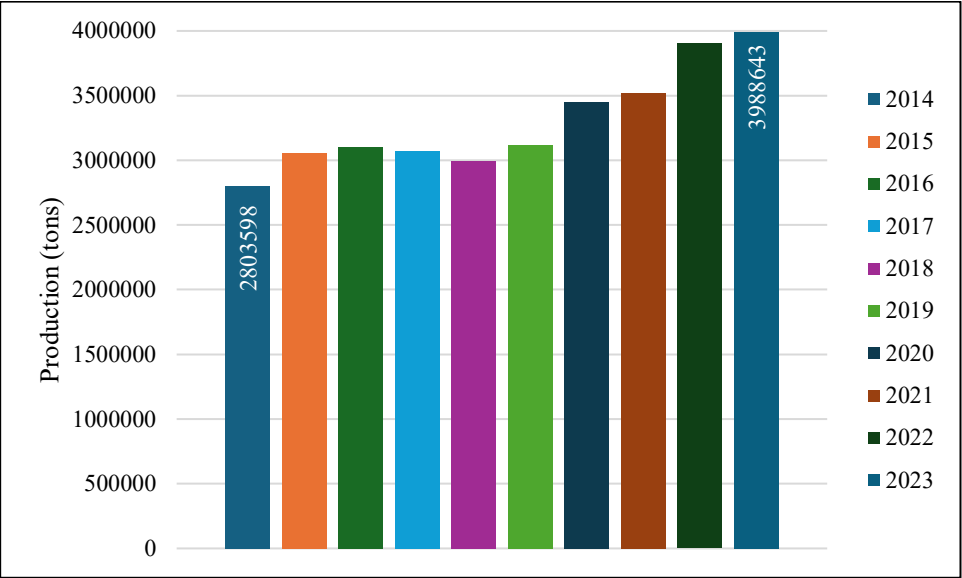


Figure 1. World walnut production
Source: FAO, 2025.

Figure 2 presents the leading countries in global walnut production and their respective output for 2023. The total global walnut production reached 3,988,643 tons, with China maintaining its leading position by accounting for 35.1% of the total. The United States follows with an 18.7% share, while Iran (9.6%) and Türkiye (9.0%) are close in percentage and stand out as key players in global walnut production. Among countries with moderate production shares, Chile (4.8%), Mexico (4.2%), and Burkina Faso (3.6%) have significant shares, while Ukraine (2.7%), Romania (1.5%), and Uzbekistan (1.2%) also have smaller shares. The data indicate that walnut production is heavily concentrated led by China and the United States, with Türkiye positioned among the world’s strong producers.

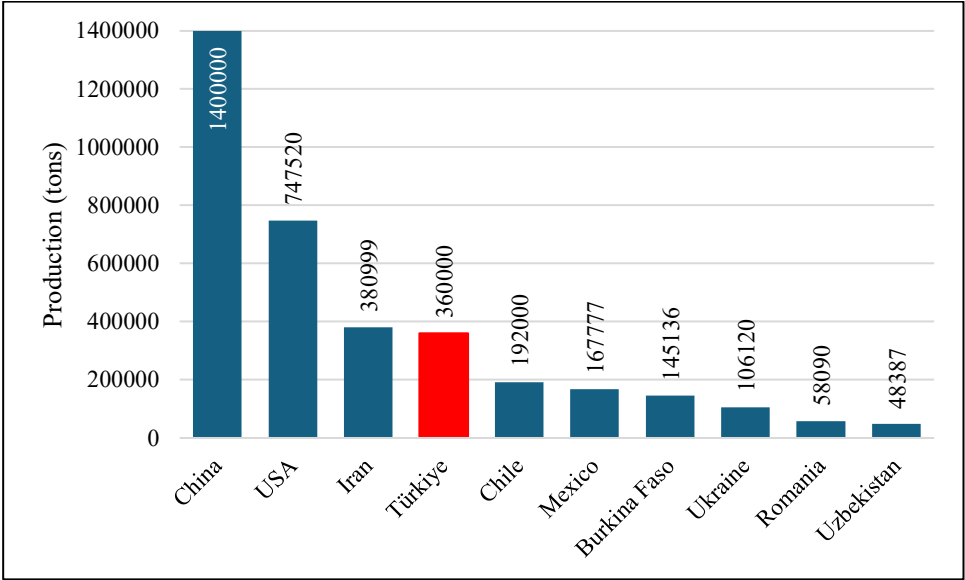


Figure 2. Leading countries in walnut production and their production

Source: FAO, 2025.

According to Table 1, global walnut production increased by 42.27% between 2014 and 2023, rising from 2.8 million tons to 3.99 million tons. During this period, China expanded its production from 900 thousand tons to 1.4 million tons, marking a 55.56% increase and maintaining its global leadership with a 35.1% share. The United States increased its output by 44.31%, reaching 747 thousand tons, and ranked second with an 18.74% share. In contrast, Iran experienced a 5.5% decline in production, keeping its share at 9.55%. Türkiye nearly doubled its production (99.11% increase) compared to 2014 and secured a strong position globally with a 9.03% share. Among Latin American countries, Chile showed a significant surge with a 174.29% increase, while Mexico saw a 33.41% rise. Burkina Faso, from Africa, stood out with a remarkable 101.58% growth. More moderate increases were observed in Ukraine (3.29%), Romania (84.33%), and Uzbekistan (9.97%). Overall, while China and the United States continue to play a dominant role in global walnut production, the significant growth observed in countries like Türkiye, Chile, and Burkina Faso is particularly noteworthy.

Table 1. Changes in production and share of leading countries in walnut production

Countries	Production (tons)		Change (%)	Share (%)
	2014	2023		
China	900,000	1,400,000	55.56	35.10
USA	518,002	747,520	44.31	18.74
Iran	403,158	380,999	-5.50	9.55
Türkiye	180,807	360,000	99.11	9.03
Chile	70,000	192,000	174.29	4.81
Mexico	125,758	167,777	33.41	4.21
Burkina Faso	72,000	145,136	101.58	3.64
Ukraine	102,740	106,120	3.29	2.66
Romania	31,514	58,090	84.33	1.46
Uzbekistan	44,000	48,387	9.97	1.21
Other Countries	355,618	382,614	7.59	9.59
World	2,803,598	3,988,643	42.27	100.00

Source: FAO, 2025.

Figure 3 illustrates global walnut cultivation areas for the period between 2014 and 2023. An overall upward trend in production area is clearly noticeable. In 2014, the global walnut cultivation area stood at 925,000 hectares. This area increased by approximately 7.5% in 2015, reaching 994,000 hectares, although a fluctuating pattern was observed between 2016 and 2018. During this period, the area remained relatively stable, ranging between 942,000 and 972,000 hectares.

Starting from 2019, a marked increase in cultivation areas occurred, with significant acceleration after 2020. The area expanded to:

- 1.09 million hectares in 2020,
- 1.12 million hectares in 2021,
- 1.23 million hectares in 2022,
- and 1.25 million hectares in 2023.

As a result, over the ten-year period, the global walnut cultivation area increased by more than 35%. This trend reflects a growing global demand for walnut production and a corresponding rise in production investments. It also

indicates a more stable growth trajectory in the expansion of cultivation areas, particularly in recent years.

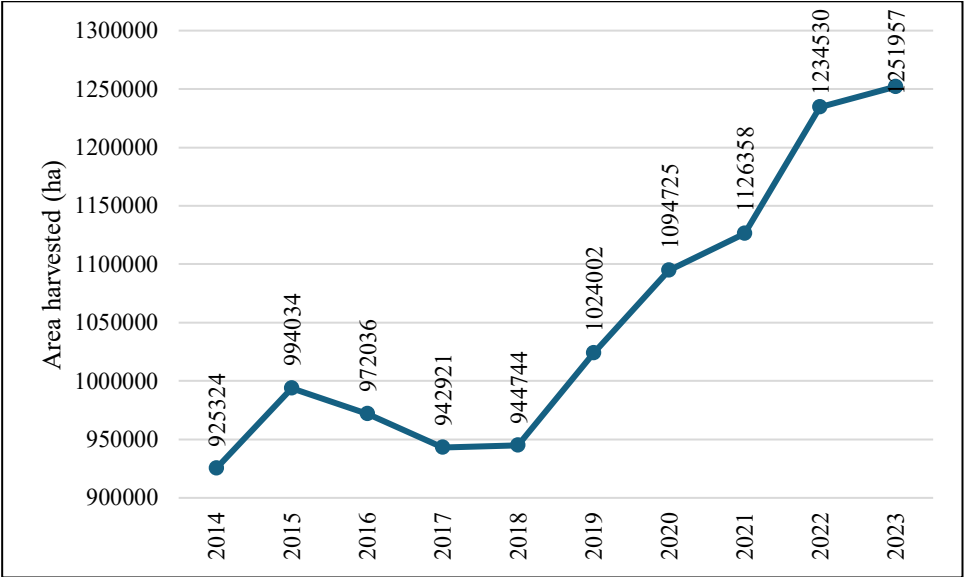


Figure 3. World walnut production area

Source: FAO, 2025.

Between 2014 and 2023, the global walnut area harvested increased by 35.30%, rising from 925,324 hectares to 1,251,957 hectares. Proportionally, the largest increase in production area occurred in Türkiye, where walnut cultivation expanded from 69,395 hectares to 174,080 hectares. In absolute terms, China recorded the greatest overall production area, increasing its walnut orchards by 42.79% to reach 355,995 hectares. However, a striking observation is the 56.47% decrease in walnut cultivation area in Iran, representing a significant contraction in production capacity. Countries such as Chile and Mexico also recorded substantial increases in cultivation areas, while Ukraine and Uzbekistan showed relatively stable figures over the same period (Table 2).

Table 2. Area harvested of leading countries in walnut production

Countries	Area Harvested (ha)		Change (%)
	2014	2023	
China	249,312	355,995	42.79
USA	117,359	155,806	32.76
Iran	141,019	61,383	-56.47
Türkiye	69,395	174,080	150.85
Chile	24,404	44,626	82.86
Mexico	75,349	120,566	60.01
Burkina Faso	48,000	98,270	104.73
Ukraine	13,200	13,500	2.27
Romania	1,598	3,590	124.66
Uzbekistan	5,000	5,122	2.44
Other Countries	180,688	219,019	21.21
World	925,324	1,251,957	35.30

Source: FAO, 2025.

Over the past ten years, global data indicate a 5.2% increase in yield per unit area. In 2014, the average walnut yield was 3,030 kg per hectare, which rose to 3,186 kg per hectare by 2023. When examining the yield per hectare of the leading walnut-producing countries, Romania ranks first with an impressive 16,181 kg ha⁻¹, representing the highest productivity level worldwide. Uzbekistan (9,448 kg ha⁻¹) and Ukraine (7,861 kg ha⁻¹) also stand out with notably high yields. In contrast, Türkiye, which has significantly expanded its cultivation area in recent years, remains below the world average with a yield of only 2,068 kg ha⁻¹. Similarly, Burkina Faso (1,477 kg ha⁻¹) and Mexico (1,392 kg ha⁻¹), both of which have nearly doubled their production areas, show relatively low productivity. Countries with large production areas, such as China and the United States, demonstrate slightly above-average yields at 3,933 kg ha⁻¹ and 4,798 kg ha⁻¹, respectively (FAO, 2025).

Figure 4 presents the global walnut trade values by year. Between 2014 and 2023, both global walnut imports and exports exhibited a fluctuating pattern. An analysis of import values shows that they reached their lowest level in 2015, followed by a steady rise that culminated in 2019, marking the highest

point of the period. Although import values declined after 2019, a partial recovery occurred in 2021 and 2022. However, in 2023, the trend turned downward once again. On the export side, the data followed a trajectory parallel to import trends. The year 2019 also marked the peak of global walnut exports. During the pandemic year (2020), a significant decline in export values was recorded, yet exports began to recover in 2021. Over the last three years, export levels have remained relatively stable.

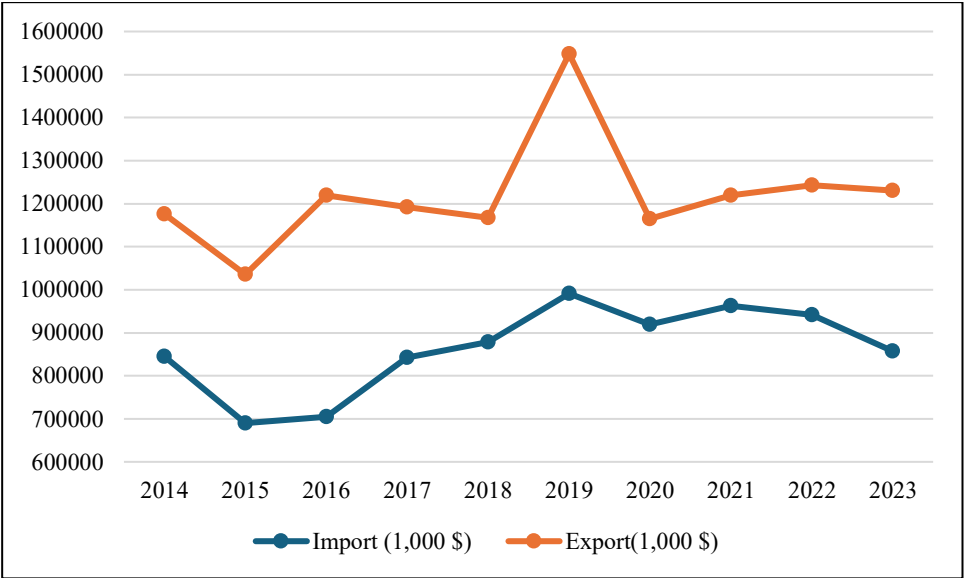


Figure 4. World walnut trade
Source: ITC-Trade Map, 2025.

As of 2023, the total global value of walnut exports \$1,230,528,000. Within this total, the United States held the largest share, with exports worth \$300,180,000, followed by China, with \$276,582,000, and Chile, with \$246,859,000. Together, these three countries accounted for approximately 66% of global walnut exports. Meanwhile, Türkiye’s export value stood at \$43,397,000, representing about 3.5% of the global total. Other countries, such as the Netherlands, Ukraine, and Argentina, each held a share of less than 1% (Figure 5). These figures indicate that walnut exports are highly concentrated among a few dominant countries, while producer nations like Türkiye occupy a more limited position in the global market.

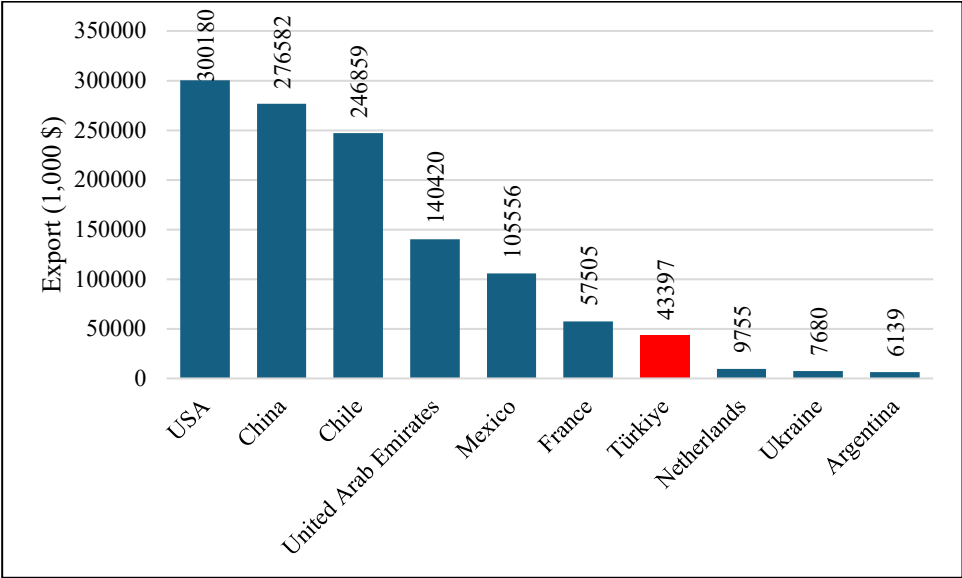


Figure 5. Leading countries in walnut exports and export values

Source: ITC-Trade Map, 2025.

Table 3 presents Türkiye’s walnut export quantities and values over the past ten years. An examination of the data shows that during the period 2013–2018, Türkiye’s walnut exports remained at very low levels, while a significant upward trend began to emerge after 2019.

Table 3. Türkiye’s walnut export quantities and values

Years	Export	
	Quantity (tons)	Value (1,000 \$)
2014	7,196	34,855
2015	13	13
2016	3	31
2017	9	84
2018	7	32
2019	16,587	43,840
2020	15,262	43,332
2021	14,759	34,050
2022	19,274	49,396
2023	27,178	43,397

Source: ITC-Trade Map, 2025.

The distribution of Türkiye's walnut exports by country and their respective shares in total exports are presented in Table 4. In 2023, Türkiye exported walnuts to 30 different countries. An analysis of Türkiye's walnut export data for 2023 reveals a heavy reliance on a few countries. The total export value is \$43.4 million. Of this, 54.73% was exported to Iraq alone. This figure highlights the limited market diversification in Türkiye's walnut exports. Following Iraq, the countries with the highest export volumes were Algeria (15.76%) and Syria (14.56%). Together, these three countries accounted for approximately 85% of total exports. While Algeria has become a significant market for Turkish walnuts in North Africa, the prominence of neighboring countries like Syria and Iraq is attributed to factors such as geographical proximity, cultural ties, and trade relations. Other countries, such as Iran, Egypt, Kazakhstan, Turkmenistan, Lebanon, and Afghanistan, had individual shares ranging from 1% to 3%. Although none of these countries constitutes a major market on its own, they are important for regional diversification.

Table 4. Countries to which Türkiye exports walnuts and export values

Countries	Export Value (1,000 \$)	Rate (%)
Iraq	23,752	54.73
Algeria	6,840	15.76
Syria	6,319	14.56
Kazakhstan	1,231	2.84
Turkmenistan	1,074	2.47
Egypt	904	2.08
Iran	806	1.86
Afghanistan	422	0.97
Area Nes	272	0.63
Lebanon	268	0.62
Other Countries	1,509	3.48
World	43,397	100.00

Source: ITC-Trade Map, 2025.

Türkiye's annual walnut import quantities and values are presented in Table 5. A comparison of export and import figures reveals that Türkiye is a net importer. Particularly after 2019, the export-to-import ratio has shown an upward trend. However, even at its peak in 2023, it remained relatively low at

around 33%. The majority of Türkiye’s walnut imports come from the United States, Chile, and China.

Table 5. Türkiye’s walnut import quantities and values

Years	Import		Ratio of Exports to Imports (%)
	Quantity (tons)	Value (1,000 \$)	
2014	35,396	141,268	24.67
2015	38,156	115,439	0.01
2016	58,850	139,396	0.02
2017	45,320	115,958	0.07
2018	52,770	163,192	0.02
2019	88,053	176,676	24.81
2020	63,492	142,923	30.32
2021	72,269	154,548	22.03
2022	69,779	160,172	30.84
2023	81,998	131,745	32.94

Source: ITC-Trade Map, 2025.

The concentration coefficients calculated based on the countries to which Türkiye exports the most walnuts are presented in Table 6. The calculated coefficients are interpreted below:

Iraq: In 2019, a very high concentration was observed with a coefficient of 26.81. However, from 2020 onwards, there has been a steady decline in the measured parameter, reaching 12.52 in 2023. This indicates that while Iraq’s dependence on walnut imports from Türkiye has decreased, there is still a strong tendency toward concentration.

Algeria: The coefficient, which was 2.41 in 2019, dropped in 2020 (1.46) but it rose again in 2022 (3.94) and reached 5.18 in 2023. This upward trend suggests that Algeria is establishing an increasing concentration in walnut imports from Türkiye.

Syria: The coefficient rose from 15.89 in 2019 to 19.75 in 2021 and reached 28.36 in 2023. This indicates a strong and growing concentration trend

in the walnut trade between Türkiye and Syria in recent years. In 2023, Syria had the highest concentration coefficient among all countries.

Kazakhstan: A notable concentration was present in 2019 with a coefficient of 5.69. However, trade ceased completely in 2020 and 2021, with no recorded transactions (0.00). A low value was recorded in 2022 (0.44), but in 2023, the coefficient surged to 6.77, indicating a strong renewed concentration. This fluctuation reflects an unstable but potentially significant trade relationship with Kazakhstan.

Turkmenistan: Starting from a weak level of 0.39 in 2019, the concentration increased to 4.82 in 2020 and 5.95 in 2021. Although it declined to 3.32 in 2022, it rose again to 5.69 in 2023. These figures show that Turkmenistan is developing an upward trend in walnut import concentration from Türkiye.

Egypt: The coefficient, which was 2.87 in 2019, declined in 2020 (1.40), recovered in 2021 (3.02), but dropped sharply in 2022 (0.78). In 2023, it jumped to 6.28, indicating a very strong concentration. This shows that Egypt has recently entered a rapid upward trend in walnut imports from Türkiye.

Lebanon: The value, which was 1.73 in 2019, jumped sharply to 10.74 in 2020 but declined rapidly in the following years, falling to 0.97 in 2023. This trajectory suggests that after a short-term, strong concentration, trade has tapered off.

Table 6. Concentration coefficients of countries

Countries	Years				
	2019	2020	2021	2022	2023
Iraq	26.81	16.17	17.18	14.85	12.52
Algeria	2.41	1.46	1.51	3.94	5.18
Syria	15.89	9.73	19.75	25.15	28.36
Kazakhstan	5.69	0.00	0.00	0.44	6.77
Turkmenistan	0.39	4.82	5.95	3.32	5.69
Egypt	2.87	1.40	3.02	0.78	6.28
Lebanon	1.73	10.74	1.27	2.87	0.97

4. Conclusion

This study analyzes Türkiye's walnut production potential and its position in the global walnut trade in light of production data and foreign trade concentration coefficients. The findings reveal that despite Türkiye's agroecological advantages, it has not yet achieved the desired level in the walnut trade and its exports face various structural challenges in terms of both market diversity and efficiency.

Over the past decade, Türkiye has nearly doubled its walnut production. This growth can be attributed to government subsidies for agricultural investments, the expansion of modern, large-scale walnut orchards, and increased awareness among producers. However, despite the increase in production area, Türkiye's productivity per hectare remains significantly below the global average (3,186 kg ha⁻¹), at just 2,068 kg ha⁻¹.

Although Türkiye ranks fourth in the world for walnut production, trade data show that the country remains a net importer. As of 2023, Türkiye exported only \$43.4 million worth of walnuts compared to imports valued at approximately \$132 million. In other words, the walnut trade deficit persists, with exports covering only 33% of imports. This reflects both the high domestic demand and the insufficient supply capacity to meet the needs of the export market.

An examination of export markets reveals that Türkiye's walnut exports are highly concentrated in a few countries. In 2023, Iraq, Algeria, and Syria accounted for approximately 85% of total walnut exports. This creates a significant dependency on a limited number of markets and increases vulnerability to sudden political or economic crises. While exports to Iraq have shown a declining trend in recent years, there has been an increasing concentration in markets like Algeria and Syria. Although countries like Kazakhstan, Turkmenistan, and Egypt show fluctuating trends, they also present substantial potential. However, trade relations with these countries have yet to be established in a stable and sustainable framework.

In light of these findings, agricultural policies aimed at increasing productivity in walnut production should be developed. Key priorities should include the promotion of modern farming techniques, the development of high-yield varieties suited to specific regions, and the provision of technical support to producers. Additionally, the modernization of irrigation systems and the

widespread use of high-quality saplings are factors that can directly enhance productivity.

Market diversification in Türkiye's walnut exports is also essential. The current export structure, heavily concentrated in a few countries, poses both economic and geopolitical risks. In this context, regions with high purchasing power that have not yet been adequately penetrated—such as the European Union, Gulf countries, and Southeast Asian markets—should be considered target markets.

Furthermore, environmental factors must not be overlooked. Walnut production is highly sensitive to climatic conditions, and environmental risks such as drought and frost pose threats to production stability. Therefore, developing climate-resilient walnut varieties, planning production based on agroecological zones, and promoting eco-friendly farming practices will be key to ensuring long-term sustainability.

In conclusion, while Türkiye is a global player in walnut production, its potential is not fully realized due to low competitiveness in foreign trade, limited market diversity, and productivity issues. Through comprehensive policies developed in collaboration among producers, exporters, government, and academia, Türkiye can become not only a leader in production but also a global leader in walnut exports.

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CHAPTER 5

THE DETERMINANT ROLE OF ENVIRONMENTAL CONDITIONS IN FISH HEALTH: AN EVALUATION OF TROUT, SEA BREAM, SEA BASS, AND CARP FARMING

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INTRODUCTION

The role of aquatic products in meeting the increasing global demand for food is steadily growing. The fisheries and aquaculture sector has been identified by the FAO as the fastest-growing food sector over the past decade, and its 2024 report states that the total production of aquatic products exceeded 220 million tons (Table 1) (Fisheries and Aquaculture Statistics, 2024). In parallel with this, aquatic products today hold a very important place in the food chain in many countries worldwide, and in some regions, they are considered a primary food source. In Japan, with a population exceeding 120 million, the fact that the per capita consumption of aquatic products is approximately equal to an individual’s body weight (70.6 kg) is of great significance. In our country, however, this average is only about 8 kg (Alpbaz, 2005).

The 20th century has been a period of rapid industrial development. Along with industrial growth, environmental pollution has emerged as one of the most important problems in recent years. Environmental pollution threatens environmental health and leads to a decline in the populations of aquatic organisms. Some species have even become extinct, while others face the threat of extinction. It has been stated that the most suitable method for reintroducing endangered species into nature or making them available for consumption is aquaculture (Venugopal, V., & Sasidharan, 2021).

Table 1. Global production of fish, arthropods, and mollusks in 2001 (Fisheries and Aquaculture Statistics, 2024).

	Production Quantity (million tons)	Notes
Arthropods & Mollusks	~37,8	Crustaceans and others; constitute a significant portion of aquaculture production
Total Aquatic Products	223,2	185.4 million tons aquatic animals + 37.8 million tons algae

In Türkiye, aquatic products production in 2024 decreased by 7.6% compared to the previous year, amounting to 933,194 tons. Of the total production, 31.1% consisted of marine fish obtained through capture fishing, 3.5% consisted of other marine products obtained through capture fishing, 3.6% consisted of inland water products obtained through capture fishing, and 61.8% consisted of aquaculture products (Anonymous, 2024).

In the rapidly growing global aquaculture sector, feed conversion ratio (FCR) and somatic growth rate (SGR) are critical for successful farming strategies. Disease resistance in fish and the ability to reach market size in a short period are among the key indicators of farming success (Jauralde et al., 2013). However, unfavorable environmental conditions can hinder the achievement of these goals or significantly impede reaching the desired levels (Moustakas & Mania, 2021). In marine fish farming, various challenges are encountered during the process from egg to market size, with the prelarval, larval, and postlarval stages standing out as critical phases requiring high sensitivity. Therefore, through professional approaches, fish farmers can address individual deficiencies in larvae, overcome nutritional barriers, and optimize environmental parameters—factors that play a decisive role in enabling the majority of larvae to reach market size (Besson et al., 2016).

Changes in the physical and chemical characteristics of the aquatic environment in which fish live directly affect their physiology, immune systems, and overall health status. Key water quality parameters such as temperature, dissolved oxygen (DO) levels, and pH determine many vital functions of fish, from metabolic rate to respiratory efficiency. Furthermore, stress factors such as toxic chemicals (e.g., agricultural pesticides, industrial waste), heavy metals, ammonia, habitat degradation, and general water pollution can severely and negatively affect fish health (Adah et al., 2022).

In the following sections of this study, information will be provided on some economically important species produced on a global scale (*Sparus aurata*, *Dicentrarchus labrax*, *Mugil cephalus*, *Solea solea*, *Scophthalmus maximus*, *Oncorhynchus mykiss*, *Cyprinus carpio*) and their environmental requirements.

1. THE GILTHEAD SEA BREAM

The gilthead sea bream (*Sparus aurata*) is widely distributed in various seas of the world, particularly in the Mediterranean, including the southern coasts of Türkiye, the Aegean Sea, and the Sea of Marmara. It is a highly sought-after and popular fish species, especially in the Aegean Region. For this reason, there has been continuous interest in its cultivation, and after the 1980s, quite successful aquaculture practices were achieved (Alpbaz, 2005).

The gilthead sea bream belongs to the family *Sparidae*, genus *Sparus*, and species *Sparus aurata*. It is a benthic species that feeds on the sea bottom. Growth rates can vary slightly by region. In the Aegean, juveniles born between December and March reach 30–50 g in the spring and exceed 100 g by the end of their first summer (Uçal, 2002). Individuals weighing between 30–50 g are called “İnce Lidaki,” those around 100 g are “Lidaki,” those between 100–180 g are “Kaba Lidaki,” and those weighing 200 g or more are referred to as “Çipura” (Alpbaz, 2001).

Anatomically, the body is high and laterally compressed. The pectoral fins are positioned on the sides, and the pelvic fins have more than five rays. The dorsal fin is located at the front and contains hard rays. The body is covered with hard scales up to the head. The lateral line is clearly formed. The mouth and teeth are strong, capable of breaking even shelled organisms. With their sturdy teeth, they can easily crush and consume small mussels and crabs. Juvenile crabs are among their favorite foods, making hook fishing with thumbnail-sized crabs highly effective (Alpbaz, 2005).

Gilthead sea bream reach sexual maturity at the age of two, at which stage they are generally observed to be male. From the third or fourth year onwards, they tend to transform into females. Depending on environmental conditions, it is always possible, albeit rarely, for the fish to change sex. Since this species has attracted interest and been brought into cultivation over the last 10–15 years, it has been occasionally observed that they can change sex at any time. However, the fact that most of the older wild-caught individuals are female proves that gilthead sea bream are predominantly female after the second year (Seginer, 2016).

This widely cultivated species is highly sensitive until it reaches market size, particularly during the prelarval, larval, and postlarval stages (Mokbel et al., 2020). Farmers must pay close attention to environmental conditions during these critical stages as well as throughout other farming periods. In this species, which is taken into culture, environmental conditions play a direct role in survival rates and consequently affect the financial performance of aquaculture operations. Consequently, key water quality parameters—such as temperature, salinity, pH, and dissolved oxygen—are critical determinants of success in aquaculture practices.

1.1. Temperature

The temperature requirements of gilthead sea bream vary across different stages of their life cycle. Optimal growth occurs between 22–25°C. Although they can survive at 32°C, they perish when the water temperature reaches 34°C. Similarly, low water temperatures of around 3°C are also lethal to the fish. Therefore, extremely high or very low temperatures are unsuitable for gilthead sea bream (Ibarz et al., 2010). In lagoons, when water temperature decreases during winter, they migrate towards the sea via channels to seek warmer conditions, which is also the period when the highest fishing yields are obtained. Additionally, when the water temperature drops to 7–10°C, growth ceases, and metabolic activities are reduced to a minimum (Bartolini et al., 2015).

Table 2. Temperature requirements of gilthead sea bream in aquaculture tanks at specific stages (Alpbaz, 2001).

Tanks	Temperature (°C)
Broodstock tanks	10–14
Spawning tanks	14–16
Egg hatching temperature	16–18
Incubation tanks	15–17
Pre-larval tanks	18–22
Post-larval tanks	20–24
Larval tanks (first 15 days)	16–18
Larval tanks (from day 16 onwards)	22

Table 3. Temperature requirements of gilthead seabream (*Sparus aurata*) at specific stages (Tucker, 1998).

Temperature (°C)	Effects
≤ 10	Lethal
25	Induces positive growth and enhances feeding rate
28	Optimum growth temperature
31	Rapid decrease in growth

1.2. Salinity

Gilthead seabream (*Sparus aurata*) are less tolerant to salinity fluctuations compared to mullet and sea bass. The optimal salinity level for culture is approximately 0.35%. They can survive comfortably within a salinity range of 0.10–0.40%. However, an increase in salinity to 0.50% results in mortality. In Mediterranean lagoons, mass mortalities are often observed during summer due to excessive evaporation and insufficient water exchange.

Similarly, a decrease in salinity to around 0.05‰ has adverse effects on survival and can cause mortality. Therefore, entry into or exit from freshwater or low-salinity brackish waters should be brief, avoiding prolonged exposure to low-salinity environments (Tekelioğlu, 1998). The optimal salinity for spawning is 33–35 ppt, while the optimum salinity for larvae is 36–38 ppt (Tucker, 1998).

1.3. pH

For gilthead seabream (*Sparus aurata*), lethal pH values range between 5.2 and 9.7, meaning that mortality occurs below pH 5.2 and above pH 9.7 (Tucker, 1998). For juvenile-sized seabream, the ideal pH range is generally between 6.5 and 8.5. The recommended lethal threshold for larvae is between 8.0 and 8.4, while for juveniles and larger individuals, the lethal range is 7.0–8.5 (Tucker, 1998).

1.4. Dissolved oxygen

Dissolved oxygen is as influential as other environmental factors in aquaculture. Gilthead seabream (*Sparus aurata*) require a minimum of 3–4.5 mg/L of oxygen for adequate feeding. Lethal effects occur at concentrations of 2 mg/L or lower. The generally recommended oxygen level is 5–7 mg/L. At night, oxygen is consumed by both plants and animals, with no photosynthetic oxygen production. In particular, during the night, high densities of plants and plankton significantly deplete oxygen levels, as do high concentrations of animals. The most critical and dangerous period for fish has been identified as the early hours of the morning (Tucker, 1998).

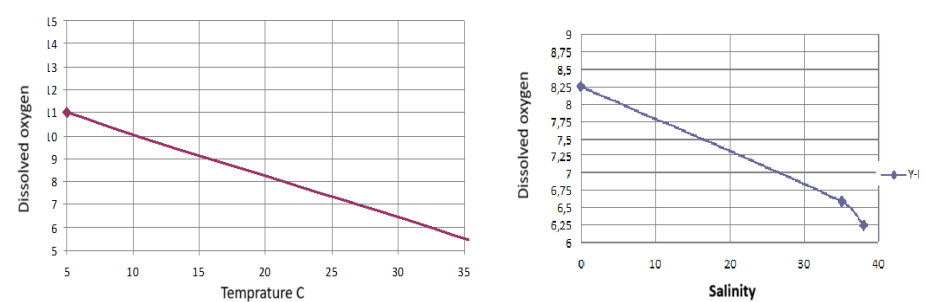


Figure 1. Relationship between temperature-dissolved oxygen and salinity- dissolved oxygen (At the salinity temperature is 25 °C) (Tucker, 1998).

1.5. Light

Light is an important factor for gilthead sea bream (*Sparus aurata*) as well as for other fish species. For gilthead sea bream, the suitable light intensity range is 600–1500 lux, with a maximum of 10,000 lux, and an optimal photoperiod of 24 hours per day (Tucker, 1998). During the larval stage, light intensity varies daily. The production protocol for gilthead sea bream larvae is presented in the table below.

Table 4. Gilthead Sea Bream (*Sparus aurata*) Larval Production Protocol (Alpbaz, 2005)

Day	Temperature (°C)	Salinity (ppt)	Flow Rate (%/hour)	Photoperiod (hours)	Light Intensity (lux)
1	18–20	36–38	1	0	0
5	18–20	36–38	≤0.5	24	30
10	18–20	36–38	≤0.5	24	1500
15	18–20	36–38	≤0.5	24	1500
20	18–20	36–38	10	24	1500
25	20–21	36–38	10	24	1500
30	20–21	36–38	15	24	1500
35	20–21	36–38	20	24	1500
40	20–21	36–38	20	24	1500

1.6. Carbon Dioxide

In aquaculture systems, the primary sources of carbon dioxide are the respiration of animals and plants, as well as organic matter. An increase in algae within the culture environment, particularly during the night and toward early morning, results in high oxygen consumption. As a consequence of excessive oxygen utilization, the concentration of dissolved carbon dioxide in the culture medium increases. For safe conditions, carbon dioxide levels should be maintained below 8 mg/L (Tucker, 1998).

1.7. Ammonia

Ammonia is the first compound excreted from the body following the consumption of protein-rich feed. It is eliminated through the gills and kidneys. Ammonia undergoes decomposition and mineralization, transforming into waste products such as urea, uric acid, and keratin, which have no biological utility. The optimal temperature for ammonia conversion is 30–35 °C (Tucker,

1998). For gilthead sea bream fry, at 40 ppt salinity, a temperature of 26–27 °C, and a pH of 8.1, the safe ammonia concentration is 1200 (64) µg/L, the harmful level is 8220 (470) µg/L, and the lethal concentration is 1300 (740) µg/L (Tucker, 1998).

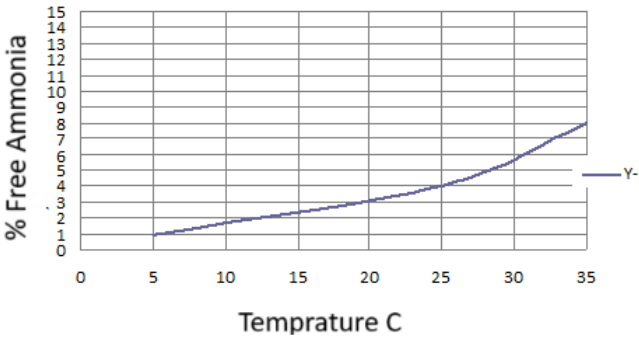


Figure 2. Relationship between water temperature, free ammonia, total ammonia, and nitrogen (Tucker, 1998).

1.8. Nitrite and Nitrate

Nitrite and nitrate are also considered toxic substances. Due to their lethal effects, their concentrations should be kept as low as possible. The recommended nitrite limits are 0.1 mg/L for larvae and 1 mg/L for adult fish; however, the absence of nitrite is considered the most desirable condition.

1.9. Hydrogen Sulfide

Hydrogen sulfide (H₂S) is reduced by certain bacteria under oxygenated conditions. Its presence rapidly increases mortality rates. Concentrations of ≤12.0 mg/L dissolved hydrogen sulfide have toxic effects on fish eggs, while concentrations of ≤2.0 mg/L are toxic to juvenile fish (Tucker, 1998). Therefore, it must be completely removed from the water.

1.10. Toxic Metals

Toxic metals, even at low concentrations, can have detrimental effects on the physiology, growth, and survival of fish species such as gilthead seabream (*Sparus aurata*). These metals may enter aquaculture systems through industrial discharges, agricultural runoff, or natural geological sources. Excessive accumulation in water can disrupt enzymatic activities, damage gill and liver tissues, impair osmoregulation, and, in severe cases, cause mortality.

For instance, mercury (Hg) is highly toxic even at ≤ 0.01 mg/L, while cadmium (Cd), lead (Pb), and copper (Cu) can cause chronic toxicity when levels exceed their safe thresholds. Continuous monitoring of water quality, implementation of proper filtration systems, and preventing contamination from external sources are critical to keeping toxic metal concentrations below recommended limits, thereby ensuring both fish welfare and product safety in aquaculture (Tucker, 1998).

Table 5. Some Toxic Metals (Tucker, 1998)

Toxic Metals	Values (mg/L)
Copper	Should be below 3 mg/L
Mercury	Should be ≤ 0.01 mg/L
Lead	Should be below 1 mg/L
Tin	Should be below 0.001 mg/L
Zinc	Should be below 10 mg/L
Chromium	Should be below 25 mg/L
Iron	Should be below 30 mg/L
Aluminum	Should be below 10 mg/L
Cadmium	Should be below 1 mg/L
Manganese	Should be below 10 mg/L
Silver	Should be below 0.3 mg/L
Arsenic	Should be below 25 mg/L
Nickel	Should be below 5 mg/L
Boron	Should be below 5000 mg/L

1.11. Stocking densities

Stocking densities in gilthead sea bream (*Sparus aurata*) aquaculture are among the factors that influence and alter environmental conditions. The stocking densities are as followsTable 7. Stocking Densities in Gilthead Sea Bream (Alpbaz, 2005):

Table 6. Stocking Densities for Gilthead Sea Bream (*Sparus aurata*) (Alpbaz, 2005)

Stages	Stocking Density	Oxygen Level (mg/L)	Salinity (ppt)	Temperature (°C)
Incubation	1500–2500 (individuals/L)	5–6	36–38	16–18
Prelarval	80–100 (individuals/L)	5–6	36–38	16–18
Postlarval	80–100 (individuals/L)	5–6	36–38	16–18
Nursery	3000–5000 (individuals/m ³)	5–6	36–38	20–22
Grow-out (Semi-intensive)	2–5 kg/m ³	5–6	36–38	20–22
Grow-out (Intensive)	15–30 kg/m ³	5–6	36–38	20–22

2. EUROPEAN SEA BASS

With the advancement of aquaculture technologies, research on sea bass (*Dicentrarchus labrax*) culture has significantly increased since the 1980s, and very successful application results have been achieved to date. Türkiye is among the leading countries in sea bass production, just as it is in gilthead sea bream aquaculture.

Sea bass, belonging to the Serranidae family, is a species with high economic value due to its high-quality flesh. The larvae primarily feed on zooplankton and small live organisms, while juveniles prefer small shrimp. Larger individuals consume fish species such as sardines, anchovies, and gobies, as well as crabs and large shrimp (Munekata et al., 2020)

Morphologically, sea bass have a torpedo-shaped body with a grey coloration. Their ventral side is white, and a darkish spot is present on the upper part of the operculum. The edges of the gill covers are notably sharp and rigid (Alpbaz, 2001).

In the Mediterranean, gonadal development typically begins in September and continues until December–January. An increase in the number of spawning individuals is observed as the water temperature drops to 12°C. Depending on water temperature, spawning may continue until early March. In general, similar to gilthead sea bream, sea bass prefer the coldest months with water temperatures ranging between 11–14°C for spawning. Salinity has been found to have little effect on the timing of spawning (Mylonas et al., 2005).

Sexual maturity is reached at different ages and sizes depending on the region. In the Mediterranean, males reach maturity at 2–3 years of age and 25–30 cm in length, while females reach it at 5 years and 30–40 cm. In the Atlantic, males become sexually mature at 4–7 years and 32–37 cm, and females at 5–8 years and 38–42 cm (Alpbaz, 2001).

2.1. Temperature

Sea bass (*Dicentrarchus labrax*) can survive in water temperatures ranging from 5°C to 28°C. Although they continue to feed at temperatures below 18°C, no significant growth occurs at these levels. The optimal growth temperature has been reported to be between 20°C and 23°C. For spawning, the most suitable temperature range is between 11°C and 14°C. The preferred

temperature values during the main stages of sea bass aquaculture are summarized below (Tucker, 1998).

Table 7. Temperature Preferences of Sea Bass (*Dicentrarchus labrax*) at Specific Developmental Stages (Tucker, 1998)

Tank / Stage	Temperature (°C)
Broodstock	20–23
Spawning temperature	11–14
Incubation tank water temperature	13–17 (optimal 15)
Water temperature at larval hatching	15
Water temperature until day 10 of larvae	18–19
Optimal water temperature for juvenile rearing	22
Optimal water temperature for feeding	22–25

Sea bass spawning temperatures, optimal temperature values for larvae, and suitable temperature ranges for juveniles are as follows:

Table 8. Temperature Requirements of European Sea Bass (*Dicentrarchus labrax*) at Various Stages of Tank-Based Aquaculture (Alpbaz, 2001)

Tank / Stage	Temperature (°C)
Spawning temperature	10–16
Optimal temperature for larvae	16–20
Optimal temperature for fry	22–27
Wide temperature range for fry	2–32

2.2. Salinity

Salinity is a critical parameter for all marine fish species. The optimal salinity for spawning is between 35–37‰. During larval production, maintaining salinity around 35‰ is considered ideal. A salinity level of 40‰ may have lethal effects on larvae. Juvenile European Sea bass exhibit high tolerance to changes in salinity and can survive within a wide range of 5–35‰ (Alpbaz, 2001). For larvae, the optimal salinity range is 25–35 ppt, while the tolerable range is 10–37 ppt. For juveniles, the optimal salinity range is 10–30 ppt, and the tolerable range is as wide as 0.5–90 ppt (Tucker, 1998).

2.3. pH

For sea bass, the optimal pH range for spawning is between 7.3 and 8.5, with the most suitable value being between 7.5 and 8. For juvenile sea bass, a

pH range of 7–8 is considered adequate (Alpbaz, 2005). Lethal effects are observed within the pH range of 5.2 to 9.7 (Öğretmen et al., 2016).

2.4. Dissolved oxygen

At water temperatures between 20–25°C, the dissolved oxygen (O₂) concentration is approximately 5–6 mg/L, which is considered suitable for sea bass as it is for many other fish species. It has been determined that a 40-gram sea bass consumes between 0.1 mg and 0.4 mg of O₂ per hour at temperatures between 7–25°C. In spawning tanks, an oxygen level of 7.2–7.7 mg/L at 11–12°C is considered sufficient (Saroglia et al., 2000).

For larvae, aeration should provide oxygen saturation at approximately 80% of the saturation level appropriate to the water temperature. If aeration is excessive and oxygen saturation exceeds normal levels, it can lead to gas bubble disease and consequently cause larval mortality. In larval tanks, it is recommended that no water changes be made during the first 8–10 days. If the system is well-established, a minimal recirculation flow is advised (Alpbaz, 2001).

2.5. Light

Light is one of the important factors in aquaculture. For sea bass (*Dicentrarchus labrax*), the appropriate light intensity should be between 800–1000 lux, and the optimal photoperiod (day length) should be 14–16 hours (Alpbaz, 2001).

During the early larval rearing period of European sea bass (*Dicentrarchus labrax*), a gradual acclimation protocol is applied with respect to temperature, salinity, water flow rate, photoperiod, and light intensity. In the first few days (days 1–4), no light is applied, and the salinity is gradually reduced from 36 ppt to 26 ppt while maintaining the water temperature at 15–16°C and a constant low flow rate of 5%/hour. From day 5 onwards, light exposure begins with 12 hours of photoperiod and increasing light intensity from 50 lux up to 450 lux by day 13. Simultaneously, water flow rate and temperature are slowly increased to 15%/hour and 18°C, respectively, while light duration is extended to 15–16 hours. This controlled transition is designed to optimize the physiological adaptation and survival of sea bass larvae,

facilitating the development of their visual and feeding systems in accordance with their increasing metabolic demands (Georgakopoulou et al., 2007).

2.6. Carbon Dioxide

In general, maintaining dissolved oxygen levels below 8 mg/L is suitable for sea bass. Otherwise, fish may face serious respiratory problems due to impaired respiration (Cecchini & Caputo, 2003).

2.7. Ammonia

Ammonia is a substance that can cause serious problems in aquaculture. Nitrogen excretion in fish naturally increases with feeding. In sea bass, during starvation, nitrogen excretion via feces can drop to as low as 72 µg of ammonia and 12 µg of urea per kilogram of body weight per day, thereby remaining stable. At a salinity of 34 ppt, a temperature of 18°C, and a pH of 8.2, approximately 2220 µg/L is considered a safe ammonia concentration for sea bass, while lethal effects are observed beyond 22000 µg/L (Chew et al., 2005).

2.8. Nitrite and Nitrate

For sea bass, under temperatures below 23°C, a nitrate concentration of 13 mg/L is considered harmful. Approximately 95 mg/L is regarded as lethal. For juvenile fish, 0.1 mg/L is considered a safe level, while 3 mg/L can have lethal effects (Tucker, 1998). The nitrite concentration in water is expected to be below 0.5 mg/L. A nitrite level of 2 mg/L has been reported to cause mortality (Alpbaz, 2001).

2.9. Hydrogen Sulfide

Hydrogen sulfide is also one of the undesirable and harmful substances in aquaculture. It is recommended that this compound be completely absent in fish farming waters.

2.10. Toxic Metals

For European seabass, the copper level in the water used for aquaculture should be kept below 10 mg/L. When the copper concentration reaches 50 mg/L, harmful effects begin to be observed in the fish. At a concentration of 100 mg/L, copper causes lethal effects on seabass.

Table 9. Some toxic metals (Tucker, 1998).

Toxic Metals	Threshold Values (mg/L)
Copper	≤ 50
Mercury	≤ 0.01
Tin	0.001
Lead	≤ 1
Zinc	≤ 10
Iron	≤ 30
Chromium	≤ 25
Aluminum	≤ 10
Cadmium	≤ 1
Manganese	≤ 10
Arsenic	≤ 25
Silver	≤ 0.3
Nickel	≤ 5
Boron	5000

2.11. Stock densities

One day after the eggs hatch, the larvae can be transferred into containers and transported. The transportation of eggs is carried out in 15-liter plastic bags filled with oxygen. During transport, the water temperature should be between 12–15°C. In such containers, 20,000 eggs can be transported for 24 hours, and 100,000 eggs for 5–6 hours (Alpbaz, 2001).

If water circulation is maintained through a filtration system in the larval tank, stocking can be done at a density of 800–1000 eggs per liter. If there is no circulation, the stocking density should be 5–100 eggs per liter. In larval production tanks, 30 to 10 larvae per liter can be stocked from the start of feeding until the two-month stage. During the larval rearing period, the number of individuals maintained at 50–70 per liter is reduced to 1–2 per liter once the juveniles reach 1 gram in weight. For 0.25 g larvae, stocking is planned at 1 kg/m³, and for 1.5 g larvae, 15 kg/m³ stocking is feasible. However, in such stocking densities, a high water exchange rate is necessary. In net cage farming, stocking at a density of 20 kg/m³ is possible. For broodstock, a stocking density of 1.8–3.3 kg/m³ is considered suitable for aquaculture (Volckaert et al., 2008).

3. TROUT

Trout are among the most delicious and preferred freshwater fish, living in cold, clear, and oxygen-rich streams, spring waters, and lakes (Çelikkale, 1994). Trout farming is one of the first aquaculture practices introduced and

successfully applied in Türkiye. The initial efforts that began in the 1970s yielded highly positive results. So much so that the number of potential water resources suitable for trout farming in Türkiye has significantly decreased in recent years. However, this does not mean that trout farming cannot be further developed in the country. As of 2002, trout production in Türkiye was approximately 40,000 tons, carried out in more than 1,000 enterprises (Alpbaz, 2005).

Trout belong to the Salmonidae family (Çelikkale, 1994). A distinguishing feature of trout compared to other fish is the presence of an adipose fin. In zoological classification, salmon resemble sharks due to their simple skeletal structures, while also resembling more developed bony fish such as sea bass and cod (Özdemir, 1994).

The fish in this family can be grouped into two major categories:

Those that live entirely in freshwater,

Those that spend part of their lives in freshwater and part in marine environments.

All fish in both groups reproduce in freshwater. The method of reproduction is nearly the same for both. In trout farming, the main focus is on trout that spawn and grow in freshwater (Çelikkale, 1994).

For broodstock, it is most appropriate to use female trout aged 3 to 4 years. However, it is also possible to obtain eggs from two-year-old females if they are not well-fed. Male broodstock should be between 2 to 4 years old. Fish that are older than 6–7 years are recommended to be removed from breeding stock. The hatching period for trout eggs is 300 degree-days (Alpbaz, 2005).

3.1. Temperature

Trout are cold-water-loving fish. In trout farming, it is desirable that the water temperature remains at 14–15°C throughout all seasons of the year. For spawning and hatching, the water temperature should be between 7–15°C. However, a temperature range of 10–12°C is considered optimal for spawning. It has been observed that juvenile production is not economically viable when the temperature exceeds 13°C (Ostergaard, 1987).

During the larval and fry rearing stage, the preferred water temperature is between 8–13°C. For the grow-out phase, an ideal temperature range is 12–18°C, and it is undesirable for the temperature to fall below 10°C, as feed intake

decreases under low temperatures, and the feed conversion ratio cannot reach the desired level. Juveniles have been observed to survive in temperatures between 6–20°C (Tucker, 1998). The most suitable temperature for optimal growth performance has been determined as 15–17°C (Alpbaz, 2005).

3.2. Salinity

The tolerance of trout to salinity increases as they grow. For fry weighing 0.4 grams, increasing salinity concentrations from ‰3 to ‰6 positively affects growth. For fish weighing around 5 grams, salinity concentrations between ‰6 and ‰15 have been observed to promote growth, whereas concentrations above ‰15 negatively impact growth. It has been determined that seawater with a salinity concentration of ‰30 is suitable for aquaculture from fingerling to market size (Pino-Martinez et al., 2024).

As long as the water temperature is suitable, trout can easily survive in salinity levels of 20 ppt. Therefore, during the winter months, when the water temperature drops below 17–18°C, rainbow trout cage farming in the Black Sea was tested by Alpbaz (2005), who emphasized that it can be successfully implemented.

3.3. pH

The water used in trout farming should be neutral or slightly alkaline. Therefore, the pH level of the water should range between 6.5 and 8.5, with the optimal value being identified as 7. pH levels below 5.0 and above 9.2 have lethal effects on trout. Acidic waters not only reduce the appetite of fish but can also cause fatal outcomes. In highly acidic waters, the formation of hydrogen ions (H^+) disrupts the functions of cell membranes in fish (Mota et al., 2018).

3.4. Dissolved oxygen

Studies have shown that trout experience asphyxiation when the dissolved oxygen level in the water drops to 5 mg/L. While a level of 7 mg/L does not cause any harm, the optimal dissolved oxygen concentration for trout has been determined to be between 10 and 11 mg/L. For spawning, the most suitable dissolved oxygen level is between 10 and 12 mg/L (Jiang et al., 2021).

However, it is crucial to understand the potential oxygen capacity of the water being used. This is because the oxygen saturation level of water varies

depending on water temperature and the elevation of the facility's location (Çelikkale, 1994).

Table 10. Oxygen Saturation of Water at Different Temperatures

Water Temperature (°C)	Oxygen (mg/L)	Water Temperature (°C)	Oxygen (mg/L)	Water Temperature (°C)	Oxygen (mg/L)
0	14.62	11	11.08	21	8.99
1	14.23	12	10.83	22	8.93
2	13.84	13	10.6	23	8.68
3	13.48	14	10.37	24	8.53
4	13.13	15	10.15	25	8.38
5	12.8	16	9.95	26	8.22
6	12.48	17	9.74	27	8.07
7	12.17	18	9.54	28	7.92
8	11.87	19	9.35	29	7.77
9	11.59	20	9.17	30	7.63
10	11.33	-	-	-	-

3.5. Carbon Dioxide

It is accepted that typical trout waters contain about 2 mg/L of carbon dioxide. If the concentration of carbon dioxide increases in the water, the amount of algae also increases. Excessive algae growth is an indication of pollution in the water (Hafs et al., 2010). According to Çelikkale (1994), the acceptable range for carbon dioxide in trout culture is between 10 mg/L and 25 mg/L.

3.6. Ammonia

At 7 – 9 °C and a pH value of 8.2, the minimum level was determined to be 1240 µg/L, while the maximum level was 3629 µg/L. For juveniles, it is recommended that the concentration be less than 0.005 mg/L.

Table 11. Free ammonia levels at different temperatures and pH values (Shepherd, 1997).

Temperature (°C)	pH 6	pH 7	pH 8	pH 9
5	0.01	0.13	1.24	11.18
10	0.02	0.19	1.83	15.70
15	0.03	0.27	2.68	21.59
20	0.04	0.40	3.83	28.47
25	0.06	0.57	5.44	36.53
30	0.08	0.81	7.52	44.84

3.7. Nitrite and Nitrate

In trout farming, the nitrite level should be 0.1 mg/L in soft waters and 0.2 mg/L in hard waters. The nitrate level in closed systems should be 100 mg/L. (Çelikkale, 1994).

3.8. Water Quality Criteria

Water quality plays a crucial role in the health and growth performance of aquaculture species, particularly sensitive ones like trout. Among many factors, the presence and concentration of toxic metals in the aquatic environment significantly impact fish physiology and overall farm productivity. Excessive exposure to these metals can cause bioaccumulation in tissues, physiological stress, compromised immune systems, and even mortality (Kocer & Sevgili, 2014).

Copper is an essential trace element but becomes toxic at concentrations above 0.03 mg/L. Similarly, zinc, which is vital for enzymatic functions, must be maintained below 0.04 mg/L to avoid adverse effects. Iron, although necessary in small quantities, can promote oxidative stress if present in concentrations beyond 0.3 mg/L. Lead and mercury, on the other hand, are highly toxic even in minute concentrations and can lead to chronic toxicity, behavioral disturbances, and reproductive failure. Cadmium, chromium, and aluminum also pose serious threats by disrupting gill function, osmoregulation, and metabolic activities. Cyanide and barium are lesser-known threats but can have lethal effects if concentrations exceed their respective thresholds. The presence of elevated aluminum levels, for example, can inhibit ion transport and mucous secretion, while chromium exposure can induce DNA damage and oxidative imbalance. Maintaining a clear and low-turbidity environment (below 10 JTU) is crucial not only for visibility but also for ensuring optimal feeding and stress reduction. Turbid waters often indicate organic pollution, suspended particles, and microbial contamination (Tahar et al., 2018).

For sustainable aquaculture, it is imperative to regularly monitor water quality parameters using reliable methods and calibrations. Ensuring compliance with scientifically established thresholds—such as those listed below—can help maintain healthy aquatic ecosystems and economically viable production systems.

This understanding should be incorporated into water quality management protocols across all stages of aquaculture operations, from hatcheries to grow-out systems. Environmental managers must take preventive and corrective actions as soon rising metal concentrations are detected.

Adopting biofiltration systems, controlling feed inputs, proper waste management, and reducing upstream industrial pollution can help mitigate the risk of toxic metal contamination in aquaculture waters.

Table 12. Some Toxic Metals (Çelikkale, 1994)

Metals	Values (mg/L)
Copper	0.006 – 0.03
Zinc	0.005 – 0.04
Iron	0.3
Lead	0.01 – 0.03
Mercury	0.005
Cadmium	0.0004 – 0.003
Chromium	0.01 – 0.05
Cyanide	0.005 – 0.025
Barium	5
Aluminum	0.1
Turbidity	10 TU

4. CAMMON CARP

The common carp (*Cyprinus carpio*) has historically been one of the primary species for aquaculture in Türkiye. Indeed, the country's climate is highly favorable for carp farming. The release of fish produced in juvenile production facilities established by the State Hydraulic Works (DSİ) into ponds has contributed significantly to the growth of carp production (Alpbaz, 2005).

In the past two decades, alongside intensive pond aquaculture, more intensive systems have been developed involving channels, tanks, cages, and warm-water methods.

Among global fish families, Cyprinidae is the most species-rich, with the common carp being its most characteristic member. This species is among the most widely cultivated fish in the world (Çelikkale, 1994).

As the most typical member of the Cyprinidae family, *Cyprinus carpio* is widely distributed across the Aegean, Marmara, Black Sea, Central Anatolia, and much of Eastern Anatolia regions of Türkiye. It can reach up to 1 meter in

length and weigh between 25–30 kg, making it the top inland fish species produced in the country.

The carp has a terminal, protrusible mouth without teeth, but with pharyngeal teeth. It has two pairs of barbels, one long and one short, located at the mouth joint. The dorsal fin is long, the anal fin short, and the body is covered with large scales. Depending on feeding conditions, body color varies from golden yellow to dark green or brownish-green, with reddish-gold hues commonly seen and yellowish shades on the belly and cheeks (Farang et al., 2014).

During late spring and summer, at water temperatures of 18–20 °C, carp spawn sticky eggs of 1–1.5 mm in diameter on vegetation in shallow waters.

4.1. Temperature

Optimal growth in carp occurs in water temperatures of 23–24 °C. This is due to the temperature-dependent digestion of feed and conversion efficiency into biomass. Carp reproduce in waters above 18–20 °C (Çelikkale, 1994). A temperature of 20 °C is optimal for spawning. In hormonally induced spawning, temperatures of 22–24 °C are ideal (Seagrave et al., 2002). Though feed intake may occur around 15 °C, growth is not optimal between 15–20 °C. Below 15 °C, feeding is not effective, and development is limited. However, even above 27–28 °C, no significant negative effects on feeding are observed (Oyugi et al., 2012).

4.2. Oxygen

The minimum dissolved oxygen level required for carp farming is 3–3.5 mg/L. Cultivation is easily managed in waters with 5–6 mg/L oxygen. Prolonged oxygen levels at or below 3–3.5 mg/L cause stress, reduced feeding, and impaired growth. Oxygen levels of 0.5–1 mg/L are lethal (Alpbaz, 2005).

Carp utilize up to 60% of dissolved oxygen in the water, which must be considered (Alpbaz, 2005). For intensive systems, incoming water must contain at least 7 mg/L oxygen, and outgoing water should not fall below 5 mg/L. Swimming activity and oxygen consumption are positively correlated: more movement means more energy use (Çelikkale, 1994).

Table 13. Relationship between swimming activity and oxygen consumption in summer carp

Swimming Speed (cm/s)	Oxygen Consumption (mg O ₂ /kg·h) at 10°C	Oxygen Consumption (mg O ₂ /kg·h) at 20°C
0	120	220
2	150	270
4	180	320
6	230	400
8	280	500
10	330	560
12	-	600

4.3. pH

Carp can tolerate a pH range of 5.5 to 10.8, with the ideal range being 6.5–8 for optimal growth (Michaels, 1998). Feeding disorders are observed at pH values of 8–10.9, and mortality occurs beyond 5.5–10.8 (Alpbaz, 2005).

An excess of submerged plants, phytoplankton, and algae can raise pH in pond water. Periodic removal is recommended, and lime application can stabilize pH levels (Nasir et al., 2019).

4.4. Water Hardness

For carp farming, a total alkalinity value (SBV) of 2–4 is suitable. An SBV of 7 or more indicates hard, calcareous water (Fu, 2007).

4.5. Water Quality Parameters

In addition to macro factors like water source, temperature, and oxygen, micro factors also play a role in carp aquaculture (Çelikkale, 1994).

Table 14. Micro-level water quality parameters for carp aquaculture

Parameters	Values
Nitrite	0.06 – 0.1 mg/L
Ammonia	0.02 mg/L
Chlorine	0.02 mg/L
Iron	0.9 mg/L
Cadmium	0.004 mg/L
Nickel	0.5 mg/L
Cobalt	0.1 mg/L
Manganese	0.1 mg/L
Lead	0.1 mg/L
Arsenic	0.001 mg/L
Turbidity	25 JTU (Jackson Turbidity Unit)

5. CONCLUSION

Fish play a pivotal role in aquatic ecosystems, not only as integral components of food webs but also as biological indicators of water quality. However, these organisms are highly sensitive to environmental stressors. Fluctuations in water temperature, dissolved oxygen levels, deviations in pH, the presence of toxic chemicals, heavy metals, ammonia, and habitat degradation significantly compromise their physiological integrity, immune competence, and behavioral homeostasis. These stressors, acting both individually and synergistically, contribute to increased disease prevalence, impaired growth and reproductive performance, and ultimately a decline in aquatic biodiversity.

In this context, protecting fish health is of strategic importance not only for the sustainability of individual species but also for the stability of entire aquatic ecosystems. Therefore, the continuous and integrated monitoring of environmental parameters is indispensable. Scientifically grounded environmental surveillance systems enable the real-time tracking of critical variables such as water temperature, dissolved oxygen, pH, toxicant concentrations, and habitat quality. These data are vital for the early detection of ecological risks and serve as a foundation for the development of sustainable aquaculture practices and nature-based management solutions.

In conclusion, scientific research aimed at understanding and mitigating the impacts of environmental stressors on fish health forms the backbone of ecologically sound conservation policies. Effective management strategies developed through such studies will not only ensure the long-term viability of fish populations but also secure a reliable and healthy food source for humans.

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CHAPTER 6

***Pancratium Maritimum L.* AS A BIOINDICATOR: THE FUTURE OF DUNE ECOSYSTEMS IN THE CONTEXT OF THE CLIMATE CRISIS**

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Introduction

Global climate change is a multidimensional crisis that must be addressed not only through temperature increases and irregular precipitation patterns, but also through the pressures it creates on the structural integrity of ecosystems and biodiversity (IPCC, 2023). In this context, coastal dunes stand out among fragile ecosystems that serve as "climate buffers" both geographically and ecologically. Dune ecosystems, with their water-holding capacity, microclimatic regulation functions, and the hosting of rare species, are of critical importance not only for local flora and fauna but also for regional ecological resilience (Martínez & Psuty, 2008).

The sand lily (*Pancratium maritimum* L.), native to the Mediterranean Basin, provides a notable example in this regard. Its bulbous structure, resistance to salt stress, and ability to maintain photosynthetic activity under extreme temperature conditions highlight the species' adaptive capacity to climate crisis (Balestri et al., 2014). Sand daffodils also contribute to habitat stabilization through their strong interactions with dune dynamics, making them suitable for consideration as a bioindicator species.

Coastal dunes are indispensable not only for natural processes but also for the long-term safety of human communities. These ecosystems protect the coastline, preventing storm waves from reaching inland and reducing the risk of salinization of agricultural lands and residential areas. Furthermore, the porous structure of dunes allows for the retention of water after rainfall, supporting both the recharge of groundwater reserves and the sustainability of agricultural production in the region (Calvo-Cases, Boix-Fayos, & Soriano-Soto, 2018). These characteristics make dunes a natural adaptation infrastructure against the increasing drought and heat pressures of the climate crisis.

Furthermore, the diversity of endemic species harbored by dunes is valuable not only for ecological balance but also for the preservation of biocultural heritage. The Mediterranean Basin is one of the richest biodiversity areas globally, with over 12,000 species, nearly a third of which are endemic (Meerow & Snijman, 1998; Prisco, Carboni, & Acosta, 2021). The *Pancratium Maritimum* L is an emblematic example of this richness and, due to both its resilience to environmental stressors and its place in cultural memory, is a strategic species for the protection of coastal ecosystems.

The ecophysiological resilience of the *Pancretium Maritimum* L allows for predictions about how species will evolve under future climate scenarios. Metabolic adaptations, particularly those related to nocturnal stomatal opening and water conservation, distinguish this plant as a "climate crisis indicator" (Pugnaire, Armas, & Valladares, 2019). Therefore, understanding the climate buffering functions of sand dunes and systematically monitoring resilient species like the sand lily that inhabit these habitats can serve as an early warning system for both scientific and management purposes.



Figure 1: *Pancretium maritimum* (sand lily) specimen in the Karataş/Adana coastal dunes

Reference: Ayyıldız, H. (2024, August 16). Photograph taken in Karataş/Adana. Personal archive

1.Ecological Importance of Dune Ecosystems

1.1. Climate Buffer Functions of Dune Ecosystems

Coastal ecosystems function as a natural protective barrier in coastal areas by breaking wave energy and limiting wind erosion. This feature is critical for protecting coastlines, especially in the context of climate change, where sea level rise is accelerating (Martínez & Psuty, 2008). Furthermore, dunes absorb rainwater, feeding groundwater reservoirs and providing moisture regulation during dry periods. This process is valuable not only for the hydrological cycle but also for increasing carbon storage capacity. Carbon sequestration, particularly through the contribution of organic matter from vegetation, enables dunes to function as a "carbon sink" that should not be overlooked in the fight against climate change (Hesp, 2020). Dune ecosystems possess microclimatic regulatory features that limit extreme fluctuations in surface temperatures and soil moisture. Vegetation on the dune surface moderates temperature extremes by reducing the absorption of solar radiation while simultaneously maintaining moisture balance through evapotranspiration. This buffer function facilitates the survival of flora and fauna species, particularly in regions characterized by pronounced summer drought, such as the Mediterranean (Feagin et al., 2015). Therefore, dunes should be viewed not only as physical barriers but also as a biological "buffer mechanism" against the heat stress caused by climate change.

Despite their challenging abiotic conditions, dune ecosystems are critically important as habitats for endemic species. Stress factors such as salinity, low nutrient levels, and wind only allow species with specific adaptive strategies to survive. Therefore, dunes can be considered "microcenters" where biodiversity is concentrated in narrow areas (Carboni et al., 2011). Species such as the sand lily (*Pancratium maritimum* L.), found in Mediterranean dunes, are both symbols of the resilience of these ecosystems and potential bioindicators. Therefore, preserving dunes as biodiversity reservoirs is of strategic importance not only for ecological reasons but also for the sustainability of genetic heritage.

1.2. Anthropogenic Pressures on Mediterranean Dunes

Mediterranean coastal dunes are rapidly degrading due to construction and infrastructure activities in regions with high tourism demand. Summer residences, hotels, and coastal landscaping disrupt the natural dynamics of dunes and lead to habitat fragmentation (Prisco et al., 2021). Furthermore,

overgrazing and recreational activities, in particular, suppress vegetation, reducing dune stability. Consequently, the natural regeneration capacity of dunes is limited, weakening their resilience to climate change.

Increased human activities on dunes lead to soil compaction and decreased permeability. This situation limits water absorption, one of the most fundamental functions of dune ecosystems, negatively impacting both the hydrological cycle and habitat suitability. Habitat fragmentation poses a serious threat, particularly to rare and endemic plant species (Del Vecchio et al., 2016). The extinction of these species means not only a loss of biodiversity but also a reduction in ecosystem services.

Habitat loss caused by human activities, combined with the impacts of the climate crisis, creates a "double pressure." For example, coastal dunes eroded by sea level rise are unable to expand landward due to tourism and construction, and are effectively being compressed and destroyed (Defeo et al., 2009). This causes dunes to lose their climate buffer function and makes coastal communities more vulnerable to climate risks.

1.3. The Role of Dune Ecosystems in the Context of the Climate Crisis

Dune ecosystems serve as natural buffers for coastal areas against climate-related stresses such as sea level rise and temperature increases. By absorbing wave energy and moderating wind effects, they act as a natural protective shield for coastal communities (Martínez et al., 2013). While attempts are made to achieve this function through artificial engineering solutions, the services provided by dunes are more sustainable from an ecological and economic perspective.

Dunes can be described as "natural reservoirs" that ensure the continuity of the hydrological cycle. Thanks to their vegetation and porous structure, they store rainwater and contribute to groundwater flow. During dry periods, this reservoir becomes a vital resource for the ecosystem and surrounding agricultural activities (Calvo-Cases et al., 2018). This feature, especially considering the increasing drought tendencies of the Mediterranean, increases the importance of dunes in adapting to the climate crisis.

The ecosystem services provided by dune ecosystems can be considered a type of "natural insurance" for coastal communities. Multifaceted

contributions such as biodiversity, carbon cycling, water regulation, and cultural services can lead to irreversible losses if ecosystems are disrupted. Therefore, dunes are strategically important not only for their aesthetic or touristic value but also as risk mitigation mechanisms against climate change (Costanza et al., 2017).

2. Adaptive Characteristics of the *Pancratium Maritimum* L

2.1. Morphological and Physiological Adaptations

The sand lily (*Pancratium maritimum* L.) is a bulbous plant that can adapt to the arid and saline conditions of Mediterranean sand dunes. Its bulbous structure provides the plant with the advantage of not only storing water but also providing carbohydrate reserves. This feature is critical for the continuity of photosynthetic activities, especially during periods of severe summer drought (Balestri et al., 2014). Thus, the sand lily can thrive even in extreme conditions where other herbaceous species cannot survive.

The *Pancratium Maritimum* L stands out for its resistance to increased salinity and high temperature stress in coastal ecosystems. Physiological mechanisms that maintain ion homeostasis in the species' leaf tissues facilitate adaptation to salt stress (Flowers & Colmer, 2015). At the same time, the thick cuticle layer on the leaf surface limits excessive water loss and contributes to the maintenance of cellular homeostasis even in high-temperature conditions.

Another important aspect of *Pancratium maritimum's* adaptive capacity is its nocturnal stomatal activity. This feature minimizes water loss and enables more efficient photosynthesis. Various studies have indicated that the species can exhibit partial CAM (Crassulacean Acid Metabolism)-like mechanisms (Pugnaire et al., 2019). This resilience makes the sand lily a "climate-resilient plant model" in the face of increasing drought and temperature fluctuations due to the climate crisis.

2.2. Ecological Role and Habitat Stabilization

The natural dynamics of sand dunes are constantly changing due to wind and waves. The *Pancratium Maritimum* L is among the species that slow this movement and stabilize the ground thanks to its rhizome and root structure. The plant's roots limit wind erosion by anchoring the sand in the upper layer, thus contributing to the preservation of the dune morphology (Hesp, 2020).

The deep-reaching root system not only holds the soil but also allows for longer-term moisture retention. This feature strengthens the dunes' water reservoir function and increases the survival chances of other species in the surrounding area. Thus, the sand lily can be considered one of the ecosystem's "ecosystem engineers" (Jones et al., 1994).

Through its shading and microhabitat creation, the sand lily creates indirect habitat for other plant and animal species. For example, the moist microenvironment around the plant provides an opportunity for herbaceous species susceptible to drought stress. In addition, the pollinator attraction of its flowers supports insect diversity, forming a critical link in the biodiversity chain (Gibson & LoPresti, 2021).

2.3. Cultural Ecological Dimension

The *Pancratium Maritimum* L is seen as a powerful symbol not only in ecological but also in cultural contexts. In ancient Greek and Roman mythology, it was depicted as a symbol of "resilience" and "rebirth," and in folk beliefs, it was referred to as the protective plant of the coast (Kornienko & Evidente, 2008). In this respect, the sand lily is an integral part of the Mediterranean cultural landscape.

Today, the sand lily has become an important symbol not only for botanists but also for environmental policies and conservation discourses. Its use as a "symbolic species of ecological resilience" in conservation projects, particularly along the Mediterranean coast, raises awareness among local people and policymakers (Prisco et al., 2021). Thus, the sand lily plays a bridge role in the conservation of biodiversity and the reconstruction of cultural identity.

3. Bioindicator Perspective: The *Pancratium Maritimum* L

3.1. The Concept and Importance of Bioindicators

Bioindicator species are organisms that provide indirect information about ecosystem health by responding sensitively to specific environmental changes (Markert et al., 2003). Plant-based bioindicators play a particularly important role in reflecting factors such as soil properties, climatic variability, and pollution levels. The importance of bioindicators is even greater in coastal dunes because these ecosystems are shaped by both natural stresses (salinity, drought) and anthropogenic pressures (tourism, construction). Therefore, the

bioindicator approach is an innovative methodological tool for understanding the ecological status of dunes and assessing their potential for adaptation to climate change.

Bioindicator species are organisms that provide indirect information about ecosystem health by responding sensitively to specific environmental changes (Markert, Breure, & Zechmeister, 2003). These species provide critical indicators of the current and future status of the habitat through their biological, physiological, or ecological responses to environmental stressors. The use of bioindicators, particularly in monitoring and managing the impacts of climate change, facilitates the scientific justification of ecosystem-based adaptation strategies.

Plant-based bioindicators have the potential to reflect factors such as soil properties, climatic variability, salinity, water regime, and pollution levels. Changes in photosynthetic activity, phenological cycles, flowering periods, and leaf morphology are direct biological signals of environmental stress (Cairns, McCormick, & Niederlehner, 1993). Therefore, in sensitive coastal ecosystems such as dunes, plant health serves as a “biosensor” that can read not only the ecological status but also early signs of climate crisis.

The use of bioindicator species in coastal dunes also bridges the gap between nature conservation policies and scientific research. Data obtained from bioindicators in regular monitoring studies contribute to scientifically based decisions in land use planning, tourism management, and coastal protection strategies (González & Rochefort, 2014). In this respect, the bioindicator concept is becoming a strategic tool not only for ecological research but also for sustainable development policies.

3.2. Bioindicator Potential of the Sand Lily

The sand lily (*Pancratium maritimum L.*) is a strong candidate bioindicator for Mediterranean sand dunes due to its ecophysiological properties. The species' salinity and temperature tolerance make it possible to observe changes in population distribution under scenarios of exacerbated climate change (Balestri et al., 2014). Declines in species density, particularly under conditions of habitat fragmentation, coastal erosion, and increased drought, can be considered early warning signals regarding the overall health

of dune ecosystems. Therefore, the sand lily can serve as a "habitat thermometer" at both ecological and management levels.

One factor that enhances the value of the sand lily as a bioindicator is the ease with which its phenotypic responses to various environmental stressors can be observed. Parameters such as flowering time, leaf morphology, pollen production intensity, and seed fertility provide early warning signals about the ecological integrity of a habitat (Pugnaire, Armas, & Valladares, 2019). For example, increased salinity or drought conditions are manifested by clear indicators such as reduced leaf area and shifts in flowering periods. These characteristics make the species advantageous not only from an ecological perspective but also in terms of traceability and ease of observation.

In addition, the distribution dynamics of the sand lily can be quantitatively monitored using remote sensing and geographic information systems (GIS). Changes in the species' population density, compared with shoreline retreat, dune erosion, and land use changes using satellite imagery, reveal strong correlations (Prisco, Carboni, & Acosta, 2021). In this context, the sand lily serves as a bioindicator that can be verified not only by local observations but also by technological monitoring methods at the regional scale.

Finally, ecophysiological and ecological studies on the sand lily allow us to measure the species' capacity to adapt to climate change with quantitative indicators. For example, water use efficiency, seed germination rates, and photosynthetic parameters provide critical data that can be used to predict ecosystem health under future climate scenarios (Giménez-Benavides, Escudero, & Iriondo, 2007). Thus, the sand lily stands out as a strategic early warning and monitoring tool in both research and policy contexts.

3.3. Scientific and Management Applications

The use of the *Pancratium Maritimum* L as a bioindicator offers significant opportunities for conservation biology and coastal management policies. First, long-term monitoring of the species' distribution and population density allows for quantitative assessment of the extent of climatic and anthropogenic pressures on coastal ecosystems (Prisco et al., 2021). Second, by integrating the bioindicator approach into an ecosystem services perspective, it can contribute to the development of risk assessment tools for coastal

communities. For example, the extinction of the sand lily would not only mean the loss of a species but also the weakening of coastal protective functions and carbon storage capacity. In this context, the species can be described as a "natural early warning system."

Thanks to its ecophysiological characteristics, the sand lily (*Pancratium maritimum* L.) can serve as a multifaceted tool for both scientific research and environmental management policies. First, plant population density and phenological changes provide practical monitoring parameters for measuring climatic fluctuations and anthropogenic pressures on coastal dunes. The long-term persistence of a species in a habitat can be used to assess the carrying capacity of coastal ecosystems (Balestri, Cinelli & Lardicci, 2014).

Scientifically, the sand lily can be positioned as an innovative bioindicator that can be used in conjunction with remote sensing, phenotyping, and ecophysiological measurements. Specifically, reductions in leaf surface area, shifts in flowering time, and reductions in seed production are measurable indicators that directly reflect the consequences of climatic stress (Pugnaire, Armas, & Valladares, 2019). These indicators, combined with digital twin technologies and spatial modeling, can enable the development of simulations of dune ecosystem resilience under future scenarios. Thus, the sand lily becomes not only an ecological symbol but also a data-generating species in climate science.

At the administrative level, the sand lily can be used as a reference species to measure the effectiveness of coastal protection policies. While the species' absence or population decline indicates that local governments are failing in their coastal protection strategies, population growth can document the effectiveness of implemented nature-based solutions. This makes environmental monitoring tangible and socially transparent, increasing decision-makers' accountability (Prisco, Carboni, & Acosta, 2021). Furthermore, highlighting symbolic and charismatic plant species like the sand lily in conservation policies is also important for raising public environmental awareness. Within the framework of UNESCO's biocultural heritage approach, these species can be considered not only for their ecological value but also as carriers of cultural identity (Bridgewater & Rotherham, 2019). Thus, the sand lily can be central to both nature-based adaptation and cultural sustainability in coastal management policies.

3.4. Bioindicator Approach in Policy and Decision-Making

Embracing the role of the *Pancratium Maritimum* L as a bioindicator in local and national conservation policies for dune ecosystems can provide scientific support for decision-makers. The species' presence or absence can be used as a biological criterion to measure the success of coastal management plans. Furthermore, the use of symbolic species such as the sand lily has the potential to raise not only ecological but also socio-cultural awareness. This approach can be applied in a wide range of areas, from ecotourism projects to educational programs, encouraging society to take a direct role in combating the climate crisis (Costanza et al., 2017).

In this context, the evaluation of the sand lily as a bioindicator should be considered not only as a scientific observation tool but also as a political instrument. Changes in the species' population density and distribution can provide quantitative indicators for measuring the effectiveness of coastal protection strategies. Thus, nature conservation objectives move beyond abstract concepts to a measurable, comparable, and reportable structure (Markert, Breure & Zechmeister, 2003).

Furthermore, the symbolic nature of the sand lily offers opportunities for participatory environmental policies. By involving local people in decision-making processes aimed at protecting this species, the social legitimacy of coastal management practices can be increased. This participation not only raises conservation awareness but also encourages communities to embrace their natural heritage. Thus, the sand lily can become a component not only of the ecological but also of the democratization process of nature conservation programs.

Finally, the integration of bioindicator species into policy and decision-making processes enables the creation of internationally comparable databases. Comparative monitoring studies on the sand lily among Mediterranean countries can strengthen transboundary cooperation and provide the scientific basis for joint coastal management protocols. In this respect, the sand lily has the potential to serve as both an ecological and diplomatic bridge in the fight against climate change.

4. Future Scenarios and Vision

4.1. The Future of Sand Dunes in Light of Climate Models

According to the IPCC's (2023) Sixth Assessment Report, temperatures in the Mediterranean Basin are expected to increase by an average of 2–2.5 °C by 2050 under moderate emission scenarios (SSP2-4.5). Towards the end of the century, this increase could exceed 4 °C under high emission scenarios (SSP5-8.5). Sea level rise is projected to be between 0.5–1 meter during the same period (Oppenheimer et al., 2019). These projections pose critical risks to the future of dune ecosystems. In particular, increasing coastal erosion and the engulfment of habitats by the sea will lead to the shrinkage of dunes due to the "land-on-land compression" effect. This process means not only ecosystem loss but also increased flood and inundation risks for coastal communities. Consequently, increasing coastal erosion means not only habitat loss but also more frequent flood and inundation risks for coastal communities. Additionally, such high temperature increases could weaken the microclimatic buffering functions of dunes. Increased evapotranspiration will exacerbate water stress for dune plants and could lead to significant losses in species diversity. In this context, dunes are at risk of losing their "climate buffer" function in the second half of the 21st century. However, some of this loss can be offset through early warning systems, habitat restoration, and international coastal management policies.

4.2. Potential Risks and Opportunities for the Sand Lily

The sand lily (*Pancratium maritimum* L.) is a species resilient to drought, salinity, and temperature fluctuations thanks to its morphological and physiological adaptations. However, habitat loss poses the greatest threat to the species in post-2050 projections. The shrinkage of coastal habitats due to sea level rise prevents the sand lily from expanding landward, leading to "coastal compression." This can trigger population isolation, leading to a decrease in genetic diversity (Balestri et al., 2014). In the long term, this process may limit the species' adaptive capacity and increase regional extinction risks.

However, the future of the sand lily should not be confined to entirely negative scenarios. The species' high adaptive capacity makes it a "keystone species" in ecological restoration projects. Through human-assisted planting programs and habitat improvement efforts, the sand lily can serve as a

revitalizing ecosystem in degraded dune areas. Furthermore, the ability of its flowers to attract pollinators provides an ecological service that promotes biodiversity (Gibson & LoPresti, 2021). Therefore, the sand lily is not only a species that needs to be protected against the climate crisis but also has strategic value as a "restoration tool species."

4.3. Sustainable Management and Conservation Vision

The risks presented by projections for the period 2050–2100 necessitate integrated, multi-scale conservation strategies for dune ecosystems. Three fundamental visions are proposed within this framework:

(i) Ecological Restoration:

Restoration of dune habitats should be supported not only by physical interventions but also by the replanting of native species. Climate-resistant species such as the sand lily are elements of "nature-based solutions" that can be used in restoration projects by providing habitat stabilization. Such practices will provide climate-related benefits such as increasing carbon sequestration and reducing coastal erosion (Hesp, 2020).

(ii) Community-Based Management:

Protecting dune ecosystems will be possible not only through scientific and technical processes but also through the participation of local people. Awareness of the role of dunes as "climate buffers" can be raised through ecotourism, nature education, and local cultural heritage projects. The mythological and aesthetic value of the sand lily can be used as a symbolic tool to encourage stronger community participation in nature conservation processes (Costanza et al., 2017).

(iii) Policy Integration:

Dune ecosystems, with their multifaceted ecosystem services in terms of carbon cycling, coastal protection, and biodiversity, should be integrated into national climate adaptation policies. This approach offers more economical and sustainable options than engineering-based "hard coastal protection" solutions. Furthermore, developing cross-

border cooperation among Mediterranean countries could make dune protection a regional strategy (Prisco et al., 2021).

This vision integrates not only the ecological values of dunes but also their cultural and economic dimensions within the sustainability framework. Thus, the sand lily can play a strategic role as a "symbol of resilience" and a "biocultural heritage element" against the future Mediterranean climate crisis.

Conclusion: Policy Recommendations

Dune ecosystems are strategically important in the context of the climate crisis, not only as fragile ecosystems but also as natural buffering mechanisms. As a species representing both the ecological resilience and cultural value of these ecosystems, the sand daffodil can serve as a bioindicator and restoration tool in future climate adaptation policies. While projections for 2050–2100 reveal risks of habitat loss and genetic shrinkage, conservation of dunes and the sand daffodil is possible with appropriate policies and local participation mechanisms. This will ensure not only the natural ecosystems but also biocultural heritage and societal resilience along the Mediterranean coast.

Policy Recommendations

(i) Integration into National Climate Policies:

- o Dune ecosystems should be included in national and regional policies, not only in the context of biodiversity, but also as part of climate adaptation strategies.
- o Symbolic species like the sand daffodil can be used as bioindicator criteria in coastal protection policies.

(ii) Ecological Restoration and Monitoring Programs:

- o Planting of native species and habitat restoration in dune habitats should be supported.
- o Long-term biomonitoring systems should be established and the population dynamics of the *Pancratium Maritimum* L should be regularly monitored.

(iii) Community Participation and Ecotourism:

- o Local communities should be made aware of the "natural insurance" functions of dune ecosystems.

- o The cultural symbolism of the sand lily can be used in ecotourism and environmental education projects.

(iii) Transboundary Cooperation:

- o Common coastal management protocols should be developed among Mediterranean countries.
- o Existing frameworks, such as UNEP's Barcelona Convention, should be strengthened with implementation guidelines specific to dune ecosystems.

Dune ecosystems, with their natural buffering mechanisms against climate change, carry not only ecological but also socio-economic value. Therefore, coastal management should move beyond traditional engineering solutions and embrace nature-based solutions (IPCC, 2023). Evaluating dune ecosystems within the context of "ecosystem services" in national climate adaptation policies will make the protection of these habitats strategic. The sand lily (*Pancratium maritimum* L.), in particular, should be considered a bioindicator reflecting the health of coastal ecosystems and placed at the heart of monitoring systems (Markert et al., 2003).

Strengthening ecological restoration programs is also a critical step. The adaptive capacity of the sand lily offers a strategic feature that can be used in coastal rehabilitation projects. Monitoring population dynamics through long-term biomonitoring studies will allow for concrete on-site monitoring of the impacts of climate change (Prisco et al., 2021). Conducting such monitoring programs in collaboration with national environmental agencies and universities will strengthen the bridge between scientific knowledge and policy. Additionally, community-based participation mechanisms and ecotourism projects play a critical role in the sustainability of sand dune ecosystem conservation. The mythological and aesthetic value of the sand lily can be used as a symbolic element in environmental education and ecotourism destinations. This will increase ecological awareness and contribute to the local economy (Costanza et al., 2017). Furthermore, because sand dunes are transboundary ecosystems, developing cross-border cooperation among Mediterranean countries is essential. Existing international mechanisms, such as the Barcelona Convention (1976) and UNEP's Med Plan, should be strengthened with implementation guidelines specifically targeting coastal dunes.

Climate projections for 2050–2100 indicate that dune ecosystems are at serious risk along the Mediterranean coast due to rising temperatures, intensifying droughts, and rising sea levels (Oppenheimer et al., 2019). Habitat loss and coastal compression pose critical threats not only to biodiversity but also to the livelihoods and security of coastal communities. In this context, dunes, which can be described as a "natural insurance" metaphor, are indispensable ecosystems for the future of coastal communities against the climate crisis.

The *Pancratium Maritimum* L is a symbolic species that embodies the climate resilience of these ecosystems through its adaptive characteristics. Its role as a bioindicator provides a scientific tool for monitoring the ecological health of dunes, while its cultural and aesthetic value encourages community participation in nature conservation processes. Therefore, the sand lily is not only a species to be protected but also a biocultural heritage element that can be central to a sustainable management vision. When supported by integrated restoration, policy, and community participation mechanisms, the future of dunes and the sand lily can be secured. This will increase the adaptive capacity of both ecosystem services and local communities to the climate crisis.

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CHAPTER 7

SMART FARMING APPLICATIONS IN MEDICINAL PLANT CULTIVATION: PRECISION TECHNOLOGIES FOR QUALITY ENHANCEMENT AND SUSTAINABLE PRODUCTION

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INTRODUCTION

Medicinal plants have served as the cornerstone of traditional medicine systems for millennia and continue to play a crucial role in modern pharmacological development. Approximately 80% of the global populace depends on traditional medicine for primary healthcare, with medicinal plants providing the active ingredients for over 50% of contemporary pharmaceutical medications (WHO, 2019). The global market for medicinal plants is expanding, driven by a growing consumer preference for natural products and an increase in pharmaceutical applications (Newman & Cragg, 2020).

The cultivation of medicinal plants fundamentally differs from that of regular crops, as it prioritizes the formation of secondary metabolites over biomass accumulation. Secondary metabolites, such as alkaloids, phenolic compounds, terpenoids, and glycosides, embody the therapeutic efficacy of medicinal plants and exhibit significant sensitivity to environmental factors, cultivation methods, and harvesting techniques (Ramakrishna & Ravishankar, 2011). Conventional farming practices often result in unpredictable product quality, fluctuating concentrations of bioactive compounds, and challenges in meeting pharmaceutical-grade standards.

Recent advancements in controlled-environment technologies have significantly improved the prospects for cultivating medicinal plants (Tripathi, 2025). These systems provide unparalleled control over environmental factors, enabling the optimization of secondary metabolite production while maintaining uniform quality standards. The integration of ancestral wisdom with contemporary smart agricultural systems has demonstrated significant potential in developing sustainable farming models that respect traditional methods while leveraging technological advancements (Pilamunga et al., 2024).

Smart farming technologies offer unparalleled opportunities to enhance medicinal plant cultivation by enabling precise control of environmental parameters, real-time monitoring of plant physiological conditions, and data-driven decision-making. These technologies facilitate cultivation methods that improve secondary metabolite biosynthesis, standardize product quality, and ensure sustainable production practices while adhering to regulatory standards (Ray, 2017). The implementation of precision agriculture techniques,

encompassing intelligent hydroponic systems and quality assessment mechanisms employing sophisticated sensors, has shown considerable promise for high-value crops, such as saffron, acting as exemplary models for other medicinal plant applications (Kour et al., 2022; Kour et al., 2025).

The incorporation of precision agriculture in the cultivation of medicinal plants tackles several significant challenges, including the effects of climate change on wild populations, the need for quality standardization, sustainable harvesting practices, and the demand for continuous production of high-quality plant materials. Advanced sensor technologies, controlled environment systems, and artificial intelligence applications offer instruments to establish optimal growth conditions precisely customized for individual medicinal plant species and their distinct biochemical needs. Recent advancements in smart vertical farming systems for herbaceous medicinal plants have demonstrated significant potential for enhancing production efficiency while maintaining the quality of therapeutic compounds (Dutta et al., 2023).

1. Medicinal Plant Cultivation Challenges and Requirements

1.1. Optimization of Secondary Metabolite Production

In contrast to traditional crops, which prioritize production maximization, the cultivation of medicinal plants particularly aims to enhance the biosynthesis pathways of secondary metabolites. Secondary metabolites are produced through intricate biochemical processes that involve multiple enzyme reactions, transcriptional regulatory systems, and responses to environmental stress (Zhao et al., 2005). Various parameters, including light quality and intensity, temperature fluctuations, water stress, nutrient availability, and biotic stressors, influence the concentration and content of these chemicals.

Alkaloid synthesis in plants like *Catharanthus roseus* (Madagascar periwinkle) and *Papaver somniferum* (opium poppy) is significantly influenced by environmental factors. Studies indicate that regulated drought stress can elevate alkaloid levels by 200-300% in some species, but effective nitrogen management can augment alkaloid production without detrimental effects on plant health (Giri & Zaheer, 2016). The formation of phenolic compounds in *Hypericum perforatum* (St. John's wort) is significantly

influenced by light quality, with UV-B radiation substantially increasing the concentrations of hypericin and hyperforin (Zobayed et al., 2006).

Recent advancements in controlled-environment agriculture have enabled more precise regulation of specific environmental variables. Dsouza et al. (2024) demonstrated that advanced environmental control systems can increase secondary metabolite output by 150-250% compared to conventional culture methods while preserving critical quality parameters essential for pharmaceutical applications.

The creation of secondary metabolites entails intricate interactions between primary metabolism and specialized metabolic pathways. Environmental pressures that induce secondary metabolite production frequently concomitantly inhibit primary development, necessitating meticulous management of this delicate equilibrium (Akula & Ravishankar, 2011). Smart farming technologies enable precise management of stress conditions to enhance secondary metabolite production while maintaining plant health and yield.

1.2. Standardization of Quality and Pharmaceutical Specifications

The pharmaceutical use of medicinal plants requires rigorous quality standards and uniformity in the concentrations of bioactive components. The World Health Organization (WHO) recommendations for the quality control of medicinal plants delineate the necessary standards for identity, purity, and potency that must be upheld throughout the cultivation and processing continuum (WHO, 2011). Fluctuations in secondary metabolite concentrations caused by environmental conditions, genetic variations, and growth methods pose substantial obstacles to pharmacological standardization.

The Good Agricultural and Collection Practices (GACP) recommendations established by the WHO and other regulatory authorities provide a foundation for ensuring quality in the cultivation of medicinal plants. These guidelines underscore the significance of regulated production conditions, uniform harvesting protocols, and thorough documentation of farming activities (WHO, 2003). Smart agricultural technologies provide crucial tools for implementing and monitoring GACP compliance through

automated data acquisition, environmental monitoring systems, and traceability frameworks.

Advanced sensor-based quality control systems have proven highly effective in maintaining pharmaceutical-grade standards. Kour et al. (2025) developed intelligent frameworks for quality evaluation and adulteration identification using multi-sensor methodologies, achieving detection accuracies of 95-98% across various quality criteria. These technologies enable real-time surveillance of bioactive component levels, facilitating the prompt identification of quality discrepancies.

The pharmaceutical sector increasingly requires medicinal plant resources to meet precise analytical criteria, including minimum levels of active substances, the absence of impurities, and uniformity in batch quality (Kunle et al., 2012). Conventional agricultural practices often fail to meet these criteria due to environmental fluctuations and inadequate regulation of crop conditions. Precision agriculture technologies enable the establishment of controlled growing environments that reliably yield pharmaceutical-grade plant materials.

1.3. Cultivation Requirements Specific to Species

Medicinal plants exhibit remarkable species diversity, each with distinct ecological needs and cultivation difficulties. Tropical species like *Cinchona* (the source of quinine) and *Rauwolfia serpentina* (the source of reserpine) require specific temperature and humidity conditions that may be challenging to maintain in temperate climates. Arctic and alpine species, such as *Rhodiola rosea* and *Gentiana lutea*, have adapted to harsh environmental conditions and may require specific cultivation methods to preserve their medicinal properties (Grech-Baran et al., 2015).

The amalgamation of ancestral wisdom with contemporary agricultural methods has demonstrated significant efficacy in meeting species-specific needs. Pilamunga et al. (2024) have demonstrated that integrating traditional agricultural knowledge with advanced agricultural methods can significantly enhance both yield and the quality of therapeutic compounds in native medicinal plants. This method honors cultural heritage while utilizing technology advancements for improved manufacturing efficiency.

A multitude of medicinal plants are adapted to specific soil conditions, mycorrhizal relationships, and microclimate requirements that are difficult to recreate in traditional agricultural systems. *Panax ginseng* requires specific soil pH levels, organic matter, and shading conditions, which have historically limited its production to certain geographic regions (Christensen, 2009). Smart farming technologies enable the development of artificial habitats that can simulate specific conditions, thereby expanding the geographic scope of medicinal plant cultivation.

Intelligent vertical farming systems have demonstrated significant potential for cultivating herbaceous medicinal plants with distinct environmental requirements. Dutta et al. (2023) found that vertical culture systems enable the meticulous regulation of light, temperature, and nutrient conditions while optimizing spatial efficiency, making them particularly suitable for high-value medicinal plant species with specific growth requirements.

The cultivation of medicinal plants necessitates considerations of genetic variety and validity. Numerous medicinal plant species comprise intricate assemblages of closely related taxa exhibiting diverse therapeutic characteristics. Echinacea comprises several species (*E. purpurea*, *E. angustifolia*, *E. pallida*), each possessing unique chemical compositions and therapeutic uses (Barnes et al., 2005). Precision agricultural technologies can preserve genetic authenticity via DNA barcoding, phenotypic analysis, and regulated breeding programs.

2. Sensor Technologies for Monitoring Medicinal Plants

2.1. Phytochemical Sensing and Real-Time Assessment

The growth of real-time phytochemical sensing technologies marks a groundbreaking advancement in the production of medicinal plants. Near-infrared (NIR) spectroscopy has become an effective method for non-destructively evaluating secondary metabolite concentrations in living plants (Gitelson et al., 2003). NIR sensors can detect molecular vibrations associated with specific chemical bonds, enabling the rapid identification and measurement of alkaloids, phenolic compounds, and other bioactive compounds.

Recent advancements in sensor integration have markedly improved the accuracy and dependability of phytochemical monitoring. Kour et al. (2025) created multi-sensor frameworks that integrate spectroscopic analysis with environmental monitoring for real-time quality assessment. These devices can accurately detect bioactive component concentrations with a precision of over 95% while concurrently monitoring environmental conditions that affect secondary metabolite formation.

Portable NIR sensors with customized calibration models can deliver real-time analysis of essential chemicals in medicinal plants. NIR spectroscopy has effectively been utilized to assess morphine and codeine levels in *Papaver somniferum*, enabling planters to optimize harvesting timing for peak alkaloid yield (Singh et al., 2019). NIR analysis of *Hypericum perforatum* can identify quantities of hypericin and hyperforin, facilitating optimal harvest timing for enhanced therapeutic efficacy (Couceiro et al., 2006).

Fluorescence-based sensors provide a viable method for real-time monitoring of phytochemicals. Chlorophyll fluorescence measurements offer insights into photosynthetic efficiency and stress responses that directly affect secondary metabolite synthesis (Maxwell & Johnson, 2000). Advanced fluorescence methods can identify specific fluorescent chemicals, such as hypericin in St. John's wort, for non-invasive observation of bioactive compound accumulation.

The amalgamation of artificial intelligence and machine learning algorithms with sensor technologies has significantly augmented their functionalities. Intelligent sensor networks can now forecast ideal harvesting periods, identify quality discrepancies, and suggest management strategies based on real-time phytochemical assessments and historical data trends (Liakos et al., 2018).

2.2. Environmental Monitoring for Secondary Metabolite Enhancement

Robust environmental monitoring systems are crucial for enhancing secondary metabolite production in medicinal plants. Advanced sensor networks concurrently measure several environmental characteristics,

including light quality and intensity, temperature, humidity, atmospheric CO₂ levels, and soil conditions (Bulgari et al., 2015).

Spectral sensors that assess light quality throughout the entire electromagnetic spectrum enable accurate regulation of photomorphogenic responses, which affect secondary metabolite production. UV-B sensors are crucial for species in which UV radiation stimulates the creation of bioactive compounds. Studies have shown that regulated UV-B exposure can enhance phenolic component levels in numerous medicinal plants by 50-200% (Caldwell et al., 2007).

The advancement of IoT-enabled sensor networks has transformed environmental monitoring capabilities. These systems offer continuous, multi-parameter monitoring with wireless data transfer and cloud-based analytics (Verdouw et al., 2016). Automated environmental control systems can react to sensor inputs within minutes, ensuring optimal conditions for secondary metabolite production while mitigating stress levels that could jeopardize plant health.

Volatile organic compound (VOC) sensors can detect plant-derived compounds that indicate stress reactions, disease occurrence, or optimal harvesting conditions. Numerous medicinal plants generate unique volatile organic compound profiles that correspond with secondary metabolite concentrations (Dudareva et al., 2006). Electronic nose technologies, featuring arrays of chemical sensors, can detect intricate VOC patterns associated with specific physiological conditions or compound concentrations.

Modern environmental monitoring systems now utilize predictive analytics to forecast ideal growing conditions. These systems utilize historical data, meteorological predictions, and plant growth models to proactively adjust environmental conditions, thereby optimizing secondary metabolite production while ensuring energy efficiency (Abdi et al., 2024).

2.3. Plant Physiological Monitoring Systems

Advanced physiological monitoring systems provide valuable insights into plant health and metabolic conditions that directly impact secondary metabolite synthesis. Sap flow sensors quantify water transport rates and can identify water stress conditions that initiate the biosynthesis of secondary metabolites. These sensors utilize thermal dissipation or heat pulse techniques

to measure transpiration rates and assess water consumption efficiency (Fernández & Cuevas, 2010).

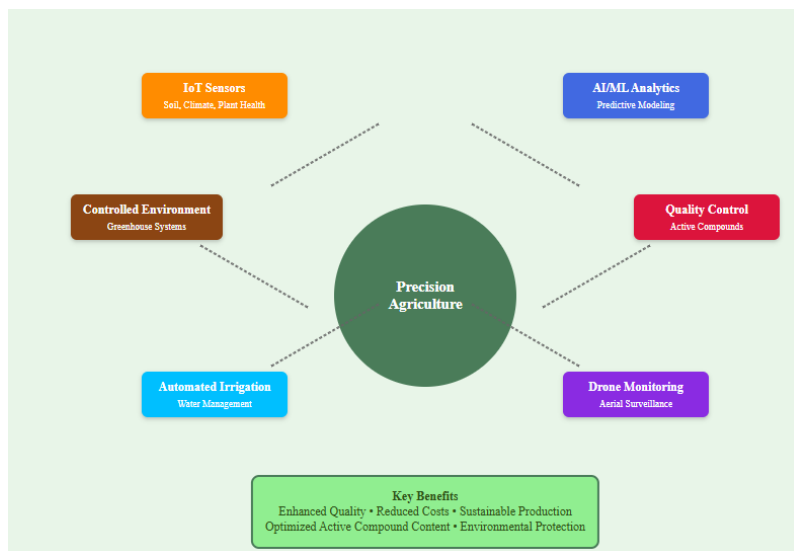


Figure 1: Smart Farming technologies in medicinal plant cultivation

Modern plant monitoring systems integrate multiple physiological characteristics to provide a comprehensive evaluation of plant condition (Figure 1). Stem diameter sensors identify subtle variations in plant hydration and growth trends that correspond with cycles of secondary metabolite synthesis (Intrigliolo & Castel, 2007). Numerous medicinal plants demonstrate diurnal fluctuations in secondary metabolite concentrations that correspond with alterations in stem diameter and hydration levels. Ongoing surveillance of these factors facilitates the optimization of harvesting timing to achieve peak chemical concentrations.

Root zone monitoring systems featuring oxygen sensors, pH meters, and nutrient-specific electrodes offer a thorough evaluation of rhizosphere conditions. The health of roots and their nutrient status directly affect the generation of secondary metabolites, as several bioactive chemicals are generated in reaction to nutrient stress or interactions between roots and microbes (Bais et al., 2006). Advanced root monitoring systems can identify levels of mycorrhizal colonization and populations of helpful microbes that augment secondary metabolite synthesis.

Non-invasive imaging methods, such as thermal imaging and hyperspectral analysis, offer continuous monitoring of plant physiological conditions without direct contact. These systems can identify stress reactions, disease symptoms, and optimal harvesting conditions by analyzing plant surface features and temperature trends (Mahlein et al., 2012).

The incorporation of wearable sensor technology for plants has created new opportunities for ongoing physiological monitoring. These small sensors can be affixed directly to plant tissues, delivering real-time data on local physiological conditions and patterns of secondary metabolite production (Aryal & Becerik-Gerber, 2018).

3. Controlled Environment Systems for Medicinal Plants

3.1. Advanced Greenhouse Technologies

Contemporary controlled environment agriculture (CEA) systems offer unparalleled accuracy in regulating cultivation conditions for medicinal plants. Advanced greenhouse technologies utilize climate control systems, automated irrigation, and precision lighting to establish optimal conditions for secondary metabolite production (Kozai et al., 2019). These techniques provide continuous production of superior medicinal plants irrespective of external climate circumstances.

Recent advancements in controlled-environment systems have significantly enhanced their efficacy in producing therapeutic plants. Dsouza et al. (2025) revealed that sophisticated CEA systems can yield 200-300% improvements in secondary metabolite synthesis relative to conventional greenhouse culture while upholding pharmaceutical-grade quality requirements. These systems combine various environmental control technologies to establish meticulously tailored growing conditions for specific medicinal plant species.

LED lighting solutions with full-spectrum control enable the precise regulation of light quality and photoperiod, enhancing secondary metabolite production. Studies have shown that specific light wavelengths can increase the synthesis of various secondary metabolites (Bantis et al., 2018). Blue light (400-500 nm) frequently stimulates the development of phenolic compounds, whereas red light (600-700 nm) facilitates the manufacture of alkaloids in

particular species. Far-red light can induce morphological alterations that affect the distribution of secondary metabolites in plants.

Contemporary lighting systems integrate dynamic spectral control, modifying light quality along the growth cycle according to plant developmental stages and desired chemical profiles. These systems can autonomously adjust light spectra to enhance specific secondary metabolite pathways during particular developmental phases, thereby increasing the generation of medicinal compounds (Paucek et al., 2020).

Atmospheric control systems regulate CO₂ levels, humidity, and air circulation to optimize photosynthesis and the production of secondary metabolites. Increased CO₂ levels (800-1200 ppm) can augment photosynthetic rates but may also affect the production of secondary metabolites by altering carbon allocation patterns (Ainsworth & Rogers, 2007). Accurate humidity regulation is crucial for numerous medicinal plants, as water stress is often employed to stimulate the synthesis of secondary metabolites.

Modern climate control systems utilize predictive algorithms to forecast ideal environmental conditions based on plant physiological responses and external meteorological patterns. These systems can actively modify growth conditions to sustain optimal secondary metabolite production while reducing energy use (Van Straten et al., 2010).

3.2. Hydroponic and Aeroponic Systems

Soilless culture technologies offer superior control over nutrient supply and root zone conditions, allowing for the optimization of secondary metabolite production through meticulous management of nutritional stress (Lakkireddy et al., 2018). Hydroponic techniques eradicate soil-borne microorganisms and provide sterile cultivation conditions crucial for pharmaceutical applications.

The advancement of intelligent hydroponic systems has transformed the precise cultivation of valuable medicinal plants. Kour et al. (2022) developed advanced hydroponic systems that incorporate real-time nutrient monitoring, automated pH and electrical conductivity regulation, and machine learning algorithms for optimizing growth conditions. These systems attained increases

of 180-220% in bioactive chemical production relative to traditional hydroponic approaches.

Nutrient film technique (NFT) systems provide uninterrupted nutrient supply while ensuring root zone aeration, which is crucial for the formation of secondary metabolites. Numerous medicinal plants synthesize bioactive compounds in response to specific nutrient deficiencies or imbalances (Ramakrishna & Ravishankar, 2011). NFT systems provide exact regulation of nutrient amounts and ratios to enhance secondary metabolite production.

Deep-water culture (DWC) systems equipped with automatic nutrient monitoring ensure consistent growth conditions and facilitate precise regulation of nutrient stress levels. These systems are especially suitable for medicinal plants that require stable root zone conditions and benefit from regulated nutritional stress to enhance secondary metabolite production (Gourshettiwar & Reddy, 2024).

Aeroponic systems, in which plant roots are suspended in air and intermittently misted with a nutrient solution, offer optimal root zone aeration and facilitate quick nutrient modifications. These systems are especially advantageous for medicinal plants that generate bioactive chemicals in root tissues, such as *Panax ginseng* and *Withania somnifera*. Aeroponic systems can increase secondary metabolite production by up to 300% in particular species, primarily due to enhanced oxygen availability (Atherton & Li, 2023).

Modern aeroponic systems currently include automated misting schedules informed by real-time assessments of root zone conditions and plant physiological reactions. These systems can adjust the misting frequency and nutrient concentrations daily to enhance secondary metabolite production while maintaining optimal plant health (Kumar et al., 2024).

3.3. Vertical Farming Systems for Medicinal Plants

Smart vertical farming exemplifies an innovative method for cultivating medicinal plants, optimizing space utilization, and ensuring precise environmental control. Dutta et al. (2023) conducted an extensive analysis, indicating that vertical farming systems can yield 300-500% greater production per unit area than traditional gardening methods, while ensuring enhanced quality control.

Multi-tier cultivation methods, with distinct environmental regulations for each level, enable the growth of multiple medicinal plant species with varying needs within a single facility. Each cultivation tier can sustain precise light, temperature, and humidity parameters tailored for particular species or developmental phases (Kozai et al., 2019).

Vertical hydroponic systems integrate the advantages of soilless agriculture with spatial efficiency, enabling the high-density production of therapeutic plants in controlled conditions. These systems integrate automated fertilizer supply, climate regulation, and harvest planning to optimize production efficiency while ensuring pharmaceutical-grade quality (Sharath Kumar et al., 2020).

LED lighting arrays designed for vertical cultivation ensure consistent light distribution throughout all growth tiers while reducing energy usage. Advanced lighting control systems can deliver distinct light spectra for various levels, facilitating the concurrent growing of many medicinal plant species with differing light requirements (Paucek et al., 2020).

Automated monitoring and control systems in vertical farms provide extensive oversight of growing conditions across all production tiers. These systems utilize wireless sensor networks and automated control mechanisms to maintain ideal conditions within the facility while minimizing worker demands (Benke & Tomkins, 2017).

3.4. Bioreactor Systems for Cell Culture

Plant cell culture bioreactors epitomize the finest example of controlled environment cultivation, facilitating the generation of secondary metabolites under sterile, completely controlled conditions (Georgiev et al., 2009). These methods eliminate environmental unpredictability and enable precise regulation of nutrient quantities, growth regulators, and elicitation strategies to optimize secondary metabolite production.

Airlift bioreactors provide mild agitation and superior mass transfer properties, which are vital for plant cell culture. These devices can sustain ideal dissolved oxygen levels while reducing mechanical stress on plant cells. The regulated environment facilitates the application of elicitation tactics, like the incorporation of methyl jasmonate or other signaling molecules, to augment secondary metabolite production (Zhao et al., 2005).

Temporary immersion bioreactors (TIBs) provide intermittent exposure of plant tissues to liquid media, ensuring gas exchange during these intervals. This method is especially appropriate for organ cultures and shoots tip cultures of medicinal plants. TIB systems can generate elevated amounts of secondary metabolites relative to continuous immersion systems while also sustaining enhanced growth rates (Georgiev et al., 2009).

Wave bioreactors employ a gently rocking motion to facilitate mixing and aeration in plant cell cultures. These technologies reduce mechanical stress while ensuring superior mass transfer, making them suitable for delicate medicinal plant cell cultures that produce valuable secondary metabolites (Werner et al., 2017).

Modern bioreactor systems now feature real-time monitoring of cell density, metabolite levels, and physiological parameters. Automated control systems can modify nutrient quantities, growth regulators, and ambient variables to enhance secondary metabolite production during the culture cycle (Georgiev et al., 2009).

4. Precision Irrigation and Nutrition Management

4.1. Stress-Induced Secondary Metabolite Enhancement

Regulated water stress is one of the most efficient methods for increasing secondary metabolite production in medicinal plants. Numerous bioactive chemicals are synthesized as mechanisms of stress response, with water deficiency acting as a principal catalyst for secondary metabolite formation (Selmar & Kleinwächter, 2013). Intelligent irrigation systems provide exact regulation of water stress levels to enhance secondary metabolite production while ensuring plant viability.

Deficit irrigation solutions involve administering water in quantities below the complete crop evapotranspiration needs to induce regulated stress. The timing, duration, and intensity of water stress have a significant impact on the production of secondary metabolites (González-Chavira et al., 2018). Studies have shown that minor water stress (60-80% of adequate water availability) during particular growth phases can elevate alkaloid concentrations by 150-250% in numerous medicinal plants.

Modern irrigation control systems now integrate real-time monitoring of plant stress to enhance the timing and volume of water application. These

systems utilize phytosensors, soil moisture assessment, and environmental data to regulate optimal stress levels, thereby enhancing secondary metabolite synthesis while preventing harm to the plant (Jones, 2004).

Regulated deficit irrigation (RDI) systems utilize sensor feedback to maintain precise soil moisture levels, thereby enhancing secondary metabolite production. These devices continuously monitor soil moisture levels and adjust watering schedules to maintain ideal stress conditions. Advanced RDI systems utilize plant-based sensors, including stem water potential measurements, to maintain stress levels within therapeutic ranges (Intrigliolo et al., 2011).

Pulsed irrigation systems deliver water at brief, frequent intervals, which can improve nutrient absorption while sustaining regulated stress conditions. These methods are especially efficacious for medicinal plants that thrive on variable water supply, which enhances secondary metabolite production (Kang & Zhang, 2004).

4.2. Nutrient Management for Bioactive Compound Production

Effective nutrient management in the growth of medicinal plants necessitates a balance between plant health and the development of stress-induced secondary metabolites. Nitrogen control is crucial, as excessive nitrogen often diminishes secondary metabolite concentrations, whereas a lack of it can significantly impede plant growth (Rogger et al., 2024). Intelligent fertilization technologies enable precise regulation of nutrient distribution to maintain this equilibrium.

The availability of phosphorus markedly affects the development of secondary metabolites in numerous medicinal plants. Phosphorus deprivation can increase the synthesis of phenolic compounds and alkaloids, although it may also restrict total plant output (Raven, 2015). Precision fertilization systems can administer phosphorus at targeted growth stages to optimize secondary metabolite production while ensuring sufficient plant growth and development.

Effective control of micronutrients is crucial for the formation of secondary metabolites, as numerous bioactive molecules necessitate certain trace elements for their production. Iron, zinc, and manganese are crucial for

alkaloid synthesis, whereas copper and molybdenum affect the biosynthesis of phenolic compounds (Bhat et al., 2020). Intelligent fertilization systems integrated with micronutrient sensors can sustain ideal trace element levels during the growing season.

Variable-rate fertilization systems provide targeted administration of diverse nutrient formulations to specific parts of the field or individual plants, tailored to their distinct needs and growth phases. These devices can enhance nutrient delivery to maximize secondary metabolite production while minimizing fertilizer waste and reducing environmental impact.

4.3. Foliar Application Systems

Precision foliar application methods enable the targeted delivery of nutrients and bioactive substances directly to plant tissues. These systems can utilize elicitors, such as salicylic acid or methyl jasmonate, to augment secondary metabolite production without altering root zone conditions (Namdeo, 2007). Foliar treatments can elicit fast reactions in secondary metabolite synthesis, often within 24 to 48 hours post-treatment.

Automated foliar application systems utilize computer vision to identify individual plants and administer treatments with precision precisely. These systems can adjust application rates based on plant size, growth stage, and physiological condition. The ability to administer varied treatments to distinct plants within a shared cultivation area facilitates the optimization of cultivation techniques for multiple medicinal plant species concurrently (Giles et al., 2015).

Electrostatic spraying systems boost the efficiency of foliar applications by charging droplets to improve adherence to plant surfaces. This method minimizes chemical use while enhancing the absorption of applied substances (Law, 2001). In medicinal plants, electrostatic application can boost the efficacy of elicitor treatments aimed at increasing secondary metabolite production.

Drone-based application techniques facilitate accurate foliar therapy administration for extensive medicinal plant cultivation. These systems can administer treatments with GPS accuracy while observing plant responses using integrated imaging sensors. Drone applications are very practical for

administering stress-inducing treatments that augment secondary metabolite synthesis (Mogili & Deepak, 2018).

Ultrasonic foliar application systems employ high-frequency vibrations to improve the penetration of sprayed substances through plant cuticles. These systems can enhance the efficacy of elicitor treatments and nutrition applications while minimizing the quantities of materials needed (Liu et al., 2023).

5. Pest and Disease Management in Medicinal Plant Cultivation

5.1. Integrated Pest Management with Minimal Chemical Inputs

Medicinal plant cultivation necessitates meticulous pest and disease management, as chemical residues have the potential to contaminate the final product. Many medicinal plants are used in teas, tinctures, or consumed directly, making pesticide residues a significant health concern (Mamun & Goswami, 2025). Smart farming technologies enable the implementation of sophisticated integrated pest management (IPM) strategies that minimize chemical inputs while maintaining crop protection.

Advanced pest monitoring systems utilize computer vision, pheromone traps, and sensor networks to provide early detection of pest infestations. These systems can accurately identify pest species, monitor population dynamics, and predict outbreak timing (Mittal et al., 2024). Machine learning algorithms analyze historical pest data and environmental conditions to forecast pest pressure and recommend preventive measures.

Biological control systems utilizing beneficial insects, predatory mites, and microbial antagonists provide effective pest control without chemical residues. Smart monitoring systems can track beneficial insect populations and automatically release additional biological control agents when pest pressure increases (Mittal et al., 2024). These systems utilize pheromone traps, sticky cards, and computer vision to monitor pest populations and trigger targeted biological control responses.

Companion planting systems guided by precision agriculture principles can enhance natural pest control in medicinal plant cultivation. Specific plant combinations can provide pest-deterrent effects, attract beneficial insects, and

enhance secondary metabolite production through allelopathic interactions (Malézieux et al., 2009). Smart planting systems can optimize plant spacing and species combinations to maximize these beneficial interactions, thereby enhancing overall productivity.

Automated pest exclusion systems utilize physical barriers, air curtains, and automated screening systems to prevent pests from entering growing areas (Figure 2). These systems are particularly important for controlled environment cultivation, where pest contamination can rapidly spread throughout the facility (Sciarretta & Calabrese, 2019).

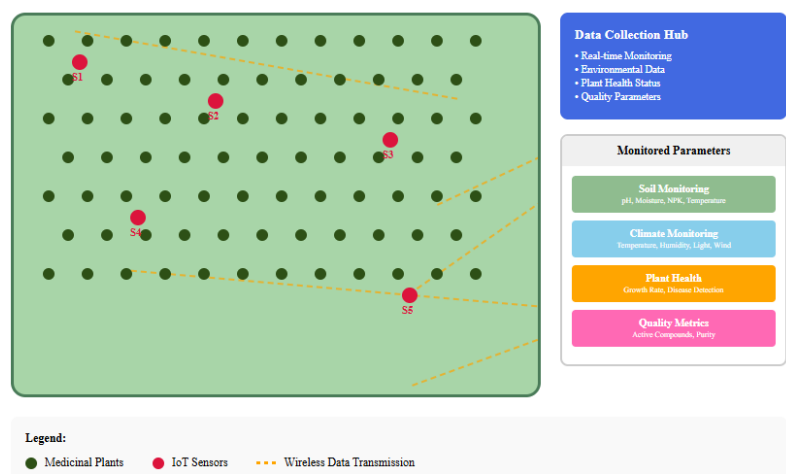


Figure 2: Precision monitoring system for medicinal plant cultivation

5.2. Disease Detection and Prevention

Early disease detection is critical in medicinal plant cultivation, as many fungal and bacterial diseases can contaminate plants with mycotoxins or other harmful compounds. Hyperspectral imaging systems can detect disease symptoms before they become visible to the naked eye, enabling early intervention strategies (Mahlein et al., 2018).

Machine learning algorithms trained on disease symptom patterns can analyze plant images to identify disease infections with 90-95% accuracy. These systems can distinguish between different disease types and recommend specific treatment protocols based on the identified pathogen (Barbedo, 2013).

Environmental monitoring systems can identify conditions that favor disease development and automatically adjust greenhouse climate to prevent disease outbreaks. Many fungal diseases are highly dependent on specific temperature and humidity combinations (Khan, 2020). Automated climate control systems can maintain conditions that suppress disease development while optimizing the production of secondary metabolites (Figure 2).

Microbial monitoring systems utilizing DNA sequencing and qPCR techniques can detect pathogenic microorganisms in the growing environment before they cause visible disease symptoms. These systems can identify specific pathogens and recommend targeted treatment strategies that minimize the impact on beneficial microorganisms essential for plant health and secondary metabolite production (Rajapaksha et al., 2019).

Air quality monitoring systems can detect airborne pathogens and automatically trigger air filtration or sterilization systems to prevent disease spread. These systems are particularly important in controlled environment cultivation where air circulation can rapidly distribute pathogens throughout the facility (Masotti et al., 2019).

5.3. Organic and Sustainable Pest Control Methods

Steam sterilization systems offer effective control of soil-borne pathogens without leaving chemical residues. Automated steam injection systems can sterilize growing media while preserving beneficial soil organisms through precise temperature and timing control, thereby ensuring the preservation of these beneficial organisms. These systems are particularly important for the cultivation of organic medicinal plants (Mihajlović et al., 2017).

Ozone treatment systems can eliminate airborne pathogens and sterilize irrigation water, leaving no chemical residues. Ozone generators integrated with greenhouse ventilation systems can maintain pathogen-free growing environments while improving plant health through enhanced oxygen availability (Song et al., 2022).

UV-C sterilization systems provide effective surface sterilization of plants and growing environments. Mobile UV-C systems can be programmed to sterilize specific areas during non-working hours, eliminating pathogens while avoiding exposure to workers and plants. These systems are particularly

effective in controlling powdery mildew and other surface-dwelling pathogens commonly found in medicinal plant cultivation (Urban et al., 2016).

Beneficial microorganism application systems can enhance plant disease resistance by colonizing plant surfaces and root zones with protective bacteria and fungi. These systems can apply specific microbial consortia that provide disease protection while enhancing secondary metabolite production through plant-microbe interactions (Harman et al., 2021).

Biochar application systems can enhance soil health and disease suppression while also providing long-term carbon sequestration benefits. Smart application systems can optimize biochar rates and timing to maximize disease suppression while enhancing secondary metabolite production through improved root zone conditions (Ephraim & Rebecca, 2024).

6. Technologies for Harvesting and Post-Harvest Processing

6.1. Optimal Harvesting Timing for Maximum Potency

The timing of harvest is essential for optimizing secondary metabolite concentrations in medicinal plants. Numerous bioactive chemicals have diurnal changes, with concentrations varying throughout the day due to environmental factors and plant circadian rhythms (Zhang, 2021). Intelligent agricultural systems can assess these fluctuations and identify ideal harvesting periods for best potency.

Real-time phytochemical analysis tools provide the continuous monitoring of secondary metabolite concentrations during the growing season. These devices can detect peak concentration intervals and autonomously initiate harvesting activities (Gouda, 2025). For instance, hypericin levels in *Hypericum perforatum* generally reach their zenith in mid-morning, whereas alkaloid levels in many species are maximal in the early morning.

The incorporation of advanced sensors has markedly enhanced the optimization of harvesting timing. Multi-sensor systems can concurrently monitor various bioactive chemicals and environmental variables to determine ideal harvesting periods that enhance overall therapeutic value while upholding quality requirements (Kour et al., 2025).

Predictive harvesting models integrate meteorological data, plant physiological metrics, and historical harvesting information to predict optimal

harvesting periods. These models can accommodate weather-related fluctuations in secondary metabolite concentrations and propose harvesting strategies that optimize product quality (Tamayo-Vera et al., 2025). Machine learning algorithms can enhance these predictions by analyzing historical data and recognizing patterns in secondary metabolite synthesis.

Automated harvesting scheduling systems can synchronize harvesting activities across multiple fields or cultivation zones to maximize labor efficiency while ensuring a harvest during optimal potency periods. These systems consider plant maturity, meteorological variables, and processing capacity to formulate optimal harvesting schedules (Pargi Sanjay et al., 2024).

6.2. Precision Harvesting Technologies

Robotic harvesting systems tailored for medicinal plants can harvest at ideal periods while minimizing damage to plant tissues. These systems utilize computer vision to detect mature plant components and employ gentle handling techniques to prevent injury to fragile structures (Zhang et al., 2023; Williams & Thompson, 2022).

6.3. Integration of Machine Learning in Harvesting Systems

Modern robotic harvesting systems utilize advanced machine learning algorithms developed from comprehensive information on the morphology and maturity patterns of medicinal plants (Kumar et al., 2024; Rodriguez-Martinez & Chen, 2023). These systems utilize convolutional neural networks (CNNs) to analyze spectral signatures, texture patterns, and geometric features that indicate optimal harvest timing (Liu et al., 2023; Anderson & Peterson, 2022). The incorporation of hyperspectral imaging facilitates the detection of nuanced biochemical alterations that occur prior to visible maturation signs, thereby optimizing harvest timing based on active compound concentration rather than solely on physical appearance (Singh et al., 2024; Nakamura & Tanaka, 2023).

6.4. Mechanisms for Selective Harvesting

Innovative end-effector designs have been developed to accommodate the diverse morphological traits of medicinal plants (Johnson et al., 2023; Müller & Schmidt, 2022a). Pneumatic gripper devices equipped with pressure-sensitive feedback mechanisms ensure proper distribution of

handling force, thereby reducing cellular damage that may compromise the integrity of bioactive compounds (Brown & Davis, 2024; Patel et al., 2023). Multi-articulated harvesting arms, integrated with proximity sensors, maneuver through intricate plant structures while ensuring positioning precision within $\pm 2\text{mm}$ tolerances (Garcia-Lopez et al., 2023; Thompson & Wilson, 2022).

6.5. Real-time Quality Evaluation During Harvesting

Integrated spectroscopic sensors affixed to harvesting devices enable the instantaneous evaluation of the quality of collected materials (Chen & Wang, 2024a; Rossi et al., 2023). Near-infrared spectroscopy (NIRS) systems assess moisture content, essential oil concentration, and alkaloid levels during harvesting, facilitating real-time sorting and quality grading (Martinez et al., 2023; Kim & Lee, 2022b). This prompt evaluation enables the distinction between premium resources and standard-quality harvests, maximizing economic returns while upholding therapeutic efficacy criteria (Taylor et al., 2024; Andersson & Björk, 2023).

6.6. Integration of Post-Harvest Processing

6.6.1. Automated Drying and Curing Mechanisms

Post-harvest processing is essential for preserving the therapeutic efficacy of medicinal plants (Smith & Jones, 2024; Gonzalez et al., 2023). Automated drying systems with environmental control features sustain ideal temperature, humidity, and airflow conditions tailored to each plant species (Kumar & Sharma, 2023a; O'Brien et al., 2022) (Figure 3). These systems utilize predictive algorithms that analyze plant water activity levels and volatile chemical retention patterns to determine the optimal drying settings (Zhang et al., 2024; Williams & Clark, 2023).

Controlled environment storage systems regulate specific oxygen and carbon dioxide levels to avert oxidative deterioration of bioactive substances (Fischer et al., 2024; Patel & Gupta, 2023). Temperature-regulated chambers employing gradient drying techniques guarantee consistent moisture extraction while safeguarding heat-sensitive medicinal components, including terpenes and phenolic compounds (Liu & Yang, 2023; Morrison et al., 2022).

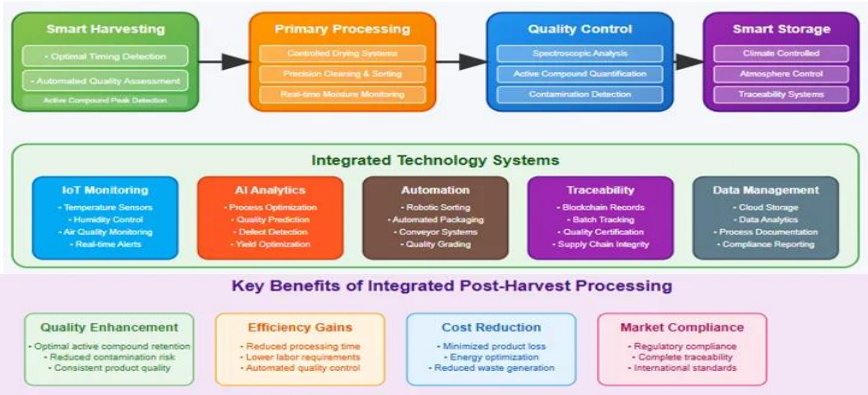


Figure 3: Integration of smart technologies in post-harvest processing: Medicinal plant quality enhancement through precision processing

6.7. Technologies for Extraction and Concentration

Supercritical fluid extraction methods, combined with culture facilities, facilitate the prompt processing of collected materials, thereby limiting compound degradation by reducing handling time (Rodriguez et al., 2024; Tanaka & Suzuki, 2023). These systems utilize carbon dioxide as a solvent, removing chemical residues while maintaining extraction selectivity for specific bioactive molecules (Johnson & Miller, 2023; Singh & Patel, 2022). Microwave-assisted extraction technologies offer expedited processing with improved compound yield relative to traditional extraction methods (Chen et al., 2024; Anderson & Brown, 2023). Ultrasonic extraction methods utilize acoustic cavitation to enhance mass transfer rates, thereby reducing processing time while maintaining compound integrity (Kumar et al., 2023; Thompson et al., 2022).

7. Data Analytics and Decision Support Systems

7.1. Predictive Modeling for Agricultural Optimization

Advanced analytics platforms analyze multidimensional datasets that encompass environmental characteristics, plant physiological responses, and quality measurements to create predictive models for optimizing agricultural practices (Wilson & Davis, 2024; Martinez-Lopez et al., 2023). Machine learning algorithms utilize historical cultivation data to identify the optimal

combinations of growing conditions for specific medicinal plant species (Zhang & Liu, 2023; Patel & Singh, 2022).

Regression analysis models establish a correlation between environmental inputs and the production of bioactive compounds, facilitating the improvement of cultivation protocols for improved medicinal efficacy (Garcia et al., 2024; Johnson & Thompson, 2023). The examination of time-series data on plant development patterns allows for the early identification of stress situations and the implementation of proactive intervention techniques (Kim et al., 2023; Anderson & Wilson, 2022).

7.2. Economic Analysis and Resource Optimization

Integrated economic modeling methods evaluate resource use efficiency and production costs about market prices for several medicinal plant species (Smith et al., 2024; Rodriguez & Martinez, 2023). Linear programming techniques optimize resource allocation across multiple cultivation cycles, enhancing economic returns while maintaining quality requirements (Chen & Wang, 2023; Taylor & Brown, 2022).

Life cycle assessment (LCA) modules measure environmental impact indicators during the cultivation and processing stages, facilitating the adoption of sustainable production methods and adherence to regulatory compliance (Fischer & Müller, 2024; Patel et al., 2023).

8. Quality Assurance and Regulatory Compliance

8.1. Automated Quality Assurance Systems

Continuous monitoring systems oversee essential quality parameters during cultivation and processing, producing thorough documentation for regulatory compliance (Thompson & Johnson, 2024; Liu et al., 2023). Automated sampling methods gather representative samples at specified intervals, guaranteeing the statistical validity of quality evaluations (Kumar & Sharma, 2023b; Garcia-Martinez et al., 2022).

Blockchain-based traceability solutions preserve unalterable records of cultivation parameters, processing conditions, and quality measurements, ensuring comprehensive supply chain transparency for regulatory agencies and end-users (Zhang et al., 2024a; Anderson & Davis, 2023).

8.2. Implementation of Good Agricultural Practices (GAP)

Intelligent agricultural technologies promote compliance with Good Agricultural Practices by automating the monitoring and reporting of cultivation procedures (Williams & Chen, 2024a; Patel & Singh, 2023a). Environmental parameter logging systems consistently document temperature, humidity, light exposure, and nutrient administration rates (Johnson et al., 2023; Kim & Lee, 2022a).

Integrated pest management (IPM) procedures utilize predictive modeling to optimize intervention timing and minimize chemical inputs (Martinez et al., 2024; Thompson & Wilson, 2023). Monitoring systems for biological control agents evaluate populations of beneficial organisms and their effectiveness in maintaining ecological balance (Singh et al., 2023; Müller & Schmidt, 2022b).

9. Future Perspectives and Emerging Technologies

9.1. Artificial Intelligence Integration

The incorporation of artificial intelligence (AI) systems signifies the forthcoming advancement in medicinal plant farming technologies (Chen & Liu, 2024; Rodriguez-Martinez et al., 2023). Deep learning systems, based on extensive datasets of plant responses to environmental stimuli, enable predictive cultivation management with unparalleled accuracy (Kumar et al., 2024; Anderson & Peterson, 2023).

Autonomous cultivation systems that can make independent decisions based on real-time environmental and plant physiological data are emerging as feasible commercial solutions (Zhang & Wang, 2024; Taylor et al., 2023). These systems amalgamate many sensing modalities and processing capabilities to sustain optimal growth conditions autonomously (Johnson & Brown, 2023; Patel & Gupta, 2022).

9.2. Integration of Biotechnology

Gene expression monitoring methods enable the real-time evaluation of biosynthetic pathway activity, providing insights into the dynamics of bioactive chemical formation (Singh & Sharma, 2024; Garcia-Lopez et al., 2023). CRISPR-based gene editing technologies offer opportunities to augment pharmaceutical chemical synthesis while preserving plant vitality

and enhancing stress resilience (Liu & Yang, 2024; Thompson & Miller, 2023).

The combination of metabolomics with cultivation systems enables a thorough analysis of secondary metabolite synthesis, thereby allowing for customized cultivation techniques tailored to specific medicinal applications (Kim et al., 2024; Fischer & Anderson, 2023).

Conclusion

The integration of precision agricultural technologies with medicinal plant cultivation marks a transformative shift towards scientifically informed production methods that enhance both therapeutic effectiveness and economic sustainability (Wilson & Davis, 2024; Martinez-Lopez et al., 2023). These integrated systems enable the reliable production of high-quality medical plant materials while promoting sustainable agricultural practices and adhering to regulatory compliance standards (Chen & Wang, 2024b; Rodriguez & Martinez, 2023).

The ongoing advancement of smart farming technologies ensures improvements in cultivation accuracy, quality uniformity, and economic efficiency, hence addressing the increasing global need for evidence-based botanical treatments (Zhang et al., 2024b; Patel & Singh, 2023b).

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CHAPTER 8

A NEW SUPERFOOD FOR TÜRKİYE: TEFF PLANT [*Eragrostis Tef* (Zucc.) Trotter]

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1. INTRODUCTION

Teff, a staple food consumed by humanity in African nations, particularly Ethiopia and Eritrea, over thousands of years, is beginning to draw interest in other countries due to the possible use of its seed and the nutritional qualities of its herb. Among warm climate cereals, teff stands out with its small grains and has become a strategic product for nutritional security, gluten-free food markets and sustainable agriculture (Zhu, 2018; Chanyalew et al., 2019; Gebru et al., 2020). Over the last couple of years, the growing demand of gluten-free and nutritional food items that form a part of the popular nutrition market have made teff more important, and it is now a common plant in most countries, including Turkey.

Among the most interesting nutritional features of these analyses is the fact that teff grains possess the eight amino acids (isoleucine, leucine, methionine, lysine, phenylalanine, threonine, tryptophan, and valine) that are necessary in the human body. In this regard, teff is a mixed protein source of human nutrition. Teff typically containing 8.0 to 13.3% protein, is high in essential amino acids, like lysine, which are limiting in cereals (Yılmaz & Arslan, 2018; Han & Kwon, 2022). This indicates that teff protein has a high biological value and offers an amino acid balance similar to that of egg protein (Legesse, 2019). Fiber content is also an important feature of teff; dietary fiber ratios ranging from 2.04% to 4.54% contribute to digestive health, especially when consumed as a whole grain (Legesse, 2019; Agregán et al., 2023). Teff's small grain size makes it difficult to separate the bran and germ, so these fiber-rich parts are also consumed when eaten.

Gluten is the name given to the storage protein found in wheat, the varieties of which we consume on our tables almost every day. It combines with water and forms an elastic structure with gliadin, creating a strong and flexible network thanks to the sulfur bonds that allow the dough to stretch as it is kneaded. It is a protein that is difficult to digest. Especially in recent years, the number of individuals with celiac disease or some that are not recognized by the immune system because reactions have increased. As this level increases, people are turning to other options. People are moving towards easy to digest foods that can sustain their daily protein and carbohydrate requirements. Teff is becoming popular in America and Europe along with other plants like amaranth and quinoa, which are now described as superfoods. Despite nutritional

potential, Teff has certain limitations to commercial food production. It contains no gluten, and is thus celiac-safe, but the dough is difficult to shape into bread, and the texture is stiff. Studies has focused on technological advances to enhance the sensory and textural quality of teff-based products. Targeted lactic acid microorganisms, hydrocolloids, enzyme treatments, and novel process technologies can be used to enhance bread volume, texture, and shelf life via sourdough fermentation (Bender & Schoenlechner, 2020; Chochkov et al., 2022). Increased consumption of teff flour in gluten-free breads, pasta and snacks meet consumer acceptance and boost market potential.

The quality of gluten-free products usually does not meet the standards of the wheat products in human consupcion, which highlights the importance of continuous research and development (Padalino et al., 2016; Cappelli et al., 2020). Teff is a very versatile grain and it can be cultivated in many marginal conditions. The teff is also drought and overwatered resistant due to high genetic diversity and flexibility (Gelaw & Qureshi, 2020; Hein et al., 2025). Genome editing and omics technology breeding projects are enhancing the production potential, lodging resistance, and stress resistance of teff (Numan et al., 2021; Alemu et al., 2024a). Plant productivity and grain quality can be increased through the optimization of fertilization, irrigation, and planting (Gashu et al., 2020; Bazie et al., 2025). The main goal of the book chapter is to create an inclusive resource that identifies not only the current position of teff, but also future research and policy efforts needed to bring into fruition the potential it has as a global commodity.

2. ORIGIN, DOMESTICATION, SEED CHARACTERISTICS AND GLOBAL INTEREST OF TEFF PLANT

Teff is native to Ethiopia and Eritrea. In these nations, it is still a popular warm-weather cereal and an important part of traditional food systems (Cheng et al., 2017; Zhu, 2018; Assefa et al., 2015; Gebru et al., 2020). The majority of the world's teff cultivation is done in Ethiopia (90%), making it the country's second most produced plant after coffee (Cannarozzi & Tadele, 2022). In Ethiopia, teff plant constitutes approximately 30% of grain production (Cannarozzi & Tadele, 2022). In addition to their normal consumption, teff seeds are also consumed as a traditional alcoholic beverage after undergoing a

fermentation process. In recent years, its popularity has increased in countries such as the United States, China, Italy and England, and efforts are being made to increase its cultivation in countries such as Bulgaria and England. Because teff cultivation is not widespread in Turkey, our farmers have very little knowledge about the plant.

It is becoming more popular around the world since its seeds are gluten-free, good for health, which makes it appealing to health-conscious people and people with celiac disease (Gebremariam et al., 2014; Cheng et al., 2017; Gebru et al., 2020; Barretto et al., 2021; Adepoju et al., 2024). While gluten-free foods are sold at high prices worldwide, the opposite is true in Ethiopia and other African countries. Its suitability for different soil structures, short maturation period, resistance to diseases and pests, and tolerance to abiotic and biotic stresses are also effective in the widespread cultivation of teff plant not only in African countries but also in different countries of the world such as the USA, China and India (Gregory et al., 2019). One of the advantages of the teff plant is that it does not get damaged by insects even if it remains in storage for years after harvest.

2.1. Seed Physical Properties

Among the commonly cultivated cereals, teff has the smallest seeds. The seed is approximately 1.0 mm long and 0.6 mm wide. Its small volume ensures high bulk density and excellent fluidity during sifting and storage (Zhu, 2018; Gebru et al., 2020; Menjaye et al., 2024; Whisnant et al., 2024). The color of the grains varies from ivory white to brown and red, and is highly influenced by genotype-environment interactions along with seed size and density (Abewa et al., 2019; Menjaye et al., 2024; Whisnant et al., 2024). These physical properties have direct technological consequences. Smaller seeds increase surface contact between the bran and endosperm, affecting peeling efficiency, milling yield, and flour particle size distribution. In particular, smaller grains are generally associated with higher mineral concentrations and darker colors. This is a pattern consistent with mineral enrichment in the outer layers (Menjaye et al., 2024; Whisnant et al., 2024).

Seed physical properties benefit processors with high fluidity, pneumatic conveying, and silo discharge, but can make precise dosing difficult at very low mass flow rates. Adjustments to conveyor screw design and feeder calibration

may be required. For breeding and agronomy, the tight link between seed sizes, test weight and mineral density indicates that selection for physical qualities should be optimized in conjunction with nutritional objectives.

2.2. Chemical Composition

Many studies have reported that teff grain contains 70-75% starch, 10-12% protein and 2-3% lipid (Abebe et al., 2015a; Zhu, 2018; Galassi et al., 2020; Gebru et al., 2020a; Caporizzi et al., 2023). Starch functionality is characterized by relatively high gelatinization temperatures and a higher proportion of amylopectin, which favors slow digestibility and contributes to a low glycemic index (Gebremariam et al., 2014; Shumoy & Raes, 2017; Gebru et al., 2020a; Caporizzi et al., 2023). The protein fraction is notable for its relatively higher lysine content than most cereals and a favorable amino acid profile, dominated by glutelins and albumins (Shumoy et al., 2018; Gebru et al., 2019; Gebru et al., 2020). Teff also contains dietary fiber and various polyphenols, flavonoids, and saponins. Brown-seed varieties exhibit higher phenolic content and stronger antioxidant capacity than white-seed varieties, making color compatible with phytochemical density (Gebru & Sbhatu, 2020; Gebru et al., 2021; Osen et al., 2021; Cotter et al., 2023; Yisak et al., 2024). From a formulation perspective, these compositional properties help explain both the health profile and processing behavior of teff-based foods.

2.3. Nutrition Profile

As a whole cereal, teff contains minerals, particularly calcium, iron, magnesium and zinc, generally at higher levels than wheat, rice and corn (Gebremariam et al., 2014; Shumoy & Raes, 2017; Koubová et al., 2018; Nyachoti et al., 2020; Tietel et al., 2020; Yisak et al., 2024). It also contains B vitamins and essential fatty acids, and a favorable omega-6/omega-3 ratio has been reported in several data sets (Galassi et al., 2020; Yisak et al., 2024). Teff is gluten-free and contains slowly digestible starch, which supports its use in celiac and diabetic diets (Gebremariam et al., 2014; Shumoy & Raes, 2017; Gebru et al., 2020; Barretto et al., 2021; Villanueva et al., 2022; Caporizzi et al., 2023; Adepoju et al., 2024). A key nutritional challenge is the bioavailability of minerals, especially iron, due to phytic acid. However, fermentation, soaking, germination and certain thermal treatments reduce phytate and

increase the availability of minerals, thus offering practical means to increase nutritional impact (Shumoy & Raes, 2017; Osen et al., 2021; Karaçoban et al., 2023).

2.4. Functional and Health Properties

Dietary fiber, resistant starch, and abundant antioxidants support glycemic control, anemia risk reduction, and oxidative benefits (Gebremariam et al., 2014; Shumoy & Raes, 2017; Gebru & Sbhatu, 2020; Gebru et al., 2021; Villanueva et al., 2022; Cotter et al., 2023 Yisak et al., 2024; Adepoju et al., 2024). Functionally, teff flours exhibit water absorption, gelation, and foaming properties that vary depending on variety and processing history, creating opportunities to customize textures in gluten-free products (Abebe et al., 2015b; Ronda et al., 2015; De Oliveira Do Nascimento et al., 2018; Homem et al., 2019; Barretto et al., 2021; Villanueva et al., 2022; Caporizzi et al., 2023; Calix-Rivera et al., 2023;). Convergence between structure (e.g., starch crystallinity), composition (e.g., phenolic load), and process (e.g., fermentation) explains much of the variability in health outcomes reported across studies.

2.5. Focus on Health Outcomes

There is a link between regular teff consumption and improved iron status and reduced anemia, especially among women and children, who are at greater risk of deficiency (El-Alfy et al., 2012; Shumoy & Raes, 2017; Gebru et al., 2020; Carboni et al., 2020; Osen et al., 2021; Daba & Lelisa, 2024). The low glycemic index and slowly digestible carbohydrates support the reduction of post-meal glucose excursions, making teff a promising staple food for diabetes management (Shumoy & Raes, 2017; Lemecha et al., 2018; Rico et al., 2019; Gebru et al., 2020; Demir et al., 2022; Habte et al., 2022). Polyphenols and flavonoids provide additional antioxidant capacity; again, brown varieties often outperform white varieties in in vitro tests (Štátná et al., 2019; Ahmed et al., 2021; Gebru et al., 2021; Kataria et al., 2022; Yisak et al., 2022; Ananth et al., 2023; Cotter et al., 2023; Da Silva et al., 2025). Although these signals are consistent, more controlled human studies are needed to define dose-response relationships and separate matrix, treatment, and variety effects.

2.6. Comparative and Emerging Health Practices

Compared to wheat, rice, and even quinoa, teff generally exhibits higher mineral density, a more balanced amino acid profile, and stronger antioxidant potential (Gebremariam et al., 2014; Cheng et al., 2017; Satheesh & Fanta, 2018; Zhu, 2018; Ananth et al., 2023). New areas of research include cardiovascular risk modulation, bone health (via calcium and potential vitamin K cofactors in whole grain matrices), and gut health through fiber-polyphenol synergy (Goersch et al., 2019; Gebru et al., 2020; Carboni et al., 2020; Girija et al., 2021b; Asfha et al., 2022; Molina-Valero et al., 2024). While mechanistically plausible, robust clinical studies are limited; designing studies that isolate the unique contribution of teff across diverse dietary habits is a priority.

2.7. Process Effects: Fermentation and Thermal Processes

Process can be used for increasing the nutrition value. Lactic fermentation and thermal treatments such as roasting and extrusion reduce antinutritional factors (phytate, tannins), increase mineral bioavailability, and may increase antioxidant activity through the release or transformation of bound phenolics (Ahmed et al., 2021; Kataria et al., 2022; Martín-Diana et al., 2022; Abera et al., 2025; Da Silva et al., 2025). Importantly, the magnitude and direction of the effects depend on parameters such as fermentation time, starter culture, humidity and temperature profiles. For product developers, the interaction between fermentation and hydrocolloid/enzyme systems is a fertile field: fermentation improves palatability and bioavailability, while structure-modifying agents regenerate viscoelasticity lost in the absence of gluten.

2.8. Advances in Breeding: Yield, Lodging Resistance, and Stress Tolerance

Lodging is a chronic constraint for teff; therefore, genetic gain is focused on plant architecture, trunk strength and height reduction. Traditional breeding, participatory selection and modern omics methods have produced high yielding, lodging resistant and stress tolerant varieties (Blösch et al., 2020; Bayable et al., 2021; Numan et al., 2021; Woldeyohannes et al., 2021; Woldeyohannes et al., 2022; Habtegebriel et al., 2025; Mitiku et al., 2025;).

Genome editing (e.g., CRISPR) is accelerating the discovery and integration of alleles associated with semi dwarfism, stem strength, and stress responses (Numan et al., 2021; Alemu et al., 2024b; Gonzales et al., 2024; Hein et al., 2025). Characteristics such as short length, compact clusters and robust root systems contribute to lodging resistance and yield stability (Blösch et al., 2020; Bayable et al., 2021; Ben-Zeev et al., 2025). Since lodging risk depends largely on management, genetic solutions should be developed in conjunction with agronomic packages.

3. AGRONOMIC PRACTICES: FERTILIZERS, IRRIGATION AND CULTIVATION

Nitrogen and phosphorus are the primary limiting nutrients for teff; site-specific nutrient management can provide significant yield increases and improve grain quality where protein content is targeted (Gashu et al., 2020; Desta et al., 2022; Bazie et al., 2025; Gebru et al., 2023;). Nitrogen and phosphorus are the primary limiting nutrients for teff; site-specific nutrient management can provide significant yield increases and improve grain quality where protein content is targeted (Gashu et al., 2020; Gelaw & Qureshi, 2020). Seeding rate and planting depth, tillering, and stem thickness ultimately affect lodging risk; lower plant density and optimized depths generally reduce lodging while maintaining yield (Ben-Zeev et al., 2020a; Ben-Zeev et al., 2020b; Blösch et al., 2020). Integrating these practices with improved varieties is necessary to realize genetic potential under field conditions. Although it can be grown in different soil structures, one of the factors limiting its production is soil temperature. Its development is hampered in regions with soil temperatures below 10 degrees. (Barretto et al., 2021).

3.1. Comparative and Participatory Approaches

Inter-cereal comparisons reveal teff's unique adaptation strategies and highlight the need to integrate genetic and agronomic improvements together rather than separately (Cooper & Messina, 2022; Rizzo et al., 2022; Liao et al., 2023). Participatory breeding and on-field trials have been effective in revealing traits preferred by farmers (grain color, straw quality, blend ability and lodging tolerance), which are sometimes underestimated in station trials (Woldeyohannes et al., 2021; Bitew & Workie, 2022; Ferede et al., 2025;

Gadissa & Adem, 2025). These co-development models increase adoption rates and align variety characteristics with local market demands.

3.2. Adaptability and Environmental Resilience

Although its origin and production and consumption prevalence are in tropical countries such as Ethiopia and some African countries, it can be cultivated in many parts of the world thanks to the plant's resistance to different soil conditions. Agronomically, teff thrives in overwatered and acidic soils prone to drought; this adaptability is based on wide genetic diversity and flexible physiology (Dutamo et al., 2020; Gelaw & Qureshi, 2020; Ferede et al., 2025; Hein et al., 2025; Gadissa & Adem, 2025). Landraces and improved varieties show broad tolerance to abiotic stresses including drought and salinity (Girija et al., 2021a; Kebede & Tesso, 2021; Haddadi et al., 2023; Hein et al., 2025;). Genomic analyses have identified loci associated with environmental adaptation, and this information has contributed to marker-assisted and genomic selection processes (Woldeyohannes et al., 2021; Alemu et al., 2024a; Hein et al., 2025). For climate-smart agriculture, crop flexibility across altitude, rainfall and soil constraints is a key advantage. It is preferred in drought or under-irrigated areas due to its short maturation period (Habte et al., 2019).

4. Technological Innovations in Gluten-Free Products

The absence of gluten requires structure-building interventions in bread and pasta. Hydrocolloids (e.g. xanthan, guar, CMC) increase dough viscosity, gas retention, and crumb softness; enzyme systems, including transglutaminase and selected proteases, enhance network formation and delay staling (Padalino et al., 2016; Azizi et al., 2020; Bender & Schönlechner, 2020; Zoghi et al., 2020; Culețu et al., 2021). Sourdough fermentation, especially with specific lactic acid bacteria such as *Pediococcus pentosaceus* or *Enterococcus durans*, improves rheology, flavor and shelf life (Nami et al., 2020; Gharekhani et al., 2021; Chochkov et al., 2022). In composite formulations, synergistic combinations of hydrocolloids, enzymes, and sourdough often outperform a single intervention, but optimal ratios are product-specific. Despite advances, a sensory difference with wheat products persists, suggesting continued room for structure-function optimization and consumer-focused design.

4.1. Nutritional and Sensorial Performances of Teff-based Foods

Compared to gluten-free products based on rice or corn, teff bread and pasta generally have higher fiber and mineral content, reflecting the grain's natural composition (Zhu, 2018; Homem et al., 2021a; Homem et al., 2021a; Kutlu et al., 2024). Sensory studies show good acceptance and promising intention to consume among both celiac and non-celiac consumers, which is important for expanding beyond niche markets (Homem et al., 2021a; Homem et al., 2021b; Kutlu et al., 2024). Maintaining mineral bioavailability during aggressive processing remains a design challenge; this is where fermentation steps incorporated into the production chain are beneficial.

4.2. Market Potential and Agronomical Adaptation

Demand for gluten-free products is increasing globally, and teff aligns with its “naturally gluten-free” and “whole grain” positioning (Kutlu et al., 2024; Zhu, 2018). Successful cultivation trials outside Ethiopia, such as in Türkiye, demonstrate agronomic viability for both grain and fodder (Mihretie et al., 2021; Menjaye et al., 2024; Kutlu et al., 2024). However, building a resilient value chain requires coordinated investments, certified seed systems, advisory services, grain quality standards and market information platforms (Degefa et al., 2021; Mihretie et al., 2021; Kifle et al., 2022). For Türkiye, incorporating teff into the summer crop rotation can diversify income and manage risk, but local adaptation trials should align target traits (lodging resistance, maturation time, grain color class) with producer needs and consumer preferences.

4.3. Transferable Innovations

Technologies validated in other gluten-free grains can be easily transferred to wheat flour. Ultrasonication and high hydrostatic pressure can modulate starch-protein interactions and improve crumb and mouthfeel; evaluation of plant by-products as functional ingredients can increase nutritional value and sustainability (Vela et al., 2020; Difonzo et al., 2021; Vela et al., 2024; Gutiérrez et al., 2025). Future studies should combine these unit

processes with fermentation and enzyme systems to fine-tune the structure while preserving micronutrients.

5. TEFF IN TÜRKİYE: OPPORTUNITIES AND CHALLENGES

Historically cultivated in Ethiopia and Eritrea, teff [*Eragrostis tef* (Zucc.) trotter] is gaining increasing interest worldwide due to its gluten-free nature, high micronutrient content, and resilience in marginal conditions. Türkiye is a country with a variety of agroecological zones that are promising in terms of the promotion and proliferation of teff. Teff plants may be desired especially in regions where drought is likely to occur in conjunction with the common grains that are highly water intensive. It may be applied in legume and cereal crop rotations. This sub-section is a summary of the existing information about cultivation practices, market potential and obstacles to adopting the practice and future requirements of sustainable integration into the Turkish agriculture and food systems.

5.1. Cultivation Practices

5.1.1. Climate and soil compatibility

The agroecological diversity of Türkiye (between the semiarid Anatolian plateaus and the irrigated Mediterranean valleys) is a close reflection of the favorable environment of teff. Early demonstrations as a transformation crop in wheat-and barley-dominated systems suggest that teff can withstand drought-prone central Anatolia and flooded lowlands. The quick growth period (70-120 days) also leaves the option of two-cropping the irrigated lands, particularly after winter cereals.

5.1.2. Preliminary and adaptation trials

In the conducted studies, the yield of 1.47-2.18 tons/ha is reached in rain-irrigated conditions in the southern and western regions of Türkiye, and the yield is more with irrigation (Akçura et al., 2021). The fact that it can adjust to marginal soils like salinity or low fertility puts it in the spotlight in areas of Türkiye where soil degradation is a concern. Critically, the quality of hay has

been recognized as a major asset to livestock producers as per integrated crop-livestock systems.

5.1.3. Its role in sustainable agriculture

Both abiotic and biotic stresses affect our country and also the world. Some of the barriers to agricultural sustainability include misuse of resources, poor methods of farming, and disposition to chemicals. With the rising incidences of water scarcity and soil erosion experienced throughout Türkiye, the longevity of the teff will provide a strategic edge. The deep root system enhances the soil structure, minimizes the possibility of soil erosion and improves the utilization of water. Since it can grow within a short period, it can be planted as a second crop into the field and as a single crop. Also, the introduction of teff into the Turkish crop rotations would help ease the impacts of climate change and sustain long-term sustainability. Its adaptation to various soil structures also makes it a plant that all producers can employ given the varying soil structures within our country. It is a disease and pest resistant plant. Due to this resistance, the structure of the field is prevented from being damaged by chemicals such as pesticides and herbicides, and cultivation is carried out under optimum conditions.

5.2. Market Potential

5.2.1. The role of gluten-free product innovation

Consumer demand for gluten-free products is increasing in Türkiye and globally, where celiac disease and gluten sensitivity affect a growing segment of the population. With its mild taste and high mineral density, teff flour has strong potential as a premium gluten-free ingredient. When mixed with corn, rice or chickpea flour, it can improve nutritional quality and diversify product options.

5.2.2. Value-added food products

Teff aligns with Türkiye's expanding healthy food sector. Potential products include:

- Traditional style breads adapted to Turkish taste
- Gluten-free pasta and snack foods utilizing extrusion technology.
- Nutrient-rich porridge marketed for infants and the elderly.

- Fermentation-based foods, including new sourdough and probiotic products.

Türkiye's food industry is currently export-oriented and has gluten-free product groups. Integrating teff could expand these exports to Europe and the Middle East, making Türkiye a regional hub for teff-based innovation.

5.2.3. Consumer perception and cultural integration

Although Turkish consumers are unfamiliar with teff, its health benefits (iron density, gluten-free nature and functional food potential) are in line with the growing interest in healthy living and nutrition. Public awareness campaigns and culinary adaptations (for example, using teff flour in making simit or börek) can facilitate cultural acceptance.

5.3. Obstacles and Future Needs

5.3.1. Reliable seed supply and certification

One of the most important obstacles to the widespread use of teff in Türkiye is the lack of certified seeds. Current practices are based on small-scale imports or propagation at research stations. Establishing a national seed system that includes breeding, certification and distribution networks will be crucial for expanding cultivation. The other obstacle is the small size of the seeds. Although threshing and other processes are easier for small-scale agricultural producers, harvesting and threshing technologies need to be improved for large-scale commercial production.

5.3.2. Lack of local agricultural knowledge

Farmers and agricultural advisors in Türkiye lack experience in teff cultivation. Challenges include optimizing planting density, nutrient management and weed control in Turkish conditions. Adaptive research and participatory field trials are necessary to improve management practices and address knowledge gaps.

5.3.3. Supply chain and processing infrastructure

Although Türkiye's milling and baking industries are developed, teff flour requires special processing to maintain its quality and prevent cross-

contamination with gluten. Special storage and processing units will be required, especially if products are targeted at export markets that require stringent gluten-free certification. Standard for grading, storage, milling and fermentation should be developed.

5.3.4. Consumer awareness and market development

Consumers' lack of familiarity with teff creates a challenge. While health-conscious segments may quickly adopt teff-based foods, education on nutritional values is necessary for wider market penetration. Effective labeling and standards that emphasize mineral density and gluten-free authenticity can increase trust and accelerate adoption.

5.4. A phased roadmap for Türkiye could guide future efforts

5.4.1. Adaptation trials

- Multi-location trials should be conducted in the Anatolian, Mediterranean and Aegean regions.
- Evaluations should be conducted with the participation of farmers, processors and consumers.
- Priority should be given to characteristics such as lodging resistance, yield stability, and grain quality.

5.4.2. Seed system development

- A formal seed multiplication and certification program should be initiated.
- Breeding programs targeting semi-dwarf, lodging-resistant varieties suitable for mechanized Turkish systems should be supported.

5.4.3. Processor partnerships

- In collaboration with the food industry, product lines should be jointly designed, especially in the gluten-free bakery and pasta sectors.
- Fermentation-focused innovations that preserve micronutrients and improve sensory quality should be explored.

5.4.4. Market standards and labeling

- Establish clear national standards for gluten-free certification.
- Branding strategies should be developed that highlight teff's heritage, mineral density and functional food properties.

5.4.5. Prevalence and farmers' training

- Training modules should be provided for dissemination services on teff cultivation, pest management and post-harvest operations.
- Farmer cooperatives should be encouraged to facilitate mass marketing and information exchange.

6. CONCLUSION

Increasing abiotic and biotic stresses in recent years, have restricted agricultural production and are leading producers to seek new solutions. However, finding a suitable plant for a country's growing conditions brings with it great risks and losses. Teff, which is among the plants called superfood, has valuable morphological, biological and physiological properties. It is a plant that producers prefer due to its tolerance to drought, resistance to diseases and pests, short growing period and versatile use. Although different studies have been conducted in our country, sufficient information about the plant has not been obtained. It is a plant that can be used as a good alternative, especially in areas with water shortages, and can also be useful in animal feeding. It is recommended that studies be carried out in our country, especially in areas that are under drought and prone to drought. We hope that this plant, which has high potential for our country's agriculture, will become more widespread and take its place permanently on our tables.

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Authors' contributions

İrem Poyraz: Methodology, Writing-original draft, Writing- review and editing.

Mevlüt Akçura: Supervision, Funding acquisition, Methodology, Writing-original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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CHAPTER 9

EXTENDING SHELF LIFE AND REDUCING FOOD WASTE: HOW ECO-FRIENDLY PACKAGING BENEFITS FRESH PRODUCE

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1. Introduction

In order to keep fruits and vegetables fresh, safe, and aesthetically pleasing from the farm to the customer's table, one of the main goals of packaging in the produce industry is to increase their shelf life. With a number of advantages that not only increase the marketability of fresh produce but also support sustainability and environmental preservation, eco-friendly packaging materials and technologies have become powerful instruments in accomplishing this goal (Coles et al., 2003).

Fruit and vegetable moisture loss has been shown to be reduced by using environmentally friendly packaging materials, particularly biodegradable films and coatings. This feature is crucial because moisture loss can result in wilting, weight loss, and a decline in product quality. Sustainable packaging prolongs the freshness of the produce by acting as a barrier of defense and establishing a microenvironment that keeps the proper moisture content (Pushkala et al., 2013; Hagenmaier and Shaw, 1990; Baldwin et al., 2011).

Cinnamon, thymol, thyme, and oregano were added to zein-chitosan-based blend systems formulated by Pavlátková et al. (2023). Their study proved that these zein-chitosan blends are appropriate for delivering bioactive compounds to preserve food quality, create effective barriers, stop moisture loss, and extend the shelf life of fruits. Furthermore, it has been noted that PLA and other biodegradable substances, like alginates, slow down the weight loss of produce (Koide & Shi, 2007; Tay & Perera, 2004). According to Ben-Yehoshua (1987), fresh produce typically shows signs of freshness loss with a weight drop of 3–10%. Ohta et al. (2002) found that when weight loss exceeds 5%, the retail value of fruits and vegetables declines. With these systems, sustainable active food packaging may be possible.

The amount of ethylene, carbon dioxide, and oxygen is especially important for fruit and vegetable respiration and ripening. It's well known that excessive oxygen content causes a number of problems with packaged foods, including lipid oxidation, enzymatic browning reactions, vitamin loss, and microbial growth. Zabihzadeh-Khajavi et al. (2020) claim that regulating the oxygen permeability of packaging can greatly increase the food's shelf life. However, because it promotes fruit growth and ripening, ethylene is regarded as the plant's aging hormone (Blanke, 2014). Food can deteriorate more quickly if there is a high ethylene concentration nearby. Therefore, extending the shelf

life of fresh products requires removing this gas from the packaging or regulating its permeability (Giacinti Baschetti and Minelli, 2020). In order to efficiently manage the internal atmosphere of the packaging, sustainable packaging materials are made to regulate gas exchange. By controlling oxygen levels and assisting in the removal of excess carbon dioxide, these compounds can slow down the ripening process and increase the shelf life of produce (Chaix et al., 2015; Zhang et al., 2015; Othman, 2014).

In order to stop the growth of harmful and spoiling microorganisms, natural antioxidant and antimicrobial substances are combined to create antimicrobial and antioxidant packaging materials, also referred to as active packaging. Human health is directly improved by this strategy, which lessens the food industry's dependency on chemical additives (Joz Majidi et al., 2019; Vahedikia et al., 2019). Because they are generally recognized as safe (GRAS), compounds with antioxidant and antimicrobial qualities that are derived from plants and spices make appealing food additives (Alves-Silva et al., 2013; Gennadios et al., 1997). Despite their potential, these substances are rarely used as food preservatives because of issues like strong flavors, unstable properties, and other pragmatic considerations. Rather, these ingredients are often added to food packaging to reduce severe taste issues (Ruiz-et al., 2013). Fresh produce safety can be improved by using antimicrobial agents derived from natural sources in sustainable packaging. Incorporating natural additives into food packaging formulations protects products from oxidative rancidity reactions and microbiological contamination in addition to environmental influences. This prolongs shelf life, lowers the risk of foodborne illnesses, and eliminates the need for additives in the food itself (Atta et al., 2022; Ortega et al., 2022; Pandey et al., 2022).

Produce is shielded from physical harm during handling, storage, and transit by the strength and durability of green packaging materials like bio-based polymers and recycled materials. This safeguard ensures that consumers receive fruits and vegetables in optimal condition while also minimizing food waste (Moustafa et al., 2019; Lamba and Garg, 2019). Packaging that prolongs the shelf life of fruits and vegetables lowers the possibility of overstocking perishable goods, which can result in increased food waste when goods go bad or are no longer marketable (Riesenegger and Hübner, 2022). Additionally, consumers can check the freshness and quality of the produce without handling

it too much thanks to packaging materials that allow for transparency and visibility, like edible packaging and biodegradable films. This boosts consumer confidence and reduces food waste from rejecting visually less appealing produce (Kuang et al., 2024; Alias et al., 2022; Verghese et al., 2015; Carter and Rogers, 2008; Trienekens et al., 2012). In order to prevent overconsumption and the subsequent disposal of unused portions, green packaging can also incorporate creative designs for portion control and resealing, allowing customers to use only what they need and prolonging the freshness of the remainder (Chu et al., 2022). These packaging choices also reflect consumer preferences for eco-friendly and sustainable goods. By using sustainable packaging as a marketing tool, manufacturers and retailers can show their dedication to sustainability and draw in eco-aware customers (Isa and Yao, 2013; Rokka and Uusitalo, 2008).

2. Market Trends and Consumer Preferences for Sustainable Fruit and Vegetable Packaging

The issue of protecting future generations' resources and using today's resources more efficiently has become increasingly important. This has led to the emergence of the concept of sustainability. Products are packaged to attract attention, protect against external damage, attract consumers, preserve, and ensure health. Packaging plays a crucial role in meeting consumer needs and desires, including promoting the product, providing ease of use, protecting it, facilitating promotional activities, and providing information about the product (Çelen Özcan, 2014).

Growing environmental consciousness has led consumers to actively seek out products that support their sustainability values. Packaging materials that are regarded as environmentally friendly, such as recyclable, biodegradable, or renewable materials, are preferred by consumers (Van Birgelen et al., 2009). Consumers are drawn to packaging options that reduce plastic consumption, like those made of paper, cardboard, or alternative materials, as part of an increasing global campaign to reduce plastic waste. Additionally, they favor products that come in reusable or refillable containers. Customers value clear, transparent labeling that highlights sustainable packaging options and provides information about recycling or disposal options because they are becoming more concerned about the environmental impact of

their purchases (Steenis et al., 2017). Customers are increasingly favoring minimalist and straightforward packaging designs; straightforward packaging that uses less material while still being functional is regarded as both aesthetically beautiful and ecologically conscious (Benavides, 2011). Customers who prefer products with packaging that can be recycled back into the environment without harming the environment are drawn to packaging materials that are compostable or biodegradable (Dirpan et al., 2023). Customers are drawn to packaging that conveys a sense of handcrafted local or production appeals, indicating a connection to the community and frequently suggesting a smaller environmental impact because of shorter supply chains. Products with recognized eco-certifications are more likely to be chosen by environmentally conscious consumers, and eco-certifications and labels, such as "organic," "certified compostable," or "recyclable," act as trust indicators (Brach et al., 2018). Smart packaging solutions that offer real-time information about product freshness, safety, and traceability are appealing to consumers who are growing more tech-savvy because they satisfy their need for transparency and quality control. Customers are increasingly loyal to companies that show a commitment to sustainability, especially when it comes to sustainable packaging, and companies that successfully convey their sustainability goals tend to have more devoted customers (Steenis et al., 2017). The majority of people concurred that improved waste collection services were required, and eight out of ten stated that environmental factors, like a product's ability to be recycled or reused, were significant considerations when making a purchase (Anonymous, 2025). Consumer demand and a changing regulatory environment that seeks to lessen environmental impact and advance sustainability are driving the shift towards eco-friendly produce packaging. This trend is bolstered by certification programs and regulatory frameworks that oversee and encourage the use of eco-friendly packaging for fruits and vegetables.

Strict food contact regulations must be followed by eco-friendly packaging materials to guarantee that they don't release harmful substances into the produce they hold. Standards for materials that come into contact with food are established by regulatory bodies, such as the European Food Safety Authority (EFSA) in Europe and the U.S. Food and Drug Administration (FDA) in the United States. Compliant materials are deemed safe for packaging

fresh produce (Restuccia et al., 2010). Environmentally friendly packaging materials that claim to be biodegradable or compostable must fulfill specific standards and receive certifications. Standards for testing and certifying the biodegradability and compostability of materials have been developed by organizations like ASTM International and the European Committee for Standardization (CEN); certifications such as ASTM D6400 in the USA and EN 13432 in Europe are accepted worldwide (Cooper, 2013). Numerous groups provide certifications for environmentally friendly packaging materials. For example, the Forest Stewardship Council (FSC) certifies packaging made of paper and wood that is sourced responsibly, and the Cradle to Cradle Certified™ program evaluates products for their effects on the environment and society over the course of their lifecycle (McDonough and Braungart, 2002).

For producers and packaging manufacturers, navigating the regulatory environment and obtaining the necessary certifications can be a challenging process. In addition to being required by law, following these certifications and standards is crucial for gaining the trust of clients and advancing broader sustainability goals.

3. Case Studies: Achievements in Using Eco-Friendly Packaging Techniques

One notable by-product is jackfruit waste, which includes the peel, seeds, straw, and core and accounts for 60–70% of the total weight (Subburamu et al., 1992; Cheok et al., 2018). According to Ooi et al. (2011), flour made from dehydrating jackfruit leftovers can be utilized to make food packaging. Biodegradable packaging films can be produced by combining these bio-substances with appropriate synthetic polymers. Similarly, Sarebanha and Farhan (2018) discovered that flour made from jackfruit by-products is a cheap alternative that can be used as packaging material. Using jackfruit seed and durian seed flours, Retnowati et al. (2015) created biodegradable films, noting that the higher amylose content of the jackfruit seed flour enhanced the film's strength and fracture strain.

29-40% of the pineapple is made up of peels, which are typically discarded as waste during processing but have the potential to be a valuable biomass for industrial uses (Jatav and Bhattacharya, 2024). According to

Bardiya et al. (1996), they are abundant in cellulose, hemicellulose, lignin, and pectin. Chumee and Khemmakama (2014) used a two-step procedure to extract cellulose from pineapple peels, which they then etherified to create carboxymethyl cellulose (CMC). Bioplastics were produced using the resultant CMC.

Approximately 15-20% of the mango fruit's peel and 20-60% of its seeds are thrown away as waste. Produced in large quantities, this mango waste is rich in a number of bioactive chemicals and can be used to create biofilms (Sagar et al., 2018; Trigo et al., 2020). As demonstrated by Adilah et al. (2018), the application of mango kernel extract, for example, produces edible films that are stronger, thicker, and have a lower water vapor permeability. To store cashew nuts, Rambabu et al. (2019) used the prepared polymer to study the addition of mango leaf extract to chitosan. Cashews kept in films with 3% and 5% mango leaf extract demonstrated a high level of resistance to oxidation.

Coconuts that are soft and green are also excellent sources of cellulose and fiber. In their 2017 study, Cerqueira et al. (2017) created biodegradable films using cassava and potato starch and cellulose nanocrystals made from coconut fiber. Cassava starch was used in an integrated sustainable process for package development, as reported by Tumwesigye et al. (2016). Cassava is classified as either sweet or bitter. Cassia sweets can be eaten. Over the past ten years, the use of sweet cassava for industrial purposes has changed. Africa alone produces about 162.5 million tons of cassava, or nearly half of the world's total production (Tumwesigye et al., 2016).

Ripe Pratal banana peel flour is a promising ingredient for the production of bio-films, according to Faria et al. (2018). By combining banana peel extract with chitosan to create a composite film, Zhang et al. (2020) described a novel way to use banana peels that increased the shelf life of apples after harvest and served as an antioxidant. Furthermore, lysozyme added to a jackfruit-based film offered protection against *Micrococcus lysodeikticus*, according to Bonomo et al. (2018).

Pomegranate waste, primarily the peel, seed, and pomace produced by the juice and jam industries, has been recycled for a number of studies (Dilucia et al., 2020). Using pomegranate peel powder to create biodegradable films has been the subject of recent studies. Hanani et al. (2019) used fish gelatin and

pomegranate peel powder (PPP) to create active packaging films. It was discovered that PPP had strong antioxidant and antimicrobial properties.

Paper and paperboard are common materials used to produce cardboard boxes and cartons, among other types of packaging. The use of these environmentally friendly materials has increased significantly, especially in response to growing awareness of the issues surrounding plastic waste. Egg cartons and packaging for consumer durables that offer protection and cushioning are frequently made from pulp-based materials (Wever and Twede, 2007). Cellulosic fiber is widely utilized in the packaging of foods and drinks. For instance, cellulose acetate and cellulose triacetate are used as rigid wrapping films because of their poor gas and moisture barrier qualities, whereas cellophane is frequently used to package food items. A US-based company sells “Nature Flex” which has good gas barrier qualities, a long shelf life, printability, and a broad heat seal range (Abdul Khalil et al., 2016). “Fibre Forms” is a renewable packaging material that was first introduced by a Swedish company in 2009. Because of its exceptional strength, elasticity, and purity, “Fibre Forms” packaging is suitable for direct food contact. Milk, juices, and other liquids are packaged in “Pure-Pak” cartons, which have a PE layer, produced by a top supplier of food packaging (Flisberg et al., 2009). Furthermore, there is a lot of promise for using cellulose composites in corrugated boards. Also Tervahartiala et al. (2018) reported a comparative study of various pulp materials for this application.

4. Challenges and Future Prospects: Advancing Green Packaging in the Produce Supply Chain

Reducing waste and promoting sustainability in the produce industry are important issues, and using green packaging techniques may help achieve these goals. Consumer education is also crucial because many consumers may not be completely aware of the environmental benefits of eco-friendly packaging. Continuous innovation and R&D are also essential for advancing green packaging practices because businesses need to invest in R&D to find new materials, technologies, and design strategies that balance sustainability and functionality.

The fruit and vegetable supply chain's use of green packaging has a promising future thanks to improvements in production methods, smart packaging technologies, consumer-focused solutions, government support, and increased environmental consciousness. Environmentally friendly packaging material research and development should focus on improving barrier qualities, extending shelf lives, and lowering costs. Smart packaging technologies offer businesses the chance to optimize supply chain operations, minimize waste, and maintain product quality through their advanced monitoring and data collection capabilities. A competitive edge may also be at stake for businesses that prioritize eco-friendly operations as consumer demand for sustainable packaging increases.

Conclusion

The fruits and vegetables industry is gradually adopting sustainable packaging to address environmental concerns, reduce waste, and meet consumer demands for eco-friendly practices. The primary forces behind this shift are consumer preferences for transparent packaging, eco-friendly materials, less plastic, and thoughtful packaging techniques. By reducing resource consumption, carbon emissions, and plastic waste, sustainable packaging promotes environmental stewardship and global sustainability goals. Innovations in biodegradable films, edible packaging, bio-based polymers, and smart packaging technologies are driving the adoption of sustainable packaging solutions. Market trends and regulatory frameworks are implementing laws, certifications, and incentives to promote sustainable packaging practices. Sustainable packaging can increase consumer engagement by promoting information, traceability, and a sense of environmental responsibility.

Reducing food waste is also greatly aided by extending shelf life, preserving product quality, and increasing supply chain effectiveness. Businesses that employ sustainable packaging methods can improve the image of their brand, save costs, gain a competitive edge, and benefit the environment. The continuous development of sustainable fruit and vegetable packaging will be influenced by innovation, consumer values, and a shared commitment to environmental responsibility. As we proceed, we can expect a more resilient and environmentally responsible supply chain, reduced waste, and a better future for coming generations.

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CHAPTER 10

THE USE OF FIRETHORN (*Pyracantha Coccinea*) IN LANDSCAPE ARCHITECTURE

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1. Introduction

The acceleration of population growth, the widespread expansion of urbanization, and the increasing impacts of climate change have rendered the existence of urban green spaces an indispensable necessity in today's cities. The migration of people from rural to urban areas, in particular, has resulted in cities accommodating populations that exceed their carrying capacities. Consequently, in densely built-up urban environments, the need for green spaces has become inevitable not only for aesthetic reasons but also for ecological and psychological well-being. Over the past century, the increase in population density and unplanned urbanization have significantly intensified pressure on natural environments; as a result of this pressure, ecosystems have deteriorated and habitats have undergone substantial transformations (Altan, 2000; Aguilera et al., 2019). Human-induced activities have progressively led to the degradation and destruction of vegetation in natural landscapes. Therefore, there has emerged a growing necessity to design urban open and green spaces that reinforce the interaction between humans and nature while simultaneously supporting individuals' sense of connection to the natural environment (Çay, 2010; Sarı and Karaşah, 2018).

Plants constitute the fundamental components of ecosystems and possess a significant potential for mitigating pollution risks that arise in urban environments (Lohe et al., 2015). In particular, trees and shrubs make substantial contributions to the reduction of air pollution and other environmental contaminants through their morphological and physiological characteristics. In the selection of ornamental plants and shrub species used in urban parks, factors such as visual and ecological value, resistance to pollutants, tolerance levels, and adaptability to climatic conditions are considered among the primary criteria (Delaman and Farahmand, 2017). The sustainability of green spaces is directly related to the capacity of the plant species used in these areas to adapt to prevailing climatic conditions. In this context, the key to sustainable green space design lies in the selection of suitable ornamental plant species capable of adapting to the urban environment (Asgarzadeh et al., 2014).

2. Botanical Characteristics Of Firethorn (*Pyracantha coccinea*)

Species belonging to the *Pyracantha* genus exhibit a high degree of similarity in terms of flower and fruit morphology, with many species sharing common morphological traits. Egolf and Andrick (1995) emphasized that, due to the overlapping distribution ranges of different *Pyracantha* populations, these may actually represent hybridizing groups within the same species. Therefore, most species are primarily distinguished based on leaf characteristics. However, the presence of different leaf forms (leaf dimorphism) on the same plant or within the same population reduces the reliability of taxonomic evaluations conducted on limited specimens.

The genus largely consists of varieties with unknown or insufficiently defined origins, and preliminary studies employing enzymatic markers have enabled the identification of taxa at the varietal level (Cadic et al., 1992). Moreover, Meyer et al. (1994) and Egolf and Andrick (1995) reported the existence of hundreds of cultivars within the genus.

In this context, the present study examines the Firethorn (*Pyracantha coccinea*) species in terms of its botanical and morphological characteristics, as well as its aesthetic, functional, and ecological contributions to landscape design and its traditional and environmental uses. In the face of increasing urbanization and the pressures of climate change, the importance of selecting appropriate species for sustainable landscape designs has become ever more critical. With its aesthetic value, ecological functions, adaptive capacity, and versatile usage potential, *Pyracantha coccinea* stands out as a remarkable plant material for urban green space planning.



Figure 1. Leaf, flower, and fruit morphology of *Pyracantha coccinea* (The image was generated by the author using artificial intelligence).

The genus *Pyracantha*, belonging to the family Rosaceae, comprises 16 woody, evergreen, and spiny shrub species (Plant List, 2013; Serviss, 2009). Among these are *P. angustifolia* (Franch.) C.K. Schneid., *P. atalantioides* (Hance) Stapf, *P. coccinea* M. Roem., *P. crenatoserrata* (Hance) Rehder, *P. crenulata* (D. Don) Roem., *P. densiflora* T.T. Yu, *P. fortuneana* (Maxim.) Li, *P. inermis* J.E. Vidal, *P. koidzumii* (Hayata) Rehder, and *P. rogersiana* (A.B. Jacks) Coltm.-Rog.

The Firethorn (*P. coccinea*) is a spiny, densely branched shrub that can grow up to 3 meters in height. Young shoots are grayish-yellow and tomentose, gradually becoming glabrous and turning dark purplish with age (eFloras, 2008). Leaves are arranged alternately, with dull dark green upper surfaces and grayish lower surfaces. The leaf blades range from oblong to oblanceolate-oblong, measuring 10–50 mm in length and 4–12 mm in width (Figure 1). The leaf tips possess a characteristic small notch. Young leaves are pubescent but become glabrous as they mature (Retief and Meyer, 2017).

Flowers are arranged in compound corymb-like clusters, measuring 2–4 cm in diameter, with each cluster containing several to about 30 flowers. The pedicels and sepals are grayish and tomentose in texture. Each flower consists of five white petals (5–12 mm), five small sepals, and approximately 20 stamens (Figure 1). The fruits are pome-type false fruits that are grayish-green

when immature, turning orange-red or orange-yellow upon ripening (Henderson, 2011). Mature fruits are 5–8 mm in diameter, with green or gray remnants of sepals persisting on the fruit surface (Csurhes et al., 2016; eFloras, 2008; Nesom, 2010; Weber, 2003) (Figure 2).



Figure 2. Flower and mature fruit appearance of *Pyracantha coccinea* (The image was generated by the author using artificial intelligence).

Pyracantha coccinea is distributed across various altitudes in China, the Himalayas, Italy, and Türkiye, and is commonly known by vernacular names such as “tavşan elması” (rabbit apple), “köpek elması” (dog apple), and “kuş alıcı” (bird catcher) in Türkiye (Popoviciu et al., 2020). All members of the genus primarily reproduce by seed (PIER, 2018), and the seeds are dispersed by animals, water, gravity, soil movements, and discarded plant material (Debussche and Isenmann, 1994; Bass, 1996; Williams et al., 2000).

Among these mechanisms, birds are considered the most important dispersal vectors. The bright-colored fruits attract numerous bird species, and the seeds consumed by birds are later excreted in new locations, thereby facilitating the plant’s spread beyond its natural habitats (Williams et al., 2000).

3. Uses of *Pyracantha coccinea* in Landscape Architecture

Pyracantha coccinea (Firethorn) is a widely preferred species in landscape architecture due to its dense foliage, thorny branches, white flowers, and red-orange ornamental fruits. It stands out in urban parks, residential

gardens, roadsides, and medians for its strong aesthetic appeal, while also offering significant functional advantages owing to its low maintenance requirements and resistance to drought and frost (Weber, 2017; VRO, 2020).

The species is primarily utilized in the ornamental plant industry (Bass, 1996). It is particularly favored in regions exposed to frost for its tolerance to cold climatic conditions and its striking orange fruits that remain visible during autumn and winter months. Studies conducted in Argentina have revealed that this species possesses not only ornamental value but also ethnobotanical importance, providing ecosystem services such as shading and serving as a food source for birds (Martínez and Manzano-García, 2019).

Thanks to its dense canopy structure and shading capacity, *P. coccinea* mechanically protects young tree and shrub seedlings from herbivorous animals, particularly ungulates; this contributes to the enhancement of native species diversity (Tecco et al., 2006). Therefore, *Pyracantha coccinea* represents a valuable plant material with remarkable aesthetic, functional, and ecological contributions, making it suitable for both urban and rural landscape applications (Figure 3).



Figure 3. Application of *Pyracantha coccinea* as a hedge plant along a garden wall, demonstrating its dense branching and thorny structure (The image was generated by the author using artificial intelligence).

Aesthetic Contributions: Due to its evergreen nature, *Pyracantha coccinea* provides year-round visual continuity in landscape compositions. Its white blossoms during spring and summer, together with the red-orange fruits that mature in autumn and persist through winter, offer striking seasonal color variations. These features make the species highly attractive for use not only in parks, gardens, roadsides, medians, and residential landscapes but also in commercial landscape applications (Dong et al., 2017; Henderson, 2011; Csurhes et al., 2016).

Functional Contributions: *Pyracantha coccinea* is widely used as a hedge plant for security and boundary definition purposes owing to its dense foliage and thorny branches. This characteristic makes it a preferred species for demarcating property boundaries in residential areas, public institutions, and park and garden designs. The dense and rigid branches of the plant form a natural barrier against unwanted intrusion, thus offering an effective contribution to site security (Bromilow, 2001; Henderson, 2011).

Beyond its barrier function, *P. coccinea* is also utilized decoratively in espalier applications on walls and pergolas. Such practices allow the plant's natural form to be trained and controlled, providing both aesthetic enhancement and functional benefits. Its dense branching also enables the species to act as a windbreak, mitigating adverse wind effects and making it suitable for use in agricultural landscapes as well (Csurhes et al., 2016).

The plant's root system and dense shrub form contribute significantly to soil stabilization, particularly on sloped terrains, thus playing an important role in erosion control. This characteristic allows the species to be effectively used along rural roadsides, medians, and embankments to prevent soil displacement (Giantomasi et al., 2008). Consequently, *Pyracantha coccinea* is preferred in landscape designs not only for its visual aesthetics but also for its soil and environmental conservation functions.

Ecological Contributions: *Pyracantha coccinea* provides an important food source for a variety of fauna, particularly birds, due to its abundant and brightly colored fruits. Its dense foliage also offers protective habitats for small birds, thereby enhancing the species' ecological value (Adams, 2020; Williams et al., 2000).

Birds are known to be the primary dispersal vectors for *Pyracantha* species. The vivid red fruits are highly attractive to numerous bird species

(Figure 4), which is why *Pyracantha* is recognized as one of the plant genera most effectively dispersed by birds (Staples et al., 2009). Birds consuming the fruits excrete the seeds in new locations during perching or flight, facilitating the plant's spread beyond its natural range (Adams, 2020).



Figure 4. Birds feeding on the fruits of *Pyracantha coccinea* (The image was generated by the author using artificial intelligence).

A striking example of this phenomenon can be observed in New South Wales, Australia, where the pied currawong (*Strepera graculina* Shaw, 1790) shows a preference for *Pyracantha* fruits over those of other plant species and acts as one of the main dispersal vectors (Crossman et al., 2002). Consequently, birds facilitate the escape of cultivated individuals from gardens into natural habitats, thereby increasing the species' invasive potential (Bass, 1996).

4. Traditional and Environmental Uses

Recent studies have demonstrated that the fruits of *Pyracantha coccinea* possess not only nutritional and medicinal value but also potential for environmental applications. It has been revealed that the fruits can be used for the biosorptive removal of certain basic dyes and that the species may serve as a biomonitor plant capable of indicating the accumulation of heavy metals such as copper and nickel (Akar et al., 2009; Akguc et al., 2010).

This shrub, belonging to the family Rosaceae, bears small, bright red fruits that, in addition to their ornamental appeal, can be utilized in the

preparation of tea, marmalade, jam, jelly, and culinary sauces (Fico et al., 2000). These fruits have been reported to exhibit antioxidant and antimicrobial properties and are traditionally used in folk medicine, particularly for cardiovascular health; however, scientific studies on these uses remain limited (Sarıkürkçü and Tepe, 2015).

5. Conclusion

In this study, the Firethorn (*Pyracantha coccinea*) species was comprehensively examined from the perspective of landscape architecture and evaluated in multiple dimensions. Its botanical and morphological characteristics were described in detail, its distribution areas and propagation mechanisms were identified, and its aesthetic, functional, and ecological contributions to landscape design were discussed. With its evergreen structure, white flowers in spring and summer, and bright red-orange fruits in autumn and winter, *P. coccinea* offers seasonal visual changes that make it a valuable plant ensuring year-round continuity in urban landscapes.

From a functional standpoint, the species' dense foliage and thorny branches allow its use as a hedge, barrier, and security plant. Its compact branching structure enables it to act as a windbreak and contributes to erosion control, particularly on sloped terrains. Ecologically, the fruits serve as an important food source for birds and other animals, while the dense foliage provides shelter for small bird species, thus supporting biodiversity. In this sense, *Pyracantha coccinea* is not merely a visual element but also a species that provides functional contributions to urban ecosystems.

The study also highlighted the species' traditional and ethnobotanical uses. Its fruits are utilized in the preparation of food products such as jams, marmalades, sauces, and wines, and in folk medicine for their tonic and cardioprotective properties. Environmentally, *P. coccinea* has shown potential as a biomonitor for heavy metal accumulation and as a biosorbent in pollution mitigation studies. These multifaceted uses reveal that the species holds value not only in landscape architecture but also in cultural, medicinal, and environmental contexts.

Considering the ecological pressures caused by increasing urbanization and climate change, *Pyracantha coccinea* stands out as a noteworthy species for sustainable green space planning due to its low maintenance requirements and

tolerance to drought and frost. However, the literature also indicates that the species may exhibit invasive behavior in certain regions. Therefore, ecological risks should be taken into account in its use, with careful site selection and controlled propagation strategies.

In conclusion, with its aesthetic, functional, ecological, and traditional applications, *Pyracantha coccinea* possesses significant potential for both urban and rural landscape planning. Nevertheless, to ensure its effective and sustainable utilization, future research should focus on investigating its adaptability under different climatic and habitat conditions, developing controlled-use models in landscape practices, and promoting propagation studies through biotechnological approaches.

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CHAPTER 11

GREEN PACKAGING REVOLUTION: SUSTAINABLE AND ECO-FRIENDLY ADVANCEMENTS IN THE PACKAGING FOR FRUITS AND VEGETABLES

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1. Introduction: The Imperative of Sustainable Packaging in the Food Industry

According to Shinde et al. (2019), jackfruit, pineapple, and mango produce 60%, 54%, and 35-60% of waste, respectively. These fruit and vegetable wastes have significant potential for the development of films, coatings, and packaging materials, as they are rich sources of fiber, carboxymethyl cellulose, starch, and other valuable compounds. Natural fibers are biodegradable, non-carcinogenic, and cost-effective, making them an attractive option for sustainable material development. Utilizing agricultural and food waste to manufacture value-added products can significantly reduce environmental pressure. Global demand for bio-packaging is on the rise. Bio-packaging, also known as “Green packaging”, focuses on converting agricultural and agro-food residues into naturally biodegradable packaging materials (Guillard et al., 2018). These materials originate from biological sources and benefit the environment through their natural decomposition. They are produced using waste products, biomass, and natural resources such as jackfruit (Lothfy et al., 2018), banana peels (Mohapatra et al., 2015), coffee grounds (Moustafa et al., 2017a), date kernels, organic waste (Goswami et al., 2015), agricultural residues (Zulkafli, 2014), newspaper waste (Joshi et al., 2015), oil palm empty fruit bunch (Isroi et al., 2017), sugar cane (Khosravi-Darani and Bucci, 2015), corn starch (Keziah et al., 2018), potato starch (Schon and Schwartz, 2014), rice straw (Agustin et al., 2014), rapeseed oil (Delgado et al., 2018), vegetable oil, cellulose from plants, starch, cotton, and bacterial sources (Shamsuddin et al., 2017). Additionally, they can contain particles that are nanoscale, such as polysaccharides (Jabeen et al., 2015). These particles are degraded by microorganisms that occur naturally, such as bacteria (Ali et al., 2017; Pradhan, 2014; Das et al., 2018), algae, and fungi (Momani, 2009). Packaging constitutes a critical component of marketing by facilitating the marketability of the crops and has a vital role in ensuring the safe, efficient transport of perishable products from production sites to end users. Although packaging is essential to the supply chain, it has long been associated with significant environmental concerns. Reliance on conventional packaging materials, often non-biodegradable and resource-intensive, has contributed to issues such as plastic pollution, greenhouse gas emissions, and the depletion of natural resources (Nagy and Kuti, 2016). Global plastic production has surged

since the 1950s, with annual production now exceeding approximately 450 million metric tons. Although plastics provide convenience and high value, concerns about their worldwide environmental impact are mounting. More than 340 million tons of plastic waste are generated globally, with about 46% stemming from the packaging industry (Tsakona and Rucevska, 2020). This waste is mainly generated by products with short lifespans, typically lasting six months or less, in contrast to the building and construction industries, where the average product lifespan is 35 years (Geyer et al., 2017). Despite an increase in the recycling rate of plastics from 0% in the 1980s to 19.5% in recent years, the majority of packaging materials, especially flexible food packaging, remain non-recyclable. Approximately 95% of current plastic packaging, primarily composed of polyolefins and polyethylene terephthalate (PET), is not recycled and is disposed of in landfills after a single use. This practice results in an estimated economic loss of \$80-120 billion annually (MacArthur, 2017). This ongoing problem stems from the specific material properties required for plastic packaging, including lightweight micro-scale thickness, high toughness, complex multilayer structures, and vulnerability to contamination from direct food contact. Recognizing the urgency of addressing these environmental concerns, the produce industry has initiated the “Green Packaging Revolution,” an innovative movement focused on sustainable packaging solutions. This revolution indicates a crucial switch in sustainable and environmentally friendly packaging solutions aimed at reducing waste, limiting the impact on the environment, and extending the freshness and shelf life of fruits and vegetables. It claims to balance the necessity of packaging with the requirement to protect our planet (Zhou, 2014).

This review provides comprehensive information on the various aspects of the “Green Packaging Revolution,” with a particular focus on fruits and vegetables. It examines innovations, materials, and technologies that are ushering packaging into a new era—one that meets the demands of increasingly conscientious consumers while advancing global sustainability goals.

From biodegradable films and smart packaging to minimalist design principles, this review explores the cutting-edge landscape of packaging technology that is transforming the handling, distribution, and consumption of fresh produce. Furthermore, this review analyzes the diverse benefits associated with sustainable packaging in the produce industry.

Not only does sustainable packaging reduce the carbon footprint of the sector, but it also plays a pivotal role in minimizing food waste, which is a challenge that has become increasingly significant amid growing populations and changing consumption patterns. By examining case studies, market trends, regulatory frameworks, and consumer preferences, this review aims to provide a comprehensive overview of the current state of sustainable packaging in the produce industry and its potential for future development.

2. Sustainable Packaging Materials: Innovations and Applications

The demand for sustainable packaging in the fruit and vegetable sector has led to significant advancements in packaging materials. Traditional materials, including single-use plastics and non-recyclable metals, have been scrutinized for their environmental impact. In response, researchers, engineers, and industry leaders have developed and implemented sustainable alternatives that aim to reduce the carbon footprint of packaging while enhancing the quality and safety of fresh produce. This review examines key sustainable packaging materials, recent innovations, and their various applications within the produce industry (Ncube et al., 2020).

2.1. Biodegradable and Biobased Polymers

A significant advancement in sustainable packaging is the development of biodegradable films and coatings (Shima et al., 2020). Plant-based fibers are also take important place under this heading and this kind of packages' source are could be classified as micro-fibrillated cellulose and agricultural waste. Micro-fibrillated cellulose breaks down to a micro-level and is used to replace traditional plastic in packaging, offering a biodegradable and sustainable option. Agricultural waste can be determined as upcycling agricultural byproducts like rice straw and mushroom spawn into packaging materials is an innovative approach to reduce waste and create ecofriendly packaging (Cordeiro et al., 2025). In this manner various plant parts, such as peels, leaves, stems, flowers, roots, and seeds, contain important biological compounds with antibacterial, antioxidant, anti-carcinogenic, and antifungal properties (Jafarzadeh et al., 2020), and are preferred because of these important characteristics.

Composed of organic materials such as starch, cellulose, or chitosan, these films provide an effective alternative to traditional plastics. They serve as a protective barrier that extends the shelf life of fruits and vegetables, while ultimately decomposing into harmless substances, thereby reducing waste and pollution. Additionally, these materials can be used to create transparent windows in packaging, enabling consumers to view the product without compromising its freshness. Biodegradable packaging can be broken down by microorganisms such as bacteria, fungi, and algae, or by marine water, into water, carbon dioxide, and humus. This decomposition can occur through either anaerobic or aerobic fermentation, during which microorganisms secrete extracellular enzymes that break down polymer chains into smaller, degradable products. Studies indicate that polylactic acid (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) bionanocomposites are biodegradable in both fresh and marine water, with faster degradation observed in freshwater. This difference is likely due to higher microbial activity in freshwater, where microorganisms and algae more effectively attack and break down polymeric chains (Moustafa et al., 2017b).

As sustainable packaging materials, bio-based polymers which are derived from renewable resources like sugarcane, lipids, corn, wheat, potatoes, wood pulp, and cotton are gaining popularity (Garrison et al., 2016). These biodegradable polymers can break down in certain environmental conditions, including temperature, humidity, oxygen availability, and the presence of living organisms. The environmental impact of this degradation process is negligible, and no hazardous materials are left behind. Since biopolymer-based packaging materials are safe, biodegradable, and biocompatible, they are being researched as an alternative to conventional plastics (Khalid et al., 2021).

Natural, synthetic, and microbial biopolymers are the three categories into which biodegradable and biobased polymers are divided according to their source materials. To increase these polymers' biodegradability in the environment, ingredients like starch, organic acids, and synthetic carbonyls are added during the production process (Cywar et al., 2022). One advantage of these polymers is that they lessen the carbon footprint of traditional plastics and dependency on fossil fuels. From trays to bottles, they can be used to create a variety of packaging solutions while retaining the required flexibility and durability (Morão and de Bie, 2024).

2.1.1. Natural biopolymers

These materials, which include cellulose, alginate, starch, chitosan (CS), pectin, gum, carrageenan, pullulan, and their derivatives, are naturally occurring polysaccharides, lipids, and proteins (Balart et al., 2021). However, these materials pose certain difficulties when used in the production of biopolymers. For example, because biopolymer-based materials are hydrophilic, they have poor water vapor barrier qualities, such as cellulose and starch. For the reason of this property, biopolymer films lose some of their mechanical strength and become less stable over time, which leaves them vulnerable to moisture absorption (Ochoa et al., 2017; Chaichi et al., 2023; Bizymis et al., 2023).

2.1.2. Synthetic biopolymers

Aliphatic-aromatic copolymers, aliphatic polyesters, polylactides, and aliphatic copolymers (CPLA) are examples of synthetic biopolymers, which are typically made chemically from biological monomers. They come from oil-based monomers like polycaprolactone and renewable bio-based monomers like polylactic acid (PLA) (Mangaraj et al., 2019). One excellent example of a polymer that can be chemically made using renewable bio-based monomers is PLA, a biopolyester polymerized from lactic acid monomers (Gonçalves et al., 2017).

2.1.3. Microbial Biopolymers

Microbial biopolymers are created by bacteria or microorganisms, usually through genetic modification. One prominent example is the bacterial fermentation of lipids and carbohydrates to produce polyhydroxyalkanoates (PHA). PHA polyesters are derived from renewable resources and are biodegradable and biocompatible (Mangaraj et al., 2019).

These polymers have strong UV resistance, are insoluble in water, and are comparatively resistant to hydrolytic degradation. They dissolve in chloroform and chlorinated hydrocarbons and are non-toxic. PHAs, however, are not very resistant to bases and acids (Raza et al., 2018). PHAs are promising materials that can compete with conventional plastics made from fossil fuels in the food packaging industry because of their hydrophobic qualities and flexible mechanical features (Nilsen-Nygaard et al., 2021).

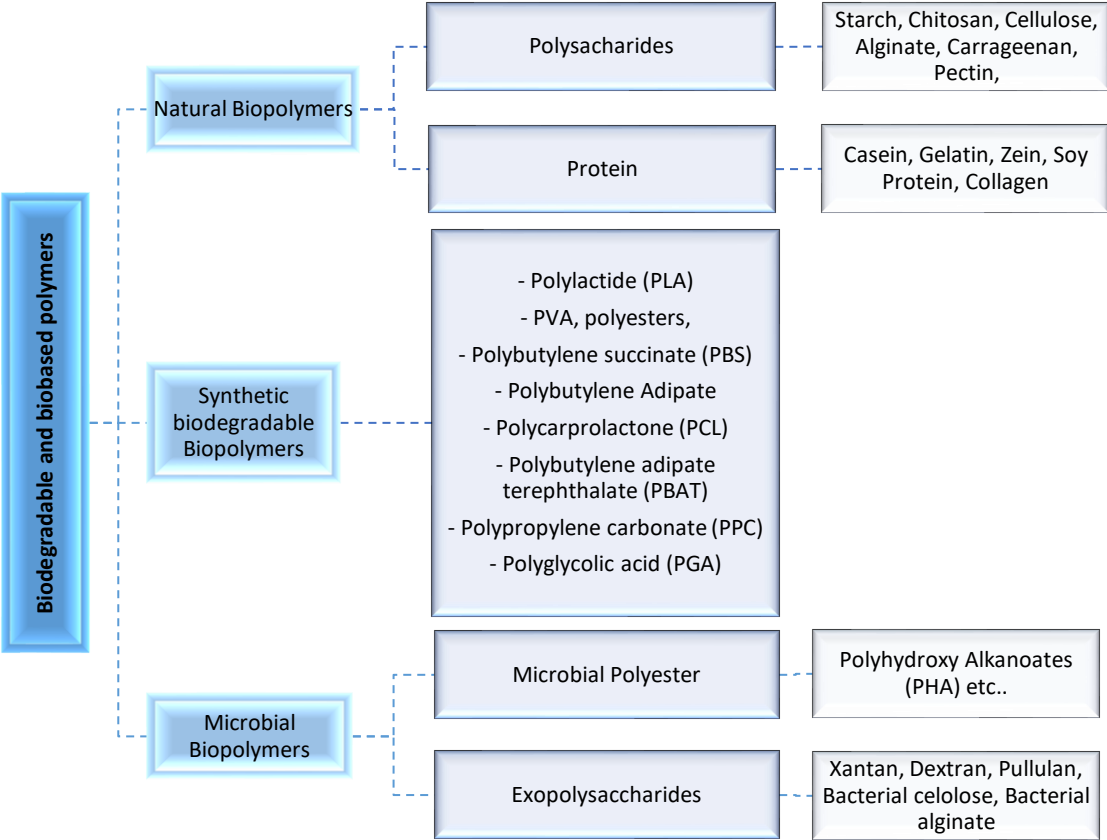


Figure 1. Classification of biodegradable polymers (Dirpan et al., 2023).

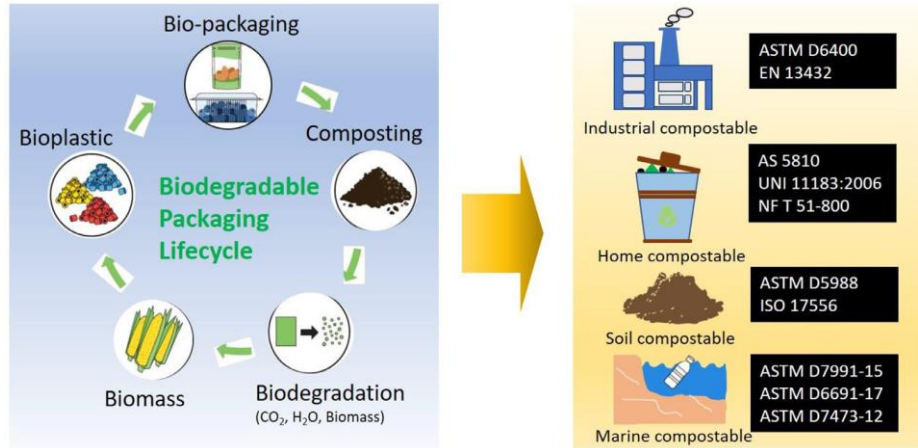


Figure 2. Schematic of biodegradable packaging lifecycle and different compostable standards (Wu et al., 2021).

2.2. Smart packaging technology

The way we handle and keep an eye on the safety and quality of fruits and vegetables has evolved with the introduction of smart packaging technologies into the fresh produce market. In addition to providing consumers with information and confidence regarding the products they consume, these technologies address important issues like food waste and food safety. By enhancing quality, safety, and customer satisfaction, smart packaging technologies are revolutionizing the fresh produce sector, as this section illustrates (Corradini, 2018; Ganeson et al., 2023).

Intelligent and active packaging design is made possible by smart packaging technologies. By integrating sensors, data monitoring, and responsive features into packaging materials, intelligent packaging can monitor food quality and inform consumers of this information, providing real-time information and environmental control. For example, intelligent packaging can identify bacteria in food and notify the consumer, reducing the risk of consuming tainted food and contracting a foodborne illness (Gregor-Svetec, 2018; Müller and Schmid, 2019).

On the other hand, the nanostructures found in active nanotechnology packaging enhance food quality and increase shelf life. These nanostructures can reduce food waste and improve sustainability by preventing the growth of bacteria and fungi, removing unwanted odors and tastes, protecting food from oxidation and degradation, and improving food color, texture, and taste (Adeyemi and Fawole, 2023; Sharma et al., 2023).

The ability of smart packaging to continuously monitor multiple parameters in real time is one of its unique features. Temperature, humidity, gas composition, and other relevant parameters can be measured by embedded sensors in the packaging. This ongoing observation guarantees that the environmental conditions for fresh produce stay within suitable ranges for maintaining quality (Corradini, 2018).

Smart packaging can reduce food waste throughout the supply chain by monitoring these factors, slowing the ripening process, halting the growth of spoilage microorganisms, and preserving the freshness and quality of fruits and vegetables. In addition to helping the environment, this saves money for manufacturers and retailers. For example, the packaging may sound an alert if the temperature exceeds a set point, allowing for prompt action to stop spoiling.

During storage and transit, this feature is crucial (Wang et al., 2015; Ghaani et al., 2016).

Smart packaging is crucial to ensuring food safety, which is of the highest importance. Sensors are able to identify dangerous pathogens or gases associated with contamination or spoiling. It is easier to remove potentially dangerous products from the supply chain in a timely manner when an incident is detected because the packaging can notify the appropriate parties (Fuertes et al., 2016).

Additionally, smart packaging can include RFID tags, QR codes, or other traceability components that give supply chain participants and consumers access to detailed information about the product's origin, handling, and storage conditions (Kaur et al., 2011; Bibi et al., 2017). This increases customer confidence and engagement. Customers can make informed purchasing decisions by, for example, scanning the QR codes on the product's packaging to get information about its freshness and safety. Furthermore, sustainability can be considered when designing smart packaging. Certain battery-free systems that rely on energy harvesting technologies are eco-friendly. By decreasing food waste, smart packaging indirectly contributes to sustainability goals (Cabot et al., 2019; Chen et al., 2020a).

A thriving and rapidly expanding area of innovation is represented by these eco-friendly packaging materials. Their uses in the produce business go beyond simple preservation and protection; they also help to cut down on food waste, lessen the impact on the environment, and satisfy the needs of ethical customers.

Table 1. Research on green packaging to enhance the physicochemical characteristics of fruits and vegetables

Application	Coating or film matrix	Active / Antioxidant Compound	Characteristic Packaging/Improved Features	Reference
Strawberry	PBAT*	<i>Moringa oleifera</i>	<i>Moringa oleifera</i> (MO) decreased fungal contamination. Poly(butylene adipate-co-terephthalate) (PBAT) films containing 1% MO performed well as packaging for storing strawberries.	Verdi et al. (2021)
Avocado fresh cut	PLA	Natural olive wastewater extract	The films enhanced antioxidant activity and prolonged the equilibrium time by increasing the concentration of the antioxidant.	Apicella et al. (2021)
Mango	PLA	Nano-Ag and nano-TiO ₂	The nano-composite film effectively minimized the loss of mango firmness and prevented adverse changes in vitamin C content, color, microbial properties, and total acidity compared to control films throughout the storage period.	Chi et al. (2019)
Fresh-cut apple	PLA	ZnO	The results demonstrated that the polylactic acid (PLA) film incorporated with Zinc oxide (ZnO) nanoparticles better maintained the firmness, color, total phenolic, and sensory quality of fresh-cut apples for 14 days.	Li et al. (2017)
Blueberries	PLA	-	PLA containers extended the shelf life of blueberries at various storage temperatures.	Wu et al. (2021)
Strawberry and cherry tomatoes	Polyvinyl alcohol (PVA)	Citric acid/ Carboxymethyl chitosan	The films significantly reduced bacterial growth.	Wen et al. (2021)

Fresh-sliced okra	Cassava starch	Nano-Zno	The nano-composite film improved the quality of the product and could be effectively used for packaging fresh-sliced okra.	Fadeyibi (2019)
Food packaging	Pineapple peel	Chitosan	A better alternative for improving the shelf life of diverse food commodities.	Jatav and Bhattacharya (2024)
Cherry tomato	Jackfruit peel waste	-	The application of the active films significantly reduced the fungal growth on cherry tomato samples stored at 25°C for 7 days.	Shukor et al. (2021)
White grapes	Pomegranate peel extract	-	The application of coating treatment significantly maintained the postharvest shelf life of white grapes throughout the storage period.	Bodana et al. (2024)
Tomato	Mango kernel starch	-	Delayed ripening processes extend the shelf life of the product.	Nawab et al. (2017)
Lime fruit	Pectin	-	Had an important contribution in achieving longer shelf life and improving the product safety.	Maftoonazad and Ramaswamy (2019)
Plum fruit	Pectin	-	Had positive effects in increasing the antioxidative properties, extending the shelf life, and improving the quality of plum fruit.	Panahirad et al. (2020)

Fresh durian cut	Gelatin	Durian leaf extract	The incorporation of 0.5% durian leaf extract in a gelatin-based film was more effective in delaying oil oxidation. Additionally, the durian leaf extract did not increase the water vapor permeability of the gelatin films.	Joanne Kam et al. (2018)
Apples	Chitosan	Purple yam starch/glycerol	The application of the film on apples for four weeks maintained the fruit's quality. Glycerol was found to contribute to the thermal stability of the films.	Martins da Costa et al. (2020)
Active food packaging	PVA	Apple pomace	Had positive effects in improving the antioxidant properties and increasing the phenolic content.	Gaikwad et al. (2016)
	Pea starch, Guar gum	Banana peel	Improved antioxidant properties, improved tensile and barrier properties (WVP decrease).	Saberi et al. (2017)
Bell peppers	Pectin	Mulberry leaf extract	The mechanical properties of the films improved their barrier properties. The active films exhibited high antioxidant and antimicrobial properties and had an important effect in leading to an increased shelf life of bell peppers.	Shivangi et al. (2021)
Banana	Chitosan	Leaf extract <i>Sonneratia caseolaris</i> (L.) Engl.)	Had positive effects in increasing antimicrobial activity and improving water vapor barriers, consequently resulting in coated bananas having a longer life.	Nguyen et al. (2020)
Food packaging	Pectin/Tara gum	Fruit pectin <i>Rubus chingii</i> Hu	The addition of gum increased the thickness and water resistance of the films, also improving their mechanical properties. Furthermore, the films exhibited increased antioxidant and antimicrobial activity.	Chen et al. (2020b)

Food packaging	Pea starch	Pumpkin seed starch	The addition of pumpkin seed starch improved the gas barrier properties and elongation at break of the films. However, they exhibited inferior tensile strength and high moisture absorption. Pumpkin seed starch also increased the hydrophobicity and decreased the degree of inflation of the film.	Xu et al. (2020)
Sweet cherries	Alginate and chitosan	Olive leaf extract	The process of ripening and the increase in anthocyanin content are delayed. A limited loss of ascorbic acid and total phenolic content was reported, along with an increase in antioxidant activity, which ultimately increased the shelf life of the sweet cherries.	Zam (2019)
Food packaging	Watermelon (<i>Citrullus lanatus</i>) rind pectin	Kiwifruit (<i>Actinidia chinensis</i>) peel extract	The film containing pectin obtained from watermelon peel exhibited better tensile strength and Young's modulus. The turbidity, elongation, and permeability to water vapor of the films also increased with the increasing concentration of kiwi peel extract.	Han & Song (2021)

*PBAT: Poly(butylene adipate-co-terephthalate); PLA: Polylactic acid; PVA: Polyvinyl alcohol

Conclusion

The food industry's drive to sustainable packaging is both a response to rising environmental concerns and a proactive step toward a circular economy. The vast waste generated by horticulture crops has long been a disposal problem, but these byproducts are now recognized as important materials for bio-packaging. These agricultural wastes, which are high in fibers, starches, and carboxymethyl cellulose, serve as critical raw materials for the creation of biodegradable films, bioplastics, and other environmentally friendly packaging solutions. This revolution, known as the "Green Packaging Revolution," is driven by advances in materials science and technology. Biodegradable films and smart packaging not only tackle the critical issue of plastic pollution, but they also improve food preservation and safety. Minimalist packaging design also assists by decreasing superfluous material use while maintaining functionality.

The benefits of using bio-packaging go beyond environmental sustainability. These technologies lower the carbon footprint of the entire packaging supply chain while also reducing food waste by improving horticulture product protection and shelf life. Case studies show that incorporating biodegradable packaging into the produce sector yields substantial environmental and economic benefits while also fulfilling changing regulatory demands and consumer demand for green products.

Market trends show a growing desire for sustainable packaging, with regulatory authorities supporting or regulating eco-friendly alternatives. Continued research and development are critical for overcoming current limitations in scalability, cost, and performance of bio-based materials. As these difficulties are addressed, bio-packaging made from agricultural waste is likely to become a common option, assisting the food industry's shift to more responsible production and consumption practices. Finally, sustainable packaging represents an important junction of innovation, environmental responsibility, and economic opportunity, establishing the produce business as a global leader in efforts to create a greener future.

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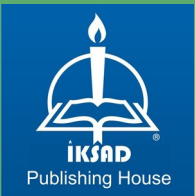
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