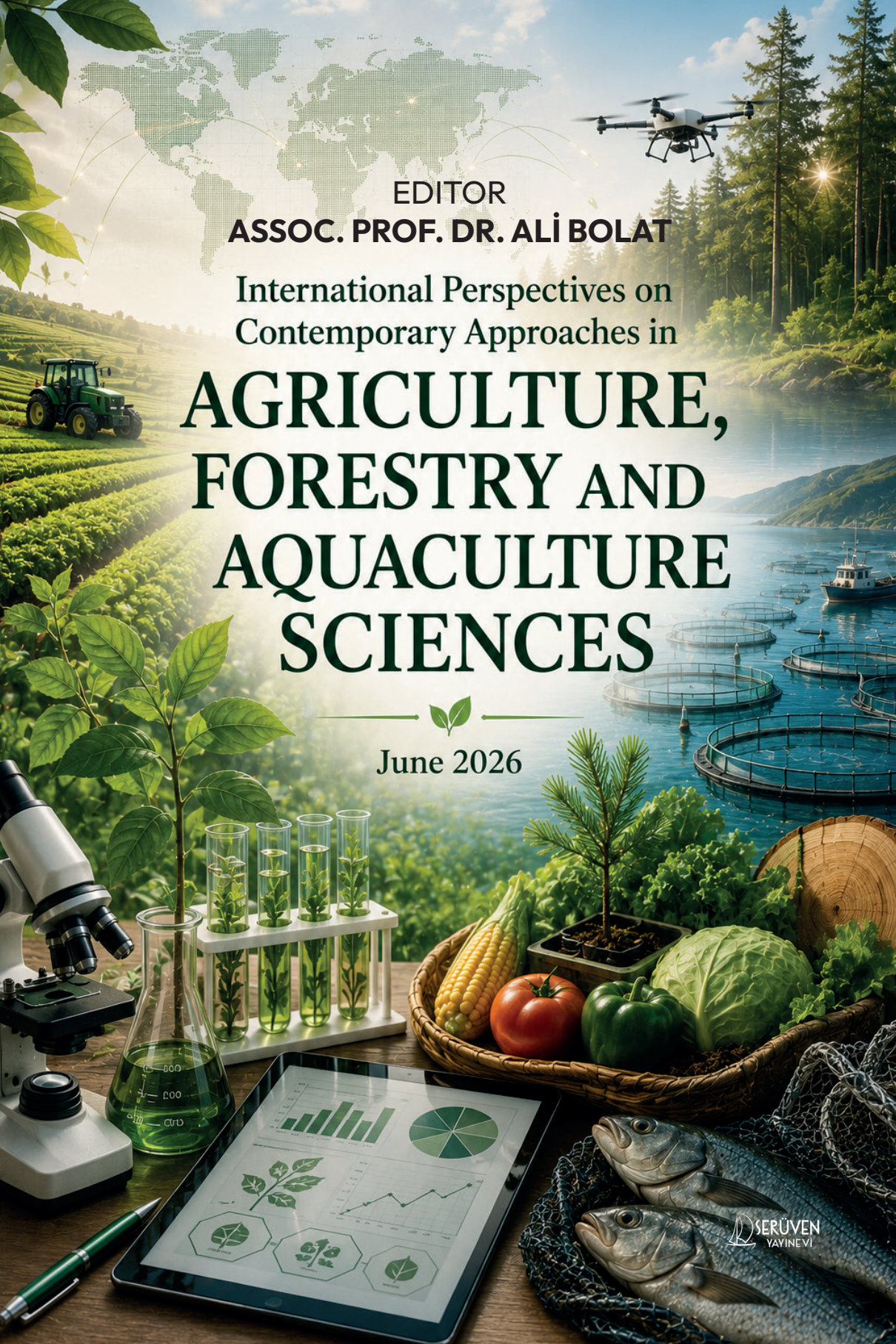

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Chapter 1

BIG DATA APPLICATIONS IN ORNAMENTAL PLANT PRODUCTION: OPPORTUNITIES, CHALLENGES AND FUTURE PERSPECTIVES

Fatih KEBELİ[1]
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Since its earliest existence, humanity has maintained a complex and multidimensional relationship with nature. Nutritional needs constituted the primary link between humans and the natural environment, shaping the direction and dynamics of this interaction. Within this context, agriculture can be defined as a deliberate and productive human intervention in the natural environment (Demirkol, 2022).

Initially, humans engaged in agriculture solely to meet their own subsistence needs; however, over time, this practice evolved across different eras into a system oriented toward producing surplus for the benefit and use of others. From a historical perspective, the first major technological advancement that directly influenced both the productivity and quality of agricultural production was the development of continuous irrigation systems. This innovation not only encouraged human societies to transition toward settled life but also enabled them to conduct agricultural activities over much larger areas (Demirkol, 2022).

Throughout the historical process, particularly between the 16th and 18th centuries, notable increases in agricultural production and crop productivity were achieved. With the expansion of trade routes, agriculture gradually evolved from a subsistence activity aimed at meeting individual needs into a profit-oriented system of production (Mouzer, 2009; Demirkol, 2022).

Profit-driven agricultural firms prioritize a range of interrelated factors to guide their strategic objectives, sustain growth, enhance competitiveness, and maximize operational profits. This approach enables them to navigate increasingly competitive global markets while ensuring long-term sustainability and reinforcing their market position over time. Foremost among these is productivity, as firms seek to obtain the highest possible yield per unit area while optimizing the use of inputs such as labor, water, fertilizers, and energy. Closely linked to this is effective cost management, which involves minimizing production expenses and maintaining financial efficiency to ensure profitability under varying market conditions. In addition, product quality constitutes a critical concern, as agricultural firms must meet market standards and consumer expectations regarding appearance, nutritional value, and shelf life, particularly in the context of export-oriented production.

Equally important is market and demand analysis, whereby firms monitor consumer preferences, price fluctuations, and supply–demand dynamics to make informed production decisions and maximize economic gains. The integration of advanced technologies has also become a key priority, with increasing reliance on precision agriculture, data analytics, artificial intelligence, and automated systems to improve decision-making processes and operational efficiency. Furthermore, risk management plays a vital role,

as agricultural production is inherently vulnerable to climate variability, pests, diseases, and market volatility; thus, firms adopt various strategies to mitigate potential losses.

In recent years, sustainability considerations have gained prominence, compelling agricultural enterprises to adopt environmentally responsible practices, including efficient water and soil management, as well as the reduction of environmental impacts such as carbon emissions. Moreover, effective logistics and supply chain management have become increasingly important to ensure that agricultural products are stored, transported, and delivered to markets in a timely and cost-efficient manner.

In agricultural production systems, factors such as productivity, product quality, cost management, and sustainability, along with the early identification and mitigation of potential risks, are crucial for maintaining operations at an optimal level. The effective management of these processes depends on the systematic collection of real-time data related to each stage of production, followed by its analysis, interpretation, and the implementation of appropriate operational responses. In complex agricultural systems characterized by numerous interacting variables, the rapid and accurate analysis and interpretation of large-scale datasets through conventional, labor-intensive methods is both time-consuming and inefficient. Consequently, the importance of collecting and processing big data has grown significantly in modern agricultural practices. In this context, the integration of artificial intelligence–based technologies into agricultural systems has gained increasing prominence as a means of enhancing decision-making, improving efficiency, and supporting sustainable production.

In contemporary agricultural systems, the sustainable use of natural resources and the adoption of practices that minimize environmental pressure throughout the production process have become increasingly important. In this regard, maintaining soil health, ensuring the efficient use of water resources and applying agrochemicals in a manner that minimizes harm to the environment are of critical importance for both human health and environmental sustainability.

Accordingly, facilitating the transition from conventional to modern agricultural systems, alongside the integration of information-age technologies into these systems, is essential. The widespread adoption of agricultural automation and artificial intelligence–based decision support systems is expected to yield positive outcomes in terms of the long-term sustainability of natural resources.

Advancements experienced in the current information age have enabled automation-driven transformations across numerous sectors, including

agriculture and healthcare, and this transformation has led to the continuous generation of large-scale data every second. Modern society is confronted not only with processes such as efficiency, innovation, and growth shaped by Big Data, but also with emerging forms of competition and value creation driven by insights derived from these data (Maya Gopal, 2020).

The concept of Big Data refers to large and complex datasets that are difficult to store and analyze using conventional data management tools and methods; these datasets are typically unstructured, high in volume, and composed of heterogeneous data types (Kaisler et al, 2015; Maya Gopal, 2020). In other words, big data is used to describe datasets that are generated at high velocity, exhibit significant variety and volume, and encompass structured, semi-structured, and unstructured data (Aktan, 2018).

Big data sets comprise heterogeneous data of varying volumes, originating from diverse forms of digital content (Guennoun and Mouftah, 2016; Aktan, 2018).

Structured Data: This category refers to data that can be readily modeled, integrated into systems as input, queried, stored, processed, and visualized with relative ease. Structured data are typically organized within predefined fields, presented in specific types and formats, and managed through relational databases and tabular structures. Due to their well-defined and systematic nature, extracting information from such data is generally easier compared to other types of data (Guennoun and Mouftah, 2016; Aktan, 2018).

Semi-Structured Data is not limited to predefined data models; it also incorporates various metadata elements, such as tags and markers, which are used to represent the hierarchical structure of different fields within the data (example: JSON, XML). Semi-structured data sets consist of a combination of structured and unstructured data (Maya Gopal, 2020).

Unstructured Data: This term refers to information that is not organized or stored within a predefined schema, consisting of freely formatted content such as documents, articles, books, videos, audio files, and images. The proliferation of such data types has led to the emergence of new data processing mechanisms, including NoSQL databases, to effectively manage and analyze these complex and heterogeneous datasets (Aktan, 2018).

Maya Gopal (2020), the term "Big Data" is conceptualized and described through the 10V model (Figure 1).

- ***Volume*** refers to the massive scale of data generated from a wide array of sources, including digital systems, sensors, and user interactions, which necessitates advanced storage and processing capabilities.

- ***Variety*** denotes the heterogeneity of data, encompassing structured, semi-structured, and unstructured formats that arise from diverse sources such as text, images, videos, and transactional records.

- ***Velocity*** describes the rapid rate at which data is generated, transmitted, and processed, particularly in real-time or near real-time systems where timely analysis is critical.

- ***Veracity*** addresses the reliability and trustworthiness of data, highlighting the challenges associated with data quality, uncertainty, and inconsistencies stemming from multiple and often disparate sources.

- ***Validity*** pertains to the accuracy and appropriateness of data for its intended use, emphasizing the importance of data governance, quality control mechanisms, and master data management (MDM) practices in large-scale and distributed environments.

- ***Value*** emphasizes the potential of data to generate meaningful insights and benefits; however, extracting value from large volumes of low-density data remains a complex and resource-intensive process.

- ***Variability*** refers to the dynamic and evolving nature of data, including fluctuations in data flow, seasonal trends, and changes in meaning or context over time, particularly in spatio-temporal and time-series datasets.

- ***Venue*** relates to the distributed nature of data sources, which may span multiple platforms, systems, and ownership domains, each with distinct access controls, formats, and infrastructures, including both private and public cloud environments.

- ***Vocabulary*** encompasses the conceptual and semantic frameworks used to describe data, including schemas, data models, ontologies, taxonomies, and metadata that define the structure, meaning, and context of data.

- ***Vagueness*** reflects the ambiguity and lack of a universally agreed-upon definition of big data, as well as the evolving nature of its scope, applications, and associated technologies.

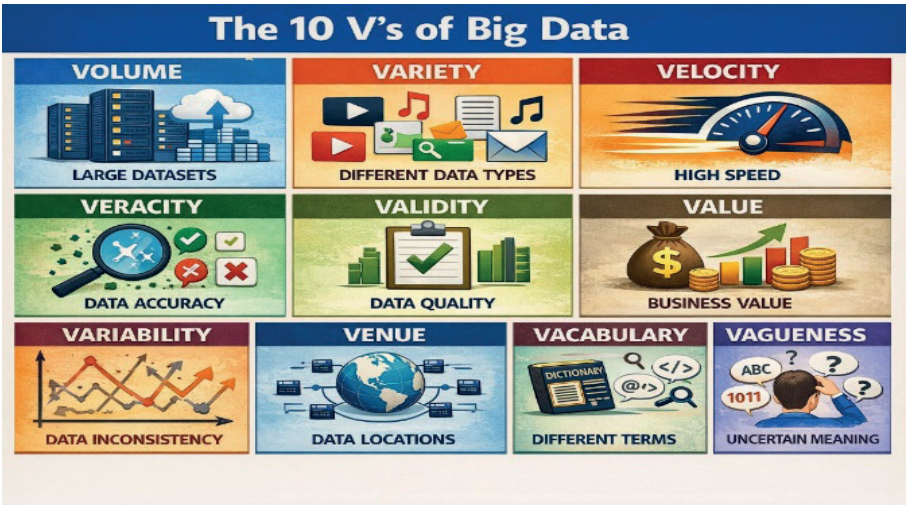


Figure 1. *The 10 V of Big data*

Utilizatıon of Big Data in Agrıculture

The increasing global demand for high-quality agricultural products, along with challenges such as climate change and environmental constraints, has accelerated the digital transformation of agricultural practices. At the core of this technological transition, big data analytics has emerged as a key driver, enabling the shift from conventional farming methods to data-driven and intelligent production systems. The ornamental plant sector, characterized by its high economic value and stringent quality requirements, represents a significant branch of agriculture with substantial potential for the implementation of big data systems.

The ornamental plant industry, which includes cut flowers, potted plants, and landscape plants, has experienced significant growth over the past decades due to rising urbanization and consumer demand for aesthetic and environmental benefits. Unlike staple crop production, ornamental horticulture demands stringent quality control, uniformity, and precise environmental management practices. To ensure optimal plant growth and market value, factors such as temperature, humidity, light intensity, nutrient availability, and pest pressure must be meticulously monitored. Consequently, traditional production methods are increasingly being supplanted by data-driven approaches.

Big data has emerged as a key driver of transformation in the agricultural sector. Defined by the 10V model, it enables the integration and analysis of diverse datasets obtained or generated from sensors, imaging systems, weather

stations, and farm management records. When integrated with artificial intelligence (AI) and machine learning (ML), big data facilitates realistic analyses, real-time decision-making, and automation within agricultural systems (Liakos et al., 2018).

In ornamental plant production, the integration of big data technologies is becoming increasingly significant, particularly in controlled environment agriculture systems such as greenhouses and vertical farms. In these operations, where environmental monitoring and control are critical, such systems provide an ideal setting for the implementation of data-intensive Technologies (Benke & Tomkins, 2017).

APPLICATION OF BIG DATA IN ORNAMENTAL PLANT PRODUCTION

The adoption of sophisticated technological solutions has substantially redefined modern agricultural practices, especially within the framework of controlled environment agriculture (CEA) systems. These technological advancements have fundamentally transformed crop monitoring and management by enabling precise regulation of environmental parameters. Nonetheless, conventional manual approaches, including field inspections, remain inherently subjective and labor-intensive, constraining both accuracy and scalability. These challenges are particularly acute in indoor farming systems, where dense plant populations and tightly controlled conditions necessitate more efficient and systematic monitoring strategies (Chen & Yin, 2024 ; Pompeo et al., 2025, Ajagekar et al., 2026).

In agricultural production, evaluations of crop yield and quality that rely on human judgment require considerable time and effort. Moreover, inspections conducted over large areas can significantly prolong the process. Traditional methods fail to provide real-time data on production fields and crops, and the largely subjective nature of these assessments limits the capacity for rapid response to emerging issues, while also reducing the reliability of the corrective measures implemented (Ajagekar et al., 2026).

Automated systems present a compelling approach to addressing the limitations of traditional methods. By incorporating advanced technologies such as computer vision (CV) and the Internet of Things (IoT), these systems facilitate a more efficient crop monitoring process specifically adapted for indoor farming environments. IoT-enabled sensors, cameras, and remote sensing devices are capable of collecting real-time data on crop health, environmental conditions, and growth dynamics. Such data can be systematically analyzed to identify early indicators of stress, enabling timely and targeted interventions (Aman et al., 2025; Ajagekar et al., 2026).

The potential applications of big data and the associated integrated decision-support systems in agricultural settings have been discussed under various topic-specific headings

a- Smart Greenhouse Menagement

Smart greenhouse systems constitute one of the most prominent applications of big data in ornamental plant production. Key environmental parameters, including temperature, humidity, light intensity, and CO_2 concentration, are continuously monitored through advanced sensor networks.

These data are processed using advanced algorithms to maintain optimal growth conditions. Automated systems adjust heating, ventilation, irrigation, and lighting in real time, resulting in improved plant growth and energy efficiency (Benke & Tomkins, 2017). Additionally, predictive models can forecast environmental changes and adjust control strategies proactively, reducing risks associated with climate variability. Thus, Artificial intelligence (AI) -driven models, by analyzing the collected data, make autonomous decisions that minimize the need for manual intervention (Chen & Yin,2024).

b- Plant Phenotyping and Growth Monitoring

Big data enables high-throughput phenotyping, allowing researchers and producers to analyze plant growth characteristics at a detailed level. Imaging technologies, combined with machine learning algorithms, can measure parameters such as:

- Leaf area
- Plant height
- Flowering time
- Color intensity

The data obtained through sensors not only provide insights into the current stage of the production process but also support decision-making aimed at optimizing production.

c- Disease and Pest Detection

The early detection of plant diseases is crucial in ornamental horticulture, where product quality is of paramount importance. When combined with deep learning models, big data analytics enables the real-time identification of diseases and pests through image recognition techniques.

Convolutional neural networks (CNNs) can identify disease symptoms with high accuracy, enabling timely intervention and reducing the use of

chemical pesticides (Mohanty et al., 2016).

d- Irrigation and Nutrient Menagement

Efficient water and nutrient management is essential for sustainable ornamental plant production. Big data systems integrate soil moisture sensors, weather data, and plant physiological information to optimize irrigation and fertilization schedules. This approach not only reduces resource use but also improves plant health and productivity (Jones et al., 2017).

e- Supply Chain and Market Analytics

Marketing constitutes one of the most critical post-production components for agricultural products. Through big data analytics, supply chains and target markets can be systematically analyzed. By developing demand forecasting models, producers can align their production with market demands, thereby reducing excessive input use and overproduction, minimizing waste, and ultimately enhancing profitability.

In addition, data analytics can be employed to optimize logistics, storage, and distribution processes, ensuring that product quality is preserved throughout the entire supply chain (Wolfert, et al., 2017).

The integration of big data technologies into ornamental plant production systems has led to significant improvements in both decision-making processes and operational efficiency. These improvements are primarily driven by the adoption of sensor-based monitoring systems that enable the continuous tracking and collection of data throughout all stages of production, as well as by the implementation of machine learning algorithms capable of processing and analyzing these data in real time.

Through these technologies, data generated by product monitoring systems can be continuously processed to produce predictive analyses. Such analyses provide growers with valuable insights that facilitate the early detection of potential risks associated with plant stress, diseases, pests, and nutrient deficiencies in cultivated ornamental crops. Consequently, producers are able to implement timely preventive measures, thereby minimizing production losses and enhancing overall product quality.

Furthermore, the integration of big data technologies contributes to the optimization of resource utilization, supports data-driven management strategies, and increases the sustainability and competitiveness of ornamental plant production systems. By enabling more accurate forecasting and informed decision-making, these technologies play a crucial role in improving production performance and ensuring the efficient management of cultivation processes.

The implementation of automation systems in agricultural production, aimed at enhancing measurability and reducing labor requirements, particularly enables the effective management of large-scale indoor cultivation systems. Consequently, data-driven and timely decision-making can be applied to various agricultural processes, including irrigation, fertilization, pest and disease management, climate control, and the determination of optimal harvest timing. The implementation of automation systems in agricultural production, aimed at enhancing measurability and reducing labor requirements, particularly enables the effective management of large-scale indoor cultivation systems. Consequently, data-driven and timely decision-making can be applied to various agricultural processes, including irrigation, fertilization, pest and disease management, climate control, and the determination of optimal harvest timing. Simultaneously, advancements in state-of-the-art computer vision techniques enable agricultural robots to perform complex and traditionally challenging tasks with greater precision, further enhancing the efficiency and reliability of indoor farming operations.

Despite significant advancements in automation and computer vision technologies for indoor farming, several limitations still exist in current systems. Many existing solutions are constrained by high initial costs, which may pose barriers for small- and medium-scale producers in establishing the necessary technological infrastructure. Furthermore, in cases where users lack sufficient knowledge and experience, periodic calibration of sensors, data integration, and real-time processing often present technical challenges, potentially reducing the overall accuracy and responsiveness of the deployed systems. The dependence on controlled environmental conditions also limits adaptability, diminishing the effectiveness of these systems under variable or suboptimal conditions. Additionally, although robotic systems are capable of performing complex tasks, their efficiency is affected by mechanical limitations, software reliability, and energy consumption. These factors indicate a clear need for further development and optimization in these areas.

The application of big data technologies in ornamental plant production possesses considerable potential to enhance productivity, product quality, and the overall sustainability of production systems. By enabling the collection, integration, and analysis of large-scale datasets from diverse production environments, these technologies facilitate more precise and informed decision-making processes throughout the cultivation cycle.

Despite their promising benefits, the widespread adoption of big data technologies within the ornamental horticulture sector remains constrained by several challenges, including high implementation costs, technological complexity, data management issues, and the need for specialized expertise. Therefore, increased investment in research, infrastructure development, and

technology transfer initiatives is essential to accelerate their integration into commercial production systems.

The transition toward data-driven horticultural production models is expected to play a pivotal role in meeting future agricultural demands. As global challenges such as climate change, resource scarcity, and increasing market expectations continue to intensify, the effective utilization of big data technologies will become increasingly important for optimizing resource use, improving production efficiency, and supporting sustainable ornamental plant production. Consequently, the development and adoption of advanced data-driven approaches are likely to represent a key component of the future of horticultural innovation and sustainable agricultural development.

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Chapter 2

ROSES AND ROSE CULTIVATION IN TÜRKİYE

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1. Introduction

There are approximately 750,000 plant species in the world. Each plant may have aspects that are liked and disliked by people. Coarse hairy and thorny plants in nature are mostly non-toxic; however, many poisonous plants are very attractive. Therefore, they stand out in landscaping and indoor floriculture. Some plants are very loved and cherished by a certain segment of people, but they don't interest most people at all. Roses are a different group of plants. Their beautiful appearance, captivating scent (only *R. foetida* and *R. hemisphaerica* are partially unscented), silky soft leaves, drought tolerance, non-toxicity, relatively easy cultivation, the visit of nightingales to rose gardens at dawn, and the fact that important statesmen have rose gardens established and occupy themselves with roses during stressful periods all tell us something. Roses are not an ordinary group of plants. They possess miraculous qualities. They have no known negative characteristics. This is why we choose rose-related names for girls. Cities, company names, and social statuses are explained with roses. We express our joy, happiness, sorrow, anxiety, desires-in short, every thought and state of mind-with a rose. The message conveyed rapidly by a rose is quickly understood by the recipient. Those who are estranged reconcile by giving each other roses. They get along as well as roses. Poems, proverbs, stories, and ways of life are described through roses. Roses are the food, medicine, and shelter of wild animals (snakes, bears, butterflies, birds etc.).

Roses are not like other plants. Those who love roses are emotional people. Emotional people don't think of roses as just a plant, a vegetation, or a source of livelihood. They confide in them, they grieve if a branch breaks or a their flower wilts. They become ill if they don't see them for a long time… Wealthy families used to live in the old mansions of Istanbul. These families had significant gardens, and each had a rose collection garden. Roses were named, classified, and sold to enthusiasts at high prices (in gold). A mansion owner would display their wealth through the variety of roses in their collection. Some had more than 1000 varieties. Some, unable to resist the scent of roses during rose season, would go and sleep at the base of the rose bushes at dawn or midnight (Baytop, 2001).

We express our feelings to the recipient with roses. Each rose carries a special and subtle meaning. Galatasaray rose, Dead rose(for human), Prophet's scent, Güla Muhammedi, Peygamber kokusu, Iridescent, Jam rose, Pompon rose, Melekhanım rose, Climbing rose, Seated rose, Tuttumsalmaz rose, Dog rose, etc.

Everyone loves roses and wants to grow them. But not everyone can. This is where the rose trade comes in. Many income-generating products are also

produced from roses. Roses are used in medicine, cosmetics, perfumery, dyes, ornaments, rootstocks, hedges, etc. This section /article is prepared based on our experiences to outline all roses in their various aspects.

2. Materials and Methods

We have been working with this genus since 2006. This section/article does not include a review of new material. To date, we have conducted and published numerous studies on roses. This article is a summary of our work. There is a GUL herbarium at Süleyman Demirel University (Isparta). The international code for this herbarium is 'GUL'. GUL means 'Rose' in Turkish. This herbarium contains approximately 4000 rose specimens, mostly collected from Türkiye. The GUL herbarium is arguably the richest herbarium in the world in terms of the rose genus. Most of the systematic studies are carried out in this herbarium and by us (Özçelik et al., 2009; Özçelik, 2010; Özçelik and Özçelik Doğan, 2018; Özçelik and Koca, 2021; Yıldırım and Özçelik, 2023). Field trials are conducted at SDÜ. The study was conducted in the Rosary plots of the Botanical Garden (Özçelik et al., 2009; Yıldırım, 2016; Özçelik, 2018). The total number of native rose genotypes collected from Türkiye is approximately 500. Of these, 350 rose genotypes were cultivated (Özçelik et al., 2009) and exhibited in this garden (Figure 1). Unfortunately, this garden has suffered significant damage recently. Observations from personal home gardens, rose gardens, parks, etc., information obtained from scientific meetings and publications, personal interviews, etc., are presented in this article along with photographs. Rose illnesses are based on observations in the field and information provided by the public, drawing upon Robert et al. (2003).



Map 1. Administrative map of Türkiye.



Figure 1. Picking roses is a relaxing activity for people (SDÜ. Botanical Garden, Rosarium plot).

3. Introduction of Turkish Roses

3.1. The History of Roses and Rose Cultivation: The history of roses goes back much

further than the history of humanity. Some rose fossils found in different parts of the world have been determined to be 35-40 million years old. According to some studies, roses have been living on Earth for 60-70 million years. Current molecular-based studies, however, indicate that roses have a history of 200 million years (Baytop, 2001; Altıntaş, 2009; 2010).

Roses have captivated people throughout history. The first written record on this subject dates back more than 4000 years. Mesopotamian clay tablets state that the Akkadian king Sargon I returned from a military expedition, probably to Southern Anatolia, with vine, fig, and rose saplings (Altıntaş, 2009; 2010). According to what is written on Mesopotamian clay tablets introduced by the British archaeologist Sir Leonard Wooley; these rose saplings were brought from the vicinity of Diyarbakır (Haspolat, 2013).

The Blue Bird fresco, which includes a rose image and was unearthed in an archaeological excavation at the Knossos palace in Crete, dates back to the 17th-16th centuries BC. This fresco shows that the rose was a well-known and beloved flower in the Minoan Civilization (Yıldırım, 2016).

During the Ottoman period, there are decrees from Sultan Murad III (1574-1595) in 1587 and 1593 regarding the importation of rose saplings from Edirne for the palace gardens. Sultan Abdulhamid II also issued a decree concerning rose cultivation. This decree stipulated that rose saplings were distributed to farmers by the state, taking into account the economic situation of the people and the ecological and geographical characteristics of the region. The oldest and most reliable information we can find regarding rose cultivation in Isparta, which began with Gülcü İsmail Efendi, comes from the 1332 (Hijri) Year Yearbook, which contains official state records. Another noteworthy point here is the beginning of industrial rose oil cultivation in Isparta (Yıldırım, 2016).

Some sources state that rose oil cultivation has existed in Iran since ancient times, and that rose cultivation first began in Iran, with rose oil first being produced in the Iranian palace (Yıldırım, 2016). It is stated that roses spread from Anatolia during the Medes (7th-6th centuries BC) and that the Medes established gardens by planting roses in valleys in Iranian lands (Kenber, 1969). Although its origin in Iranian lands is not clear, rose production developed considerably in Shiraz and its surroundings from the 10th to the 17th centuries in the Middle Ages (Orozoff, 1906; Timor, 2011). These roses are thought to be *R. stipulata.*

In the history book Historia, written by the famous historian Herodotus (484-425 BC), it is mentioned that King Midas of Phrygia, who lived in Central Anatolia around 700 BC, had rose gardens with a musk-like scent, and that after being defeated in a war with the Persians, he took his roses with him when he left his country and established new rose gardens in Macedonia. It is estimated that the roses grown in the rose gardens established by the Phrygian king Midas in Gordion (Polatlı) near Ankara were also *R. stipulata* (Syn: R. damascena var. semperflorens) (Baytop, 2001; Altıntaş, 2010; Torlak, 2012). These works provide information on the history of roses (Widrlechner, 1981), as well as their names and uses (Korkmaz and Özçelik, 2015). The Lake District is the heart of rose cultivation today. Rose farming is carried out on 40,000 decares of land, and they are processed in 35-40 factories or workshops.

3.2. Systematics: Roses belong to the Rosaoideae subfamily of the Rosales order within the Rosaceae family. All roses belong to the genus *Rosa* L. Approximately 30 of the 100 species of wild rose hips that grow worldwide naturally in Türkiye. Encyclopedic books describing all roses in various

aspects (Roberts et al., 2003; Cumo, 2013) provide a great deal of scientific and technical information on roses. Numerous publications have been made on their systematics and origin (Ercişli, 2005; Özçelik, 2010; Özçelik and Özçelik Doğan, 2018; Özçelik and Koca, 2021). It is estimated that there are approximately 150 rose species worldwide, with about 45,000 genotypes of cultivated roses, of which about 18,000 cultivars are found in Europe. Almost 100 species of them are wild. In Türkiye, a total of 45 rose species are registered. About 30 of them are wild roses, and about 15 are ancient garden roses. Considering modern roses and roses that have not been named and are thought to be new species, it can be said that there are about 70 *Rosa* species in Türkiye. However, there is no identification key to distinguish these taxa. The work entitled 'Flora of Turkey' (Nillson, 1972) only contains an identification key for wild roses, and this key is insufficient for identification purposes. he systematics of Turkish roses have not been sufficiently studied. While it is known at the species level, the under categories are not well understood. A sufficient systematics will become clearer after the subspecies taxa (subspecies, varieties, clones, cultivars, registered rose seedlings, etc.) of the species are identified.

3.3. Ecology and Geography: It grows naturally or is cultivated in the Northern Hemisphere, encompassing North America, Europe, Asia, and the Middle East. The highest number of species is found in regions west of China (Ercişli, 2005; Özçelik et al., 2009). The Greek scientist Theophrastus (370-287 BC) was the first to provide a detailed botanical description of the rose. In his botanical book (Natura Historalis), he dedicated a separate section to roses, introduced many rose varieties, and noted that it was easier to propagate roses from cuttings rather than seeds (Altıntaş, 2010). Of the approximately 100 wild species, about 30 are found in Türkiye. The highest number of species and genotypes are in the Mediterranean region, and based on the fact that rose cultivation is best practiced in the Lake District within this region, it has been suggested that the genetic center is Dedegül Mountain (Isparta) (Özçelik et al., 2012). The Kaçkar Mountains (between Trabzon and Rize) rank second in terms of the number of taxa. This data suggests that the center of origin is Turkey (Map 1). Roses are drought-resistant plants with deep roots, and their wild varieties have rhizomes. Those grown in the shade become climbing plants and have soft wood. They can grow in any soil with good drainage. Generally, they prefer sandy soils and a temperate climate. They are long-day plants.

3.4. Rose Diseases: Fungal diseases such as honeydew by *Aulacaspis rosae*(Ballıbasara), Scale Insects (Kabuklubit in Turkish), Aphids(Gül Yaprakbiti in Turkish), flower thrips by *Frankliniella occidentalis,* shoot borer by *Agrillus aurichalceus* (Gül Filizburgusu in Turkish), Rose scale(Gül koşnili

in Turkish), Rose chafer by *Macrodactylus subspinosus* (Gül Karanfili in Turkish, the insect dries out the pedicel in bud form, preventing flowering), Powdery mildew (Külleme), Rust (Pas in Turkish), and Black spot (Karaleke in Turkish) are common in old garden roses. Powdery mildew and other fungal diseases are of plant origin, while others are of animal origin. Aphids, in particular, are very common in fragrant roses. Various types of galls occur when insects bite the fresh organs (primarily leaves and stems). The type of gall varies depending on the type of insect infecting the rose. In *R. gallica*, insects often infect young fruits, and the fruit can become diseased and grow up to four times from its normal size. These fruits have no economic value, because they are infected. Powdery mildew is very common in old garden roses like *R. stipulata, R. alpina, and R. banksia* cultivars. Gall formation on leaves and stems of roses (*Diplololepis* spp.) and snails, caterpillars, etc., cause serious damage to *R. rugosa.*

3.5. Contribution to the ecosystem: Honey bees are very attracted to *R. arvensis and R. phoenicia.* Honeydew blight is very common on these roses. Honey bees readily feed on the remnants of blight. Snakes nest at the base of the roses, while birds nest in the densely packed branches at the top. Bears and other wild animals feed on the fruits of wild roses. Butterflies such as *R. dumalis, R. horrida, and R. canina* feed heavily on the flowers of roses. Butterflies reproduce abundantly in areas with many roses. Roses serve as habitats and breeding grounds for flies, insects, and other animal groups. Ladybugs (*Coccinella septempunctata*) and ants feed on aphids. Gall formation is very common in the Malatya region (Map 1).

Wild roses, with their deep roots, hold the soil together and reduce the rate of erosion. Due to their drought resistance, they play an important role in soil formation in rocky areas and in the vegetation of natural areas with their strong root system (*R. gallica* in the Çankırı region) Every rose, but especially the climbing type, wraps around trees, adding color and harmony to nature. (Fig. 3).



Figure 3.1. Ground cover, soil-holding wild species: A: Dog rose(*Rosa hirtissima),* B: Rosehip (*Rosa villosa*).



Figure 3.2. *Rosa heckeliana* is a casmophyte species that grows off marble rocks.

4. Rose Products

4.1. Essential Oil from Rose: This is a volatile oil produced by steam distillation. On average, 1 liter of essential oil is obtained from 3500 kg of rose flowers. This depends on the amount of volatile oil in the flower. 1 liter of essential oil is obtained from 8 tons of flowers of Halfeti Black rose and other old garden roses. Distillation takes approximately 3 hours. In the first distillation, oily rose water is obtained. In the second distillation, the oily rose waters are distilled again at a low temperature. Volatile oil and hydrosols underoil are obtained. The small amount of greenish rose oil obtained in the first distillation is extra quality, the second is conventional oil. The composition of the oil also varies depending on the flower, the distillation time, the production date of the oil, and the storage conditions. If the distilled rose flowers belong to different species, the scent of the rose oil is more attractive. However, its shelf life is shortened. During the Ottoman period, rose water obtained by distilling these partially fermented flowers was called 'Sage oil' and used for medicinal purposes. It was distilled by adding 10% *R. alba* flowers to *R. damascena* flowers. This ratio was adjusted in the rose gardens of the Lake District by planting 9 rows of *R. damascena* and 1 row of *R. alba*. The 9/1 ratio improves the quality of the oil (Fig. 4-8).



Figure 4. The Halfeti black rose has a strong aroma. Its essential oil and oily water(hydrosol) can be obtained.

4.2. Rose Hydrosols: Rose water is a colorless liquid with a rose scent, obtained as a byproduct of rose oil production, and has an antiseptic effect (Baytop, 1990). The water remaining after the first and second rose oils are extracted is called 'oil-under rose water'. Its quality is poor. Oily rose water and extra-quality essential oil are used for medicinal purposes, while the others are for cosmetic purposes. Those used for medicinal purposes are more expensive and must be distilled from flowers grown through organic farming. If rose water is to be produced for cosmetic purposes, the flowers of different garden roses must be mixed and distilled. According to the 2025 year figures, 1 liter of oily rose water is 800 TL.



Figure 5. Rose processing: A: Historical development of distillation systems: A1: Peasant-type still, A2: A rose oil production facility in Burdur in the 1930s (Özata, 2014), A3: Modern rose oil factory. B: Tools/equipment used in cosmetic and essential oil production during the Ottoman period.



Figure 6. Various rose products.

4.3. Rose Concrete (Solid Rose Oil): Rose concrete, a reddish, buttery consistency, is obtained by treating rose flowers with a chemical solvent (such as hexane) and then removing the solvent under low pressure (Baytop, 1990). 1 kg of concrete is obtained from 300-400 kg of rose flowers (Karlı et al., 2014). Approximately 350 kg of rose flowers yield 1 kg of concrete.

4.4. Rose Absolute: Concrete is used to produce absolute. 1 kg of rose absolute, which has a light red color, is obtained using 1.7-2.0 kg of rose concrete (Karlı et al., 2014). The concrete is washed with ethyl alcohol 4-6 times in succession. 8-10 times the amount of ethyl alcohol is used for 1 kg of concrete. The ethyl alcohol extracts obtained after washing are collected in a container and kept at -20°C Celsius to allow waxy substances such as paraffin and non-aromatic substances such as oils/fatty acids to settle to the bottom. Then, the ethyl alcohol is evaporated under vacuum, leaving behind 'rose absolute'. The paraffinic waxy substances that are produced as a secondary product in absolute production and are called 'wax' are used in the manufacture of cosmetic products such as scented candles, soaps and lipsticks (Baydar, 2009).

4.5. Dried Roses: This is a recently developed product. They are dried in industrial ovens. There are ovens that can handle 50 kg to 1000 kg. Dried roses are used as tea, placed in vases, or crushed into granules and added to confectionery products such as Turkish delight. They are generally consumed domestically (Özçelik and Özçelik, 2019). Fragrant roses with dark, thick petals are preferred for dried roses. In this case, black roses such as the Halfeti black rose stand out (Özçelik, 2018). In confectionery, granular or powdered form of dried roses is very popular.

4.6. Glass Roses: In Isparta, glass roses were produced at the GÜLAR unit of S. Demirel University between 2012-2014 years. This product is made by growing roses from disease-free, small-flowered rose genotypes in a sterile cabinet using tissue culture methods, then placing them in a glass tube and sealing it. It's a unique product. It was popular in the market for a few years, then abandoned. Roses were carried around like pens in jacket pockets. However, these roses lacked any functionality such as fragrance, and their cost was high.

In Eğirdir district, between 2024-2025, there were various dried animal specimens in glass containers on the lakeshore within the MAREM facility. These included butterflies, crabs, fish, etc. There were also well-dried plant specimens, placed in glass containers, and some of these were rose flowers. These can also be considered glass roses. They are purely for visual purposes and serve tourism.

5. Economy and Trade

In Türkiye, modern industrial rose cultivation is currently only carried out in the Lake District (Isparta, Burdur, and Afyonkarahisar). Around 40 workshops or factories process rose (*R. damascena*) flowers. The production of *R. stipulata* and *R. alba,* which were previously cultivated, has decreased significantly in the last 50 years and is now completely abandoned. The economic value of 1 liter of rose oil is approximately 10,000-12.000 USD. It is mostly exported to France and for cosmetic purposes. On average, 3000-4000 kg of rose flowers are needed to produce 1 liter of essential oil. Almost all rose oil is exported. All rose water is used domestically for food, cosmetics, etc.

The rose industry is not limited to the cultivation, economy, and trade of oil and landscape roses. Oil rose cultivation in Türkiye has a history of over 100 years. Rose species hold an important place in the ornamental plant group. Members of the Rosaceae family are currently used in food and for medicinal purposes. Due to the richness of phenolic compounds (citronellol, geraniol, and nerol) in their structure, members of this family have important physiological functions. Rosehip plants have a wide range of uses and consumption areas. They are used as rootstock for cut flowers like roses, as a landscape plant in parks and gardens due to their shrub form, for afforestation and hedges along roadsides due to their thorns, for planting infertile lands due to their high tolerance, and for preventing erosion due to their deep root structure; their wood is used as firewood in rural areas; and their fresh shoots (stems), leaves, and seeds are used as animal feed (Arslan et al., 1996; Karaçalı, 1990). Food, medicine, cosmetics, and dyes are other areas of use. Their resistance to diseases and pests, and their tolerance to different climates and soil conditions, have increased their areas of use. Rose flowers, rose oil, and rose water have many uses in food, medicine, beauty, fragrance, care, and ornamentation due to their physical, psychological, and spiritual effects.

Flowers of *R. damascena* are an economically valuable plant used in the perfumery and cosmetics industry to alter the scent of some ointments and galenic preparations, and are also of significant value for research from a medicinal perspective. Today, more than 100 products are obtained from the rose (*R. damascena*) plants, including rose water, rose cream, rose lotion, rose Turkish delight, rose jam, rose syrup, and rose soap (Baydar, 2009; Özçelik and Koca, 2021). Rose essential oil, oily and under-oil rose hydrosol, concrete, and absolute are industrial raw materials of rose cultivation. These products have different economic values. The most expensive is rose oil.

Rosa damascena is the most important of the four main rose species used in essential oil production worldwide. The other species oil roses are *Rosa*

gallica, R. moschata, and *R. centifolia*. We can also add *R. alba, R. stipulata, R. centifolia*, and *R. borboniana* to these (Özçelik, 2010). The most commonly cultivated genotype of *Rosa damascena,* known by names such as Isparta rose, Damascus rose, Kazanlık rose, Pink Rose, and Oil rose, for rose oil production is 'Trigintipetale'. Approximately 30 genotypes of *R. damascena* and about 10 genotypes of *R. stipulata* have been identified in Türkiye. The exact number of genotypes of each species is not known (Yıldırım and Özçelik, 2023). In Isparta, the flowering time of oil roses varies depending on the year and altitude, but generally covers a period of 35-45 days, starting in the 2nd and 3rd weeks of May and continuing until the 2nd and 3rd weeks of June. During the harvest period, which lasts an average of 40 days, oil rose flowers must be collected in the early morning hours and processed immediately through distillation or extraction. Factors affecting yield and quality in oil rose cultivation include cultural practices (planting, pruning, irrigation, fertilization, disease and pest control, etc.), ecological conditions (temperature, light, humidity, rainfall, etc.), and harvest time (Sarıbaş et al., 2014).

Rose essential oil is obtained by distilling the fresh flowers of *R. damascena*. The petals of the rose flower contain volatile oil, tannins, gallic acid, quercetin, cyanine, sugars, and waxes. Natural rose oil contains substances such as citronellol, geraniol, nerol, eugenol, methyl eugenol, and phenylethyl alcohol. Rose oils were analyzed using gas chromatography (GC/MS), and 26 different components were identified in the essential oil composition, consisting of: monoterpenic alcohols such as citronellol, geraniol, nerol, and linalol; hydrocarbons such as nonadecane, 1-heptadecene, heneicosane, tricosene, heptadecane, and eicosane; ethers such as methyl eugenol.



Figure 7.1. Roses that form the basis of rose oil cultivation: Isparta Oil Rose (*Rosa damascena*) seedling production, cultivation and post-processing pulp.



Figure 7.2. Sakız gülü/Triyandafil (*Rosa alba)* is an important rose for its essential oil, fruit, and landscaping purposes.



Figure 7.2. A: Misk gülü *(Rosa moschata),* B: Reçellik gül/Yağ gülü (*Rosa stipulata).*



Figure 7.4. Frenk gülü (*Rosa gallica*); A: Grows wildly in Türkiye, B: Cultivated improved form.



Figure 8.1. Old garden roses: Sadberk gülü/Yüz yapraklı gül (*Rosa centifolia*).





Figure 8.2. Okka gülü (*Rosa borboniana*).

Isparta province is an important province in the world for memorization training. It is known that hafiz (Qur'an memorization) candidates place rose petals between the pages of the Holy Qur'an while memorizing it, thus making it easier to memorize the verses (Özçelik, 2018a).



Figure 8.3. The Hafız rose is one of Isparta's old garden roses, known for its musk-like fragrance, pink flowers, and long flowering period.

5.1. Landscape Roses: These are roses used in landscaping. The majority are improved and registered varieties. They are mostly of European origin. The majority belong to *Rosa odorata,* known as 'tea roses', or *R. comantema* (Syn: R. damascena var. versicolor), also known as 'ever-blooming roses'. The most common of these roses are 'Yediveren roses'.



Figure 8.4. Tea roses (*Rosa odorata*) are most commonly used in landscaping. They are showy and fragrant, and are among the old garden roses.

5.2 Cane Roses: These roses are preferably sold after grafting small, long-blooming roses (such as *R. chinensis, R. banksia*, *R. odorata*) onto rooted wild rose stakes. While these roses are very showy, their lifespan is generally short due to tissue incompatibility. *R. canina, R. alba, R. laxa,* and *R. multiflora* are the most commonly preferred rose species as rootstocks. They are resistant to diseases (Fig. 9).



Figure 9. Cane roses are the most expensive roses in landscaping. *They are created by grafting numerous small-flowered roses onto rose bushes.*

5.3. Cemetery Roses: While all types of roses can be planted in cemeteries, fragrant, showy, and profusely flowering varieties are preferred. Small, long-lasting, or frequently flowering roses (such as *R. chinensis*) are preferred for planting on graves. However, climbing roses can be planted in cemetery medians and along roadsides. R. foetida was commonly planted in the cemeteries of Korkuteli (Antalya) and Uluborlu (Isparta). *R. foetida* is particularly preferred for decorating cemeteries. Not only its flowers but

also its leaves are very fragrant. It is preferably planted to eliminate odors in cemeteries. Its flowers are showy and drought-tolerant (Fig.10).



Figure 10.1. Cemetery roses: A: Chinese rose(*R. chinensis)*, B: Yellow rose(*R. foetida).*



Figure 10.2. A: *Rosa banksia* 'Lutea', B: *Rosa banksia* 'Alba', C: *Rosa banksia* 'Albo Plena'.

5.4. Cutting and Indoor Roses: The roses in this group are mostly improved, registered roses belonging to *R. odorata* and *R. chinensis*. Genotypes of *R. chinensis* are commonly sold in small pots. Improved, registered varieties of *R. odorata,* such as 'Cardinal', are grown in greenhouses as cut roses and sold to the relevant sector on important occasions. There are many greenhouses producing cut roses and landscape roses in Türkiye. Cutting roses can be transported abroad by plane and marketed daily.

6. Wild Roses

These roses grow naturally in Türkiye. They have strong thorns and underground organs, and their flowers are simple and showy. They are used in erosion control (*R. histissima, R. canina* etc.), in fences to protect fields from animals (*R. canina, R. horrida, R. tomentosa, R. alba* etc.), their fruits

are used industrially in food production (*R. canina, R. dumalis, R. alba, Rosa heckeliana* etc.), and their thick stems are used in the manufacture of household goods, bags, pencil cases, etc. (*R. canina, R. alba, R. dumalis* etc.). There are rosehip processing facilities in Tokat and Isparta. Rosehip fruits are a source of vitamin C and lycopene. The highest amount of vitamin C has been found in *R. dumalis* (endemic).



Figure 10.1. Wild roses: A*: Rosa horrida,* B: *Rosa heckeliana*.



Figure 10.2. *Rosa dumalis* *subsp.* *boissieri* *var.* *antalyensis).*

6.1. Fruit Rose Cultivation: This term was first coined by us (Özçelik et al., 2009). It refers to industrial fruit production. It is an alternative agricultural production to oil rose cultivation. While domestic needs can be met to the extent possible with rosehip varieties, it is important to cultivate rosehip varieties that produce abundant, high-quality fruit and have a high yield. Although there are many facilities that process rosehips, they cannot provide the expected service due to a shortage of raw materials.

Recently, thorny or thornless, bush or climbing type cultivated forms originating from *R. canina* and *R. gallica* have emerged. These forms are preferred for harvest and yield in fruit rose cultivation. Rosehip fruits are generally collected from the wild. However, there is no standard for rosehip fruits collected from the wild. They belong to different species. Therefore, studies on cultivating specific genotypes are ongoing. Fruit roses are preferred both to meet domestic food needs and for landscape arrangements. Climbing

types are more productive and showy than bush types. Some are purely thornless, some are partially thorny (chimera), and some are original natural rose genotypes. There are about 60 rosehip genotypes in Türkiye that can be used in fruit cultivation (Fig.11).



Figure 11.1. There are improved reproductive types of *Rosa canina*, both short and ivy.



Figure 11.2. Important rosehip genotype (chimeral) with fruit.

7. Discussion and Conclusions

The rose, one of the most cultivated plants in the world today and known as the queen of flowers, has a history that dates back to ancient times, along with the history of humanity. Rose remains have been found in fossil beds in different regions of the world. According to some fossil records, the age of the rose is 25 million years; according to others, it is 40 million years ago. Molecular biologists, however, have estimated it to be 200 million years old by examining the DNA of the rose. These differences undoubtedly stem from differences in age determination methods. The earliest written record to date is found in Mesopotamian clay tablets from 5000 years ago (Mendi, 2011). The oldest records come from Rhodes, meaning the place where roses grow, and Syria, i.e., the Mediterranean region. The oldest garden rose is *R. richardii,* depicted in the artworks of the Minoan civilization of Crete 3500 years ago. Molecular analyses do not adequately support classical taxonomy, leading to significant differences in rose classifications. For example, while classical taxonomy identifies *R. foetida* as closely related to *R. hemsiphaerica*, molecular analyses may show relatedness to other species (Oğraş et al., 2017).

During the Middle Ages, especially in the Abbasid period, roses were cultivated in abundance in Al-Jazira (Northern Mesopotamia), and there were numerous rose water factories. Around 25 varieties of roses are mentioned, including Yediveren (*R. comantema*), the Muhammadî rose (*R. stipulata*), Triyandafil (*R. alba*), the Hundred-petaled rose (*R. centifolia*), the Nesrin rose (*R. canina*), the Climbing rose (*R. banksiae*), the Sultan rose (*Rosa gallica* var. *violacea*), and the wild white rose (*R. pimpinellifolia*). These roses are still considered native roses of Türkiye today. Works on roses in ceramics, poetry, art, and literature also support this idea. Mesopotamian civilization laid the first foundations for rose cultivation in Türkiye. Roses in Southeastern Anatolia region, both landscape roses and oil roses, are based on *R. stipulata* (Muhammadî rose, Güla Muhammedî, Jam rose). However, modern rose cultivation is based in the Lake District(Göller Yöresi) and relies on *R. damascena*. The most famous rose of Southeastern Türkiye is the Halfeti black rose(*R. odorata*) and Triyandafil(*R. alba*), a fragrant, showy, and historical rose in the time. Today, these roses are sold commercially in Europe. R. alba, in particular, is widely produced as a rootstock in Germany. This rose was also cultivated. Ministry of Agriculture of the Ottoman State by order of Sultan Abdulhamid II, had initiated efforts to establish 'rose gardens' throughout the Ottoman lands from the 1880s onwards. Diyarbakır Sanjak held an important place within this program (Haspolat, 2013). Roses are given a wide variety of names in different regions. The culture and livelihoods of the region influence these names (Özçelik, 2018c).

Roses serve many purposes, including landscaping, houseplants, and cut flowers. However, in Türkiye, rose cultivation is primarily associated with oil rose production and the Lake District, its center. Recently, interest and investment in oil rose cultivation have increased in provinces like Mardin and Diyarbakır in the Southeast region. Unfortunately, oil rose cultivation is not recognized as an industrial type; incentives are given to oil roses as if they were landscape roses. Harvesting rose flowers is a laborious task. They are picked in the early hours, thorns damage to the hands, and insects hidden in the flowers sting those, picking to the hands. Rose buyers determine the price after the oil is sold and pay for the flowers. This situation is not pleasing to the farmers. Rose flowers can be produced in two ways. Organic rose cultivation is more difficult; a yield of 300 kg/da is not enough to satisfy rose farmers. In conventional rose cultivation, the flower yield is higher (500-800 kg/da). Factories value organic rose flowers slightly more than conventional ones. Therefore, in recent years, farmers have been establishing new rose gardens using plants called 'Centifolia' (*R. centifolia*), or chimeric roses, considered to be hybrids of *R. damascena x R. canina*, which are either thorny or thornless, bush or climbing types (Fig. 11).

In Bulgaria, 4 types of oil rose seedlings or saplings are produced. Producers choose the variety according to their purpose. This is not the case in Turkey. Classical oil rose cultivation is practiced for all purposes. Raw materials are processed into finished products. Rose cultivation is a serious agricultural sector. Diversification is undoubtedly beneficial.

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Chapter 3

THE ROLE OF MYCORRHIZA IN ROOT DEVELOPMENT OF FABA BEAN (*Vicia faba L.*)

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1. INTRODUCTION

The rapid growth of the world's population has made it imperative to sustainably increase agricultural production to meet rising food demand. This situation has also significantly increased the need for fertilizers used in crop production. However, the high cost and environmental impacts of chemical fertilizers have increased interest in alternative and environmentally friendly practices. In this context, the use of nitrogen-fixing bacteria (NFB) in crop production is considered one of the most promising approaches for improving nitrogen fertilizer management, supporting plant nutrition, and increasing agricultural productivity. This practice contributes to reducing the use of externally supplied fertilizer inputs, enabling plants to utilize nitrogen more efficiently, and preventing environmental pollution by reducing nitrogen leaching through the soil profile (Sánchez-Navarro et al., 2020).

Symbiotic relationships established between legumes and microorganisms constitute one of the fundamental biological mechanisms underlying sustainable agricultural systems. The N_2 fixing symbiosis that develops between most legume species and bacteria is based on nodule formation and the colonization of these nodules by specific *Rhizobium* species. In this process, *Rhizobium* bacteria fix atmospheric nitrogen and, in return, obtain carbon compounds derived from plant photosynthesis (Nadeem et al., 2020).

The efficiency of biological nitrogen fixation depends not only on rhizobial bacteria but is also closely associated with plant phosphorus nutrition. At this point, mycorrhizal fungi play essential roles in plant nutrition. Phosphorus is one of the least accessible nutrients for plants and is critically important for both nodule formation and the activity of the nitrogenase enzyme involved in biological nitrogen fixation. By establishing symbiotic associations with plant roots, mycorrhizal fungi enhance the acquisition and utilization of phosphorus, along with numerous other nutrients and water, thereby promoting plant growth and development (Sanchez-Navarro et al., 2020).

The faba bean (*Vicia faba* L.) is an important legume species with high nutritional value that is widely cultivated worldwide. In addition to being a valuable protein source in human nutrition, it is also widely used in animal feed (Cazzato et al., 2012). It is also an important field crop that contributes to the maintenance and improvement of soil fertility through biological nitrogen fixation. Today, faba beans are cultivated in many regions of Australia, the Americas, Europe, Asia, and Africa, and hold a significant position in global production among dry legumes (Etamadi et al., 2019).

The significance of faba beans in agriculture is attributable not only to their high nutritional value. Furthermore, the capacity of faba beans to fix nitrogen is approximately 50–330 kg per hectare, contingent on climatic conditions and cultivation practices (Galloway et al., 2004). This characteristic

renders faba beans a fundamental crop in the context of reducing reliance on chemical nitrogen fertilizers and contributing to the establishment of sustainable crop production systems. Furthermore, its incorporation into crop rotation systems has been demonstrated to engender several notable benefits, including enhanced soil fertility, diminished disease and pest pressure, effective weed control, and a marked improvement in overall soil health (Aschi et al., 2017).

One of the most important biological factors supporting plant root development is mycorrhizal fungi. Mycorrhiza is the general term for the mutually beneficial symbiotic relationship established between plant roots and fungi. The term is derived from the words "myco," referring to fungi, and "rhizo," referring to roots (Sousa, 2023). Arbuscular mycorrhizal fungi, commonly found in many field crops such as faba beans, form specialized structures called arbuscules within root cells, enabling direct exchange of nutrients with the plant (Smith & Read, 2008).

In recent years, mycorrhizal fungi have been the subject of intensive research due to their ability to help plants utilize nutrients more efficiently. Studies have shown that mycorrhizae make significant contributions to plant nutrition, particularly in phosphorus-deficient soils and those subject to heavy leaching. Mycorrhizae do not directly increase the amount of phosphorus in the soil; instead, they help plants absorb phosphorus and other nutrients more effectively by expanding the roots' effective absorption area (Hartmann et al., 2009). In addition, they increase water uptake, promote plant growth, enhance tolerance to stress conditions, and contribute to the maintenance of soil health (Barznjy et al., 2025).

The region surrounding plant roots, known as the rhizosphere, is a home to a vast number of microorganisms. These microorganisms include pathogens, saprophytes, and beneficial organisms that form symbiotic relationships with plants. Mycorrhizal fungi are among these beneficial microorganisms and constitute one of the most important components of root rhizosphere interactions.

Soil health is defined as the capacity of soil to sustain its functions as a vital ecosystem that supports plants, animals, and humans. This concept encompasses not only crop production but also its relationships with water quality, climate change, and human health. Therefore, in sustainable agricultural systems, the biological, physical, and chemical properties of the soil must be evaluated together (Lehmann et al., 2020). Mycorrhizal fungi contribute to maintaining this balance as a key component of soil biology.

In this chapter, the morphological characteristics and root system architecture of faba bean (*Vicia faba* L.) are comprehensively discussed, together with an overview of mycorrhizal associations. Particular emphasis is placed

on the role of mycorrhizal fungi in the growth, development, and root functioning of faba bean, as well as its significance for sustainable agricultural production.

2. BOTANICAL AND AGRONOMIC CHARACTERISTICS OF THE FABA BEAN

2.1. Agricultural Importance and General Characteristics of Faba Beans

The faba bean (*Vicia faba* L.) is an important field crop with versatile uses. The yield and quality characteristics of faba bean are strongly influenced by numerous factors, including environmental conditions, cultivation techniques, nutrient content, medicinal properties, and biological nitrogen fixing capacity. Therefore, to maximize the benefits of faba bean cultivation, careful planning is required for appropriate variety selection, proper sowing time, suitable cultivation techniques, plant density, planting depth, and balanced fertilization and irrigation practices (Deb & Paul, 2024). Due to its versatile uses, high nutritional value, and ability to adapt to various agroecological conditions, faba beans are recognized as a suitable crop for sustainable production systems in many regions where their agricultural potential has not yet been fully realized (Gasim et al., 2015).

Faba beans are widely consumed worldwide due to their richness in essential nutrients and their wide range of uses. While they are used directly as human food in developing countries, in developed countries they are primarily used as feed for pigs, horses, poultry, and pigeons (Singh & Bhatt, 2012).

Faba beans are a highly valuable crop, valued not only for their yield but also for their nutritional composition. The high protein, starch, and dietary fiber content of these plants has led to an increased focus on their role in human nutrition, and their economic value is rising alongside the increasing demand for plant-based protein sources. Incorporating faba beans into different production systems provides various ecological benefits. In recent years, faba beans have not been sufficiently utilized as an effective component of crop rotation in many production systems. However, incorporating faba beans into the agricultural production cycle is of great importance in reducing the use of chemical fertilizers and the associated environmental impacts (Deb & Paul, 2024).

2.2. The Spread and Origin of the Faba Bean

Faba bean (*Vicia faba* L.) is considered one of the oldest cultivated legume crops and is generally believed to have originated in the Middle East. Archaeological evidence from Northern Iran indicates that faba bean was cultivated approximately 11,000 years ago, where its seeds were stored and consumed by early human populations. Although the exact wild progenitor of faba bean has

not yet been clearly identified, most closely related species possess relatively small seeds. Similarly, small-seeded faba bean genotypes are still widely distributed throughout the Middle East (Cubero, 1974). The major centers of diversification and cultivation of faba bean include Southern Europe, Northern Europe, Ethiopia, and Southern China. In many of these regions, faba bean continues to represent an important source of human nutrition. Large-seeded cultivars were particularly developed in Europe and Southern China, where cultivated populations generally exhibit greater genetic homogeneity (Torres et al., 2006). Despite its agronomic and nutritional importance, global faba bean production has declined over the past century, especially in Asia and the Mediterranean region. Several factors have contributed to this decline, including the widespread cultivation of local varieties with low yield potential, high susceptibility to pests and diseases, reduced reliance on faba bean as a green manure and biological nitrogen source due to the extensive use of synthetic nitrogen fertilizers, and the replacement of faba bean with alternative crops offering higher economic returns (Torres et al., 2006).

2.3. Climate and Soil Requirements

The faba bean (*Vicia faba* L.) has been shown to grow optimally in heavy-textured soils, yet it is a versatile species capable of adapting to a range of soil types. Faba beans demonstrate a high degree of tolerance to a wide range of soil pH levels (6–9), with optimal performance observed in neutral, well-drained, medium-textured, calcareous, and loamy-clay soils, particularly in humid regions (Jensen et al., 2010).

Neutral or slightly alkaline soil conditions are generally preferred to maximize biological nitrogen fixation in root nodules of legumes. However, faba beans can also adapt to more acidic soil conditions compared to many other legume species (Singh et al., 2013).

As Gasim and Link (2007) demonstrate, the optimal climatic conditions for the optimal growth of faba beans are cool climates with an annual total rainfall of 650–1000 mm. The optimal temperature range is reported to be 18–27 °C.

Although faba bean is generally considered a frost-tolerant legume crop and sensitive to drought and flooding. The growing period can vary between 90 and 220 days, depending on climatic conditions and genetic properties. Although many legume species are sensitive to low soil temperatures during the germination period, the faba bean is one of the legume species with the highest germination capacity at low temperatures among cool-season grain legumes (Deb & Paul, 2024).

2.4. Cultivation Characteristics and Biological Nitrogen Fixation

For successful faba bean production, particularly under subtropical climatic conditions, it is crucial to evaluate the performance of different varieties under these environmental conditions. Sowing time and soil temperature are among the most critical environmental factors influencing seed germination, early seedling establishment, plant development, and final yield formation in faba bean (*Vicia faba* L.). Under suitable environmental conditions, faba bean seeds generally require approximately 20–25 days to complete germination and emergence. During this period, maintaining adequate soil moisture is essential to ensure successful germination and healthy seedling development. Due to the hard texture of faba bean seeds, water uptake and germination occur more slowly compared to many other legumes. Therefore, sowing depth is a critical cultivation factor. In faba bean cultivation, harvest time is one of the most important agronomic practices directly affecting product quality and yield. Harvesting too early or too late can lead to reduced seed quality and yield losses. Harvest maturity generally occurs 80–120 days after planting, depending on the variety and environmental conditions. (Deb & Paul, 2024).

Although *Rhizobium* bacteria can survive in the soil for several years, the existing population may not always include the most effective nitrogen fixing strains. Therefore, even though *Rhizobium* bacteria can survive in the soil for three to five years, it is recommended that seeds be inoculated annually to ensure maximum biological nitrogen fixation (Deb & Paul, 2024). To ensure that the infection process occurs rapidly as roots begin to form and that *Rhizobium* bacteria can effectively colonize the root zone, seeds must be inoculated immediately before sowing. These bacteria can rapidly infect the roots and initiate nodule formation. The most common cultivation method for faba beans is direct seeding. However, that in regions with a short growing season, transplanting seedlings may allow for earlier cultivation compared to direct seeding. (Etemadi et al., 2019).

3. ROOT SYSTEM AND DEVELOPMENT OF THE FABA BEAN

The faba bean (*Vicia faba* L.) has strong taproot and densely branched secondary (lateral) roots. As the growing season progresses, the lateral roots thicken and develop, particularly in areas close to the soil surface. Although the root system is generally robust, it may not always penetrate deep soil layers (Nourthern, 2017). The faba bean root system consists of a broad but relatively shallow taproot, along with numerous lateral roots. However, there are significant differences in root architecture among varieties. Varieties with deeper root systems generally exhibit higher tolerance to drought conditions (Zhao et al., 2017).

Faba bean roots can retain moisture in the deeper layers of the soil profile as the season progresses. This situation can limit the plant's access to

water under dry conditions, thereby reducing its drought tolerance. While root growth occurs most rapidly during the pre-flowering stage, it can continue until maturity under suitable environmental conditions. The faba bean plant is sensitive to compacted soil layers (subsoil). Therefore, it prefers deep, well-structured, and well aerated soils to allow roots to penetrate deeply. Various limiting factors present in the subsoil layers can restrict root development (Nourthern, 2017).

A symbiotic relationship develops in faba bean roots with *Rhizobium leguminosarum* bv. *viciae*, a nitrogen fixing bacterium. These bacteria form nodules on the roots. The size of the nodules varies; nodules actively fixing nitrogen are white on the outside and reddish on the inside. These nodules typically begin to appear about one month after emergence and, over time, become slightly flattened, taking on a fan like structure. Most nodules are found in the top 30 cm of the soil, with approximately 90% located within the first 15 cm. When active nitrogen-fixing nodules are cut open, a pinkish or reddish color is visible inside. This color stems from the presence of the leghemoglobin pigment, which plays a role in nitrogen fixation, and serves as an important indicator of the nodule's activity. While the plant provides the carbohydrates it produces through photosynthesis to the bacteria, the bacteria reciprocate by converting atmospheric nitrogen (N_2) into a form the plant can utilize (Jensen et al., 2010).

The selection of suitable crop varieties is considered one of the key factors in ensuring high yields and economic production in agricultural production. Advances in modern agricultural technologies necessitate the widespread adoption of environmentally friendly and sustainable practices. In this context, the use of biofertilizers is gaining increasing importance because they are environmentally safe and serve as a natural source of nutrients for plants. Biofertilizers contribute to improving soil fertility by increasing the amount of nutrients in the soil, thereby positively affecting crop yield (Barznjy et al., 2025). Furthermore, the beneficial microorganisms used as biofertilizers secrete plant growth regulators (phytohormones), produce antibiotic like compounds to promote plant growth, and enhance plant growth performance (Mitra et al., 2021).

4. THE IMPORTANCE OF MYCORRHIZAL FORMATION

Mycorrhizae are the result of a permanent association based on mutual exchange between plant roots and certain soil fungi. They are among the fundamental components of soil plant microorganism relationships. Mycorrhizal fungi form partnerships with a wide variety of plant species, and this symbiotic relationship benefits both organisms. Through this symbiotic association, fungi gain access to carbon fixed by the plant, while the plant benefits from improved acquisition of essential nutrients such as phosphorus, which would

otherwise be difficult to obtain (Taktek et al., 2015).

Mycorrhizae are fungal microorganisms that live in the soil. Mycorrhizal fungi can colonize many cultivated plants, and their effects on host plants vary. While mycorrhizal fungi absorb nutrients from the plant roots, they colonize, they also promote the plant's vegetative growth. These fungi also help plants absorb certain elements that cannot be directly taken up through the roots. Additionally, mycorrhizae stimulate the host plant's defense systems through the compounds they produce, thereby helping plants become more resistant to diseases and pests. These fungi also interact with many pathogens, plant-parasitic nematodes, and fungi, and these interactions can inhibit or promote fungal growth or influence the development of the organism with which they interact (Öztürk et al., 2022).

As previously explained in detail, mycorrhiza is a symbiotic relationship formed between plants and soil fungi, from which both parties benefit. In this symbiotic relationship, organic carbon is first transferred from the host plant to the fungus, and then inorganic elements are transported from the fungal structures to the plant; thus, both parties benefit. Mycorrhizal fungi can only survive in association with plants because they are unable to produce their own food. Although they can break down organic compounds to obtain energy, this alone is insufficient; they must live in association with plants to grow and develop (Jobim et al., 2019).

The vast majority of plant species cannot develop normally without a functional mycorrhizal symbiosis in their root systems. The fungal component of this symbiotic relationship significantly improves plant growth under conditions of mineral deficiency particularly phosphorus and nitrogen deficiencies commonly found in degraded Mediterranean soils and during water shortages. It also makes the plant more resistant to pathogen attacks (Razack et al., 2024).

4.1. Types of Mycorrhizae

Razack et al. (2024) define the rhizosphere as the soil volume that develops under the influence of roots and is characterized by intense microbial activity resulting from the diffusion or secretion of organic compounds at the root level. The rhizosphere is the portion of the substrate that is in direct contact with living roots and is under their direct influence.

Mycorrhizae are the result of a permanent association based on mutual exchange between plant roots and specific soil fungi. They are among the fundamental components of the soil plant microorganism relationship. Arbuscular mycorrhizae are considered the most primitive and widespread symbiotic structures in natural and agricultural ecosystems. Indeed, among these symbiotic fungi, arbuscular and vesicular endomycorrhizal fungi are the most

common group and are known for their positive effects on growth and stress tolerance (Razack et al., 2024).

When a fungus forms a symbiotic relationship with the roots of certain plant species, this relationship is called mycorrhiza. Mycorrhizae are divided into three main categories: arbuscular mycorrhizae, ectomycorrhizae, and endomycorrhizae. This classification is based on the morphological and anatomical characteristics of how fungi colonize plant roots. Mycorrhizae result from a permanent association between plant roots and specific soil fungi based on mutual exchange. They are among the fundamental components of the soil plant microorganism relationship (Razack et al., 2024).

Arbuscular mycorrhizae are considered the most primitive and widespread symbiotic structures in natural and agricultural ecosystems. Indeed, among these symbiotic fungi, arbuscular and vesicular endomycorrhizal fungi constitute the most common group and are known for their positive effects on growth and stress tolerance (Razack et al., 2024).

Ectomycorrhizae (ECM) do not penetrate plant roots or invade plant tissues. Instead, they live around the roots, forming a network of "spheres" or "sheaths" (mantles) that envelop the root surface. This mantle not only facilitates the uptake of nutrients but also provides protection against certain pathogens. This type of ectomycorrhizal association is most commonly observed in forest tree species (Sousa, 2023).

Another classification of mycorrhizae is endomycorrhizae. These fungi have the ability to penetrate plant roots via their hyphae. The hyphae form structures within the root cortex cells and can also develop between cells. Inside the cells, these hyphae swell to form an organelle-like structure where nutrients are stored; these nutrients are later utilized in the plant's metabolism (Sousa, 2023).

4.2. The Importance of Mycorrhizae in Plant Growth

Numerous studies have shown that root colonization by mycorrhizal fungi significantly increases the productivity of various plants, particularly in low fertility soils. The primary reason for this is the ability to absorb higher levels of essential nutrients such as phosphorus, zinc, and copper, which are necessary for plant growth. In turn, fungus also benefits greatly from this symbiosis, as it can feed on sugars, amino acids, and other organic compounds (photosynthetic assimilates) produced by plants through photosynthesis (Feijen et al., 2018).

In modern agriculture, under conditions where soil degradation and excessive reliance on chemical inputs have become increasingly problematic issues, mycorrhizal fungi offer a sustainable and natural solution for increasing crop production. These are beneficial fungi that form symbiotic associations

with plant roots, expanding the roots' effective surface area in the soil and thereby enabling the uptake of water and, particularly, limited amounts of phosphorus and micronutrients. By improving nutrient uptake, supporting root health, and enhancing resistance to drought, salinity, and soil-borne diseases, mycorrhiza emerges as a critical factor in enhancing plant growth and yield (Lokhande, 2025).

Plants inoculated with mycorrhizal fungi have a much greater capacity to absorb nutrients from the soil. These fungi extend their extremely fine hyphae deep into the soil, increasing the surface area from which nutrients are absorbed; thus, through the symbiotic relationship established with the roots, they reach far beyond the area accessible to root hairs. This enables plants to absorb vital nutrients including phosphorus, nitrogen, and essential micronutrients from a much larger volume of soil. The use of mycorrhizal inoculants in crop production not only enhances crop performance but also forms part of a more sustainable and regenerative agricultural practice (Sousa, 2023).

5. FUNCTIONAL MECHANISMS OF MYCORRHIZAL ASSOCIATIONS IN PLANTS

Phosphorus is one of the primary elements responsible for plant growth. Phosphorus deficiency can cause imbalances in plant growth and lead to reduced yields or stunted growth. Therefore, controlling phosphorus levels in the soil is of great importance for maintaining profitability in crop production. In the soil, phosphate ions are bound to colloids in the form of iron or aluminum phosphates; consequently, even if phosphate is present in the soil, a large portion of it remains unavailable to plants (Gaveriaux, 2012). Many researchers have emphasized the importance of arbuscular mycorrhizal fungi (AMF) in phosphorus uptake (Smith et al., 2011). demonstrated that under phosphorus deficiency conditions, plants can absorb approximately 90% of the phosphorus they require through AMF.

Phosphorus is present in all plant tissues, and its concentration varies depending on the plant organ. Plant species with high phosphorus requirements benefit significantly from the multifaceted functions of mycorrhizae. Studies have shown that plants inoculated with mycorrhizal fungi have a higher capacity to solubilize natural phosphates and mobilize phosphorus compared to non-inoculated plants. Microorganisms that utilize organic acids secreted by mycorrhizal fungi can also act as natural phosphate solubilizers. Phosphorus deficiency can also lead to the inefficient utilization of nitrogen and potassium (Razack et al., 2024).

The most significant effect of arbuscular mycorrhiza on plant growth is its role in the uptake of phosphorus by plants, particularly in the absence of this element when soil nutrients have low mobility. Phosphorus with low solubility cannot be taken up by plants. In plants with thick roots, in particular,

the surface area of roots in contact with the soil is small, resulting in low uptake of water and nutrients. In such cases, these plants establish a symbiotic relationship with arbuscular mycorrhizal fungi and are able to absorb elements such as phosphorus (P), calcium (Ca), manganese (Mn), copper (Cu), sulfur (S), and zinc (Zn) via fungal hyphae that can reach far distances. Arbuscular mycorrhizal fungi regulate soil pH through the secretions they produce, converting phosphorus into a form that plants can absorb, or by incorporating organic phosphorus compounds into their hyphae and transforming them into a form beneficial to the plant before transferring them to the plant (Öztürk et al., 2022).

Mycorrhizae play a beneficial role in the fixation of atmospheric nitrogen. Mycorrhizal fungi are often found in association with other microorganisms beneficial to plants, such as nitrogen fixing bacteria. In this way, mycorrhizal fungi promote the formation of nodules, which allow the roots to be colonized by these bacteria and enable the plant to access atmospheric nitrogen. In some mycorrhizal (Glomales) species, extra radical hyphae absorb nitrogen from the soil in the form of nitrate, nitrite, and ammonium. These molecules are converted by the fungus and stored in the extra radical mycelium cells in the form of arginine. This amino acid is then transported to the intra radical mycelium, where it is broken down into ammonium and subsequently transferred to the plant at the mycorrhizal level (Razack et al., 2024).

Nitrogen (N) in the soil is primarily lost through leaching or evaporation in the form of dissolved nitrate (NO_3). Arbuscular mycorrhizal fungi improve soil structure, enhance soil aggregation, and consequently increase the soil's water-holding capacity. Additionally, mycorrhizae take up nitrogen in the form of ammonium (NH_4) and retain it within their structure, preventing its loss from the soil. Furthermore, nitrogen released into the soil or water through the weathering of rocks is also retained by mycorrhizae. They can also acquire nitrogen released during the decomposition of organic matter. Studies have shown that approximately 20–75% of the total nitrogen uptake by arbuscular mycorrhizal plants can be transferred to their hosts by arbuscular mycorrhizal fungi (Sosa-Hernández et al., 2019).

Plants' mineral element requirements are not limited to phosphorus and nitrogen. Other elements such as sulfur, as well as trace elements like copper, zinc, iron, and manganese, are also essential for plant growth. These less mobile substances also benefit from the support of arbuscular mycorrhizal fungi (AMF), particularly because the extra root hyphae enable more efficient utilization of the soil (Gaveriaux, 2012).

In arbuscular mycorrhizal fungi (AMF), the extra root hyphal network facilitates more efficient water transport to root cells under limited conditions. Mycorrhizal plants are more tolerant to transplant shock and respond

positively to water stress. The following mechanisms are generally proposed to explain these physiological effects: improved mineral nutrition (particularly increased phosphorus uptake), expansion of the surface area covered by hyphae, activation of hormonal processes controlling stomatal opening and closing, and maintenance of water continuity at the soil plant interface (Gaston et al., 2017).

Mycorrhizal plants are more tolerant to abiotic and biotic stress factors. According to Egli and Brunner (2002), arbuscular mycorrhizal fungi (AMF) enhance plants' defense against soil-borne pathogens by synthesizing antibiotics, promoting tannin formation, and supporting the microbial flora within the fungal mycelium. In addition, phytohormones such as auxin, gibberellin, cytokinin, and ethylene secreted by mycorrhizal fungi promote plant growth.

The second mechanism that makes mycorrhizal plants more resistant to diseases is related to changes in physiological activity occurring in the roots. Plants under pathogen attack respond by producing antibiotic-like substances against these organisms (Razack et al., 2024).

Plants with arbuscular mycorrhizal fungi thrive under high-temperature conditions and are not significantly affected by heat. In plants colonized by arbuscular mycorrhizal fungi, under cold stress conditions, mycorrhizae can prevent water loss in plants, promote the synthesis of secondary metabolites to increase plant resilience, and cause an increase in protein content to protect against cold damage (Öztürk et al., 2022).

6. MYCORRHIZA AND ROOT DEVELOPMENT IN FABA BEAN

Certain natural properties of the soil can limit the yield increase that can be achieved through *Rhizobium* application alone. The primary limiting factor is the deficiency of essential nutrients required by both the plant and the *Rhizobium* bacteria. It is known that mycorrhizal associations enhance plant growth and nutrient uptake, particularly under conditions where nutrient deficiencies limit plant development (Sánchez-Navarro et al., 2020).

In addition to *Rhizobium* species, arbuscular mycorrhizal fungi (AMF) also play a significant role in the uptake of nutrient elements from the soil. This is because AMF act as phosphate-solubilizing microorganisms capable of mineralizing organic phosphorus and enhancing the availability of inorganic phosphorus. Phosphorus is considered one of the nutrient elements with the lowest availability to plants. This nutrient is closely associated with nodule formation and the effective functioning of nodules. Additionally, phosphorus is an essential element for the nitrogenase enzyme, which plays a role in the biological nitrogen fixation (BNF) process, to maintain its function (Sánchez-Navarro et al., 2020).

Mycorrhizal relationships not only enhance nutrient uptake but also improve the plant's overall vitality, root biomass, and stress tolerance. As a result, better flowering, pod formation, and seed development occur, leading to increased yields in terms of both quantity and quality.

Furthermore, since legumes are often grown in organic farming or crop rotation systems, the combined effects of mycorrhizal colonization and biological nitrogen fixation enhance soil fertility and reduce dependence on synthetic fertilizers. In addition to improving soil health and microbial diversity, this symbiotic relationship makes legume farming an environmentally sustainable and high-yielding option for long-term production systems. The ability of legume plants such as faba beans, beans, peas, lentils, chickpeas, and soybeans to form symbiotic partnerships with nitrogen fixing bacteria like *Rhizobium* sets them apart. Furthermore, when inoculated with mycorrhizal fungi, the productivity and soil-improving properties of these plants can be significantly enhanced. These fungi and nitrogen fixing bacteria work together to improve the uptake of phosphorus a nutrient that is often a limiting factor in legume growth. Energy transfer, root development, and effective nodulation that is, the formation of nitrogen-fixing nodules on the roots are entirely dependent on phosphorus. Through their extensive hyphal networks, mycorrhizae reach deeper and more distant soil layers, increasing root access to phosphorus and enhancing the availability and accessibility of nutrients for both the plant and its microbial partners (Lokhande, 2025).

Barznjy et al. (2025) evaluated the influence of mycorrhizal inoculation on growth, nutrient acquisition, and yield characteristics of faba bean. The findings revealed that mycorrhizal treatment significantly improved plant height, chlorophyll concentration, nutrient uptake, and overall yield. Moreover, the beneficial effects of mycorrhiza were enhanced under phosphorus fertilization. The study highlighted that improved phosphorus acquisition through mycorrhizal associations stimulated root development, which subsequently contributed to enhanced plant growth and productivity.

Argaw and Mnalku (2017) reported that mycorrhizal applications exerted significant effects on nodulation and yield performance in faba bean. In particular, inoculation treatments combined with *Rhizobium* markedly increased nodule number, nodule dry weight, and grain yield. The authors emphasized that the synergistic interaction between mycorrhizal fungi and *Rhizobium* enhanced symbiotic efficiency, thereby improving biological nitrogen fixation and overall plant performance.

Nodulation and biological nitrogen fixation in faba beans are directly influenced by phosphorus nutrition and the symbiotic relationships established with beneficial microorganisms in the rhizosphere. Sánchez-Navarro et al. (2020) reported that arbuscular mycorrhizal fungi enhanced phosphorus

uptake, thereby promoting nodule formation and biological nitrogen fixation. Similarly, Argaw and Mnalku (2017) demonstrated that effective *Rhizobium* inoculation increased nodule number and nodule dry weight, resulting in improved nitrogen fixation capacity. Sammama et al. (2022) further showed that the combined application of mycorrhizal fungi and plant growth-promoting rhizobacteria enhanced nutrient uptake, plant growth, and grain protein content. Collectively, these findings indicate that the complementary interaction between mycorrhizal symbiosis and *Rhizobium* bacteria plays a crucial role in nodulation, biological nitrogen fixation, and overall plant development in faba bean.

Numerous studies have demonstrated that mycorrhizal colonization positively influences root development in faba bean. This improvement in root growth is primarily associated with enhanced phosphorus acquisition through the extensive fungal hyphal network. Improved phosphorus uptake, in turn, promotes nodule formation and biological nitrogen fixation, thereby contributing to overall plant growth and development. Furthermore, the combined application of arbuscular mycorrhizal fungi and *Rhizobium* bacteria has been reported to enhance nutrient uptake, root biomass, plant growth, and yield performance more effectively than either treatment applied alone (Sammama et al., 2022). Through mycorrhizal symbiosis, roots are able to explore a larger volume of soil, enabling plants to utilize water and nutrients more efficiently. Consequently, this interaction contributes to improved root functioning and enhanced overall plant performance in faba bean. Therefore, mycorrhizal inoculation is considered an important biological tool for promoting root development, enhancing biological nitrogen fixation, and supporting the development of sustainable production systems in faba bean cultivation.

7. CONCLUSIONS

Faba bean (*Vicia faba* L.) is one of the most strategically important legume crops in global agriculture due to its high protein content, rich nutritional composition, biological nitrogen fixation capacity, and versatile uses. Its seeds, immature pods, and green biomass can be utilized for both human and animal nutrition, while also containing valuable bioactive compounds that contribute to human health.

One of the most important agronomic advantages of faba bean is its ability to fix atmospheric nitrogen through symbiotic associations with *Rhizobium* bacteria located in its root nodules. This characteristic not only contributes to plant nutrition but also enhances soil fertility and reduces the nitrogen requirements of subsequent crops. In addition, arbuscular mycorrhizal fungi (AMF) improve the uptake and utilization of several essential nutrients, particularly phosphorus, enhance water acquisition, stimulate root development, and increase plant tolerance to both biotic and abiotic stress conditions. The-

refore, faba bean plays an important role in sustainable agricultural systems and crop rotation practices.

The studies reviewed in this chapter demonstrate that the complementary interaction between mycorrhizal fungi and *Rhizobium* bacteria exerts positive effects on root development, nodule formation, nutrient uptake, and yield performance in faba bean. In particular, enhancing mycorrhizal colonization under phosphorus-deficient soil conditions improves the efficiency of biological nitrogen fixation, thereby promoting plant growth and development. Therefore, the utilization of mycorrhizae and other beneficial microorganisms is considered one of the key components of sustainable agricultural practices.

Future efforts aimed at improving faba bean production are expected to focus on the development of new cultivars with enhanced resistance to diseases and environmental stresses, the wider adoption of biofertilizers and microbial applications, improved resource-use efficiency, and the advancement of sustainable cultivation techniques. In particular, studies involving *Rhizobium*, arbuscular mycorrhizal fungi (AMF), and plant growth-promoting rhizobacteria (PGPR) offer significant opportunities for reducing chemical inputs while enhancing productivity in faba bean cultivation.

Considering the increasing global population, climate change, and the growing demand for plant-based protein sources, faba bean is expected to play an even more important role in ensuring food security and promoting sustainable agriculture in the future. Therefore, further research on faba bean and the effective transfer of scientific knowledge into agricultural production systems are of paramount importance.

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Chapter 4

EFFLUENT MANAGEMENT IN LAND-BASED AQUACULTURE ENTERPRISES: PRACTICES IN DIFFERENT COUNTRIES AND TÜRKIYE

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Introduction

Aquaculture is one of the main solutions to addressing global food scarcity. As the global population increases, the demand for aquaculture also rises. Aquaculture is the fastest-growing major food production sector in the world and already provides more fish for human consumption than capture fisheries. Because most wild fish stocks are being fished at or beyond their maximum capacity and land-based resources face intense competition, aquaculture presents a vital opportunity for increasing and sustaining food production. In fact, with the global population expected to reach 8.5 billion by 2030, aquaculture must continue to expand in order to meet current and future demand for fish for human consumption.

The main sources of pollutants in the effluent water of aquaculture operations include feed and fertilizer applications. Fresh feeds, farm-made feeds, or commercially produced feeds are the key components of aquaculture, and among these, commercial feed is widely used in aquaculture. Fertilizers are generally applied in pond aquaculture to enhance production. Approximately 75% of the nitrogen and phosphorus in feed is not utilized and remains in the water as waste. Therefore, uneaten and undigested commercial feeds, as well as applied fertilizers, are the primary sources of water pollution in aquaculture due to their high phosphorus and nitrogen content (Aşır and Pulatsü, 2008; Pulatsü and Kaya, 2016).In addition, feces—the final metabolic waste of aquatic organisms—can cause various changes in water due to their high nitrogen and phosphorus content (Ackefors and Enell, 1994). Most dead fish decompose in the water, and the resulting increase in organic load leads to water quality deterioration and toxic effects on aquatic life (Hlordzi et al., 2020; Liu et al., 2024).

Potential drugs and chemicals present in aquaculture effluents are widely used in the industry due to their important roles in increasing productivity, promoting the growth of aquatic organisms, and controlling diseases. Commonly used chemicals and pharmaceuticals in aquaculture include antibiotics, anesthetics, antifoulants, pesticides, PCBs, and disinfectants (Yun et al., 2020).

Although existing treatment technologies applied to aquaculture wastewater can remove certain pollutants, their effectiveness must be further improved in order to achieve zero-discharge and support the sustainable development of aquaculture. In Türkiye, the management of effluent water from fish ponds is a critical process aimed at both protecting environmental sustainability and ensuring compliance with legal regulations. This management includes various techniques and legal procedures to maintain water quality, particularly in land-based trout and marine fish farms. In this

review study, an overview of effluent management practices in land-based aquaculture operations in several countries that play a significant role in global aquaculture is presented, and the current practices in Türkiye are discussed.

Legal Regulations and Practices Regarding Effluent Water Management in Some Countries

The countries that produce the most aquaculture in inland waters are concentrated in Asia, thanks to their geographical features and abundant water resources. More than 90% of global inland aquaculture production comes from this region.It has been reported by Anonymous (2023a) that China is the world's largest aquaculture producer and that its pollutant emissions are also quite high. It has been emphasized that total phosphorus emissions originating particularly from aquaculture have reached twice the level of emissions from industrial sources; therefore, control of water pollutant emissions from aquaculture must be strengthened to protect and improve water environmental quality.

In China, effluent (discharge water) management in land-based aquaculture facilities is a critical environmental policy issue due to the country's massive aquaculture sector. China holds the largest share of global aquaculture production and is increasingly turning toward sustainable methods and technologies (Anonymous, 2026a).

In China, the "Law on the Prevention and Control of Water Pollution" provides for the establishment of national standards for water environmental quality and the discharge of water pollutants. The law also requires the development of integrated and rational planning for the designation of protected areas, particularly in relation to water bodies designated for the spawning, feeding, wintering, or migratory passage of fish or shrimp, as well as water bodies designated for the cultivation of fish, shrimp, or shellfish and the farming of algae (FAO, 2026a). Article 28 of China's revised Fisheries Law (2025) states that "those engaged in aquaculture must protect the ecological environment of water areas and tidal flats, scientifically determine the density and scale of aquaculture, carry out feeding and medication practices in a rational manner, ensure that the discharge of aquaculture wastewater complies with relevant pollutant discharge standards, and must not cause environmental pollution or ecological damage to water areas and tidal flats" (Anonymous, 2026a). In China, the "Technical Guidelines for the Development of Water Pollutant Discharge Control Standards in Local Aquaculture," issued by the Law and Standards Department of the Ministry of Ecology and Environment, entered into force on March 1, 2023. Within this framework, it is envisaged that wastewater discharge from aquaculture will be standardized, and wastewater treatment will be encouraged in large-scale

aquaculture production areas. The guideline recommends that local authorities define control measures according to local needs for improving water quality, taking into account different aquaculture types such as marine and freshwater aquaculture, closed and open systems, pond and industrial (factory-based) aquaculture, fish farming, and shellfish cultivation. The guideline specifies five mandatory indicators for wastewater discharge standards: suspended solids, pH, chemical oxygen demand (COD), total phosphorus, and total nitrogen. In addition, it states that local authorities may select additional discharge control indicators—such as biochemical oxygen demand (BOD_5), ammonia nitrogen (for freshwater discharge), inorganic nitrogen and reactive phosphate (for seawater discharge), color, odor, heavy metals, and antibiotics, as well as other parameters necessary for improving local water quality—as part of wastewater control measures (Anonymous, 2026b; c).

Inland fisheries and aquaculture in India are rapidly growing sectors that focus on the cultivation of carp and freshwater shrimp species. The general "Discharge Standards for Inland Surface Waters" (such as BOD: 30 mg/L, COD: 250 mg/L, and TSS: 100 mg/L), implemented by the Central Pollution Control Board (CPCB) of India, are based on "Schedule VI" of this regulation.

Freshwater aquaculture facilities are required to comply directly with these limits (Bhushan et al., 2016). In addition, the "Coastal Aquaculture Authority (CAA) Act (2005)" is the primary federal environmental law enacted to regulate the uncontrolled growth of shrimp and seafood farming in India's coastal and brackish water regions. According to this law, shrimp farms larger than 5 hectares are required to have a wastewater treatment system. Ponds designated for this purpose can also be used for secondary aquaculture activities, particularly for the cultivation of oysters, mussels, seaweed, and other fish species. However, it has been reported that in some regions, there are also wastewater treatment pond systems constructed in an unscientific manner on farms, with issues such as insufficient capacity, the use of low-quality materials, and inadequate bypass arrangements (Salunke et al., 2020).

In Indonesia, the Ministry of Environment and the Environmental Control Agency have enacted Ministerial Regulation No. 1 of 2025 to address one of the most urgent environmental issues in aquaculture, namely the effective and sustainable treatment of wastewater generated from shrimp farms. This regulation requires all shrimp farms to treat their wastewater using standardized technological methods before discharge. In relation to compliance with wastewater quality standards, it defines the maximum permissible concentrations for key pollutants such as BOD (50 mg/L), TSS (100 mg/L), ammonia (5 mg/L), phosphate (0.5 mg/L), and pH (6–9). Technical standards provide guidance to shrimp farms on how to consistently meet these

criteria, including through biological aerobic treatment systems, constructed wetlands with surface flow systems, and appropriate sedimentation and filtration units. Through operations compliant with these guidelines, shrimp farms reduce the risks of water pollution and legal non-compliance. The regulation requires government agencies to conduct annual evaluations of farm reports, guiding enforcement actions, capacity-building efforts, and pollution control initiatives. This, in turn, supports a continuous feedback loop, compliance, and a culture of continuous improvement (Anonymous, 2026d).

Aquaculture in Vietnam, particularly in coastal regions (e.g., the Mekong Delta and Ben Tre), is a sector subject to environmental standards (Anonymous, 2026e). The management of pond effluent is carried out using water treatment ponds, constructed wetland filters, and recirculating aquaculture systems (RAS) (Anonymous, 2026f; That and Hoang, 2024). Legal regulations concerning pond effluent (wastewater) from fish and shrimp farms in Vietnam are based on national technical legislation implemented by the Ministry of Natural Resources and Environment (MONRE) and the Ministry of Agriculture and Rural Development (MARD). In this official standard regulating the technical and sanitary conditions of brackish and marine shrimp farms, treatment and sedimentation areas are mandated by the following two provisions: a) The area of the water storage and primary sedimentation pond within the farm must be at least 15% of the total pond area, b) The area of the wastewater treatment pond must be at least 10% of the total pond area (Anonymous, 2026g). Similarly, in this standard— which governs commercial ponds engaged in intensive Pangasius farming, particularly in the Mekong Delta—it is stipulated as a technical infrastructure requirement that at least 10% of the total area must be allocated for the settling and biological treatment of wastewater prior to discharge (Anonymous, 2026h).

Bangladesh is one of the leading countries in inland fish production worldwide, and the sector is characterized by freshwater polyculture ponds in inland areas and shrimp farming in coastal regions. Most ponds in Bangladesh are semi-controlled extensive systems influenced by tidal movements. This situation can lead to pond effluents mixing directly with coastal ecosystems or estuaries (FAO, 2026b). In Bangladesh, the discharge of water from fish and shrimp ponds is primarily regulated under the Environment Conservation Act (ECA) and the Environment Conservation Rules (ECR). Traditional aquaculture in Bangladesh, which began in the 1980s, has rapidly developed over the past decade, doubling its production through more intensive farming techniques. However, the unplanned intensification of aquaculture and farm operations has raised significant concerns regarding environmental sustainability, particularly in coastal shrimp and marine

prawn farming. It contributes to soil salinization, mangrove degradation, flooding, loss of biodiversity, ecosystem destruction, climate change impacts, and adverse effects on local communities. In particular, regarding water pollution, the Department of Environment (DoE) is responsible for pollution control, standardization of water use and wastewater discharge, conducting environmental impact assessments, issuing environmental permits, and declaring and protecting degraded ecosystems. However, although the directive is of major importance in all aquaculture certification schemes, it lacks clarity regarding the aquaculture wastewater management system. Therefore, it has been stated that aquaculture wastewater management guidelines should be revised by prioritizing environmental management systems in order to regulate water use, optimize wastewater discharge, protect natural water resources, and ensure the proper disposal of pond sludge (Alam and Haque, 2026).

In European countries, wastewater and discharge management for land-based fish farms is regulated through a combination of general EU directives and specific national legislation. In the field of water policy, the aim of the Water Framework Directive (WFD) is to require Member States to take measures to achieve at least "good status" or "good potential" by 2015, 2021, or at the latest 2027, and to prevent the deterioration of all water bodies, including surface waters. The concept of "surface water bodies" in the Directive also includes coastal waters. The status of a specific surface water body is assessed based on both chemical status (maximum concentrations of priority substances listed in the Directive) and ecological status, which is determined through biological, hydromorphological, and physicochemical quality standards established by Member States for each water body. "Good status" is defined as specific conditions in which a surface water body shows only slight deviation from those normally associated with that water body type under undisturbed conditions (Anonymous, 2026i). While the EU Water Framework Directive (Water Framework Directive) sets an overarching objective for all water bodies to achieve "good ecological status," actual discharge limits and permitting requirements are determined at national or regional level by Member States within the European Union. Although the Water Framework Directive provides an innovative system for monitoring and regulating ecological and chemical quality, its complex requirements are considered challenging for Member States, and it is stated that a universally applicable assessment method has not been fully developed. Member States are required to establish a baseline status study for each river basin district, a river basin management plan, a program of measures necessary to achieve environmental objectives, and monitoring activities (Qu and Peng, 2025).

Sweden, Denmark, and Finland (including the autonomous region of the Åland Islands) are European Union member states in Northern Europe that share the Baltic Sea as a common marine resource. These Scandinavian countries share similarities in their legal traditions and histories, and they are all subject to the same EU legal framework. Nevertheless, their jurisdictions have adopted distinctly different approaches to regulating aquaculture, leading to varied impacts on the sector and different responses to the so-called common EU requirements. Kyrönviita et al. (2021) stated that the most important legislation protecting inland and coastal waters is the Water Framework Directive, an EU directive aimed at preventing further deterioration as well as improving the environmental quality status of the EU's fresh and coastal waters; however, it does not aim for the full harmonization of water legislations among EU member states. Indeed, there are significant differences in the ways member states regulate nutrient emissions originating from aquaculture and other environmentally hazardous activities in coastal regions. Aquaculture and the resulting nutrient emissions from this production are subject to permit requirements in each jurisdiction. Across all jurisdictions, establishing and operating a production facility requires one or more environmental permits of limited scope and duration, and approval is contingent upon compliance with national and EU legislation.

Wastewater management in land-based aquaculture facilities in Denmark is strictly regulated under the Environmental Protection Act and the Water Planning Act, focusing on minimizing nutrient discharges (nitrogen and phosphorus) and promoting sustainable technology. Following the 2015 Food and Agricultural Package, regulation shifted from production volume limitations to nutrient discharge permits based on Best Available Technology (BAT), aiming to reduce environmental impact, particularly in coastal areas.

All land-based aquaculture facilities with a direct water outlet are required to obtain environmental approval from the municipality, which is typically valid for 8–10 years. This permit establishes limits on the total annual discharge of nitrogen, phosphorus, and organic matter.

Nutrient-based regulation focuses on nutrient discharge rather than solely on fish production volume. This approach also allows for an increase in production capacity if the facility utilizes efficient technologies, such as Recirculating Aquaculture Systems (RAS). Post-2021 regulations classify land-based facilities according to their recirculation levels (low, medium, high), with high-recirculation facilities being defined as those that consume less than 1,000 liters of water per kilogram of feed.

Furthermore, there is a regulation concerning sludge, the output of land-based aquaculture, which promotes the reuse of sludge for biogas production or as fertilizer on agricultural land.

Denmark applies the "polluter pays principle," requiring aquaculture facilities to cover the costs of wastewater collection and treatment; this also includes a discharge tax based on the kilograms of nutrient discharged, thereby incentivizing the adoption of advanced treatment technologies. Municipalities are responsible for auditing compliance, with operators required to conduct mandatory self-monitoring and submit regular reports on effluent quality.

For coastal marine fish farms, there are provisions concerning the design of water intake and discharge systems, as well as requirements related to the quality of both inlet and outlet water (FAO, 2026c).

In Norway, wastewater management in land-based aquaculture is regulated by a strict legal framework aimed at promoting sustainable growth while protecting the marine environment, with particular emphasis on Recirculating Aquaculture Systems (RAS) and sludge management. The key regulations updated in 2025 require, especially for land-based salmon and trout facilities, strict environmental discharge permits, disinfection of intake water, and advanced treatment of wastewater. In this context, for land-based facilities, it has been specified that backup systems must be in place in the event of system failure, and that oxygen, pH, temperature, and salinity levels within the facility must be systematically monitored (FAO, 2026d). The filtration standards applied in Norway require that suspended solids larger than 0.45 μm in wastewater be reduced by at least 50% before discharge into the receiving environment. In addition, the regulations encourage the collection of waste sludge rather than its direct discharge, promoting its conversion into a source of organic fertilizer. It has been increasingly required that land-based facilities use technologies such as magnetic particle separation (MPS) or advanced drum filters to meet phosphorus (P) and suspended solids (SS) removal standards, and the regulatory framework treats aquaculture waste not merely as wastewater but as a potential resource. In line with EU directives, Norwegian authorities generally require that process wastewater and equipment cleaning be carried out using Best Available Techniques (BAT) (Anonymous, 2026j).

In Germany, wastewater management for aquaculture operations is strictly regulated primarily under the Federal Water Act (Wasserhaushaltsgesetz – WHG) and the Wastewater Ordinance (Abwasserverordnung – AbwV), which require compliance with the "best available technology." The regulations mandate that wastewater from commercial fish farms, including recirculating aquaculture systems (RAS), must be treated to remove solids and nutrients—

particularly phosphorus and nitrogen—before being discharged into water bodies. The EU Water Framework Directive (WFD), transposed into German law, requires water bodies to achieve "good status" (both chemical and ecological) by 2027. It has been indicated that land-based RAS facilities must apply advanced treatment methods for nitrogen removal, such as Moving Bed Biofilm Reactors (MBBR) and mechanical filtration systems (Anonymous, 2026k).

Wastewater management for land-based farms (including aquaculture and intensive livestock farming) in Spain is strictly regulated through a combination of European Union directives, national laws, and specific regional (Autonomous Community) regulations. The primary areas of focus include securing water rights, treating wastewater prior to discharge, and obtaining specific discharge permits. It is reported that land-based aquaculture must comply with regional rules on water abstraction and discharge, which are generally linked to Law 23/1984 on Marine Aquaculture or the Coastal Law (Law 22/88) (FAO, 2026e).

In Poland and Romania, freshwater pond aquaculture is generally addressed as a pressure factor on water bodies within River Basin Management Plans (RBMPs). However, many existing plans are criticized on the grounds that they lack specific funding or measures to effectively address these pressures (Anonymous, 2026l).

In the United States, fisheries and aquaculture operations are subject to the National Pollutant Discharge Elimination System (NPDES) permit program to manage pollution in their effluent. Established under the 1972 Clean Water Act, this system is administered by the U.S. Environmental Protection Agency (EPA) and regulates point sources that discharge pollutants into water bodies. Specifically, warmwater facilities that discharge wastewater for 30 days or more per year, or produce more than 45,454 kilograms (100,000 pounds) of fish annually, require NPDES permits; smaller facilities may also be subject to permitting under certain conditions. Furthermore, these permits impose limits on the amount of pollutants that can be discharged into a water body. These limitations are generally technology-based and designed to provide minimum pollution control, incorporating Best Management Practices (BMPs) that cover solids control, material storage, and record-keeping (Anonymous, 2026m).

In Australia, aquaculture is primarily managed by state and territory governments through various agencies (e.g., NSW DPI, PIRSA in South Australia). Adopted under the South Australian Aquaculture Act, the "Aquaculture Regulations (2005)" include provisions regarding environmental monitoring and reporting that address benthic assessment and water

quality. Furthermore, land-based facilities utilizing RAS are required to obtain an "operating license" or an "Environmental Authority" (EA) from the Environmental Protection Authority (EPA) and must comply with daily wastewater discharge limits (Anonymous, 2020). It has been reported that effluent must be passed through sedimentation ponds, biofilters, or similar treatment systems before being released into the environment, and that the nitrogen, phosphorus, and total suspended solids (TSS) levels of the wastewater must be limited so as not to exceed the carrying capacity of the receiving environment. Operations are obliged to regularly monitor effluent quality (temperature, pH, oxygen, ammonia, nitrogen, phosphorus) and report it to the EPA (FAO, 2026f).

In Japan, legal regulations applied directly and specifically to land-based aquaculture facilities are not separated from general industrial facilities, but are explicitly defined as a "Specified Facility" under the "Water Pollution Control Law." According to national legislation, water quality protection standards (BOD, COD, TSS, etc.) are mandatorily applied to all aquaculture facilities with an average daily wastewater discharge of 50 cubic meters or more (Anonymous, 2026n). In addition, standard values have been established for 13 substances, including BOD, COD, and DO, as well as total nitrogen and total phosphorus, to protect aquatic habitats and prevent eutrophication in lakes and coastal waters. Furthermore, to protect aquatic life resources, standard values for total zinc, nonylphenol, and linear alkylbenzene sulfonic acid and its salt were recorded in 2003, 2012, and 2013, respectively, as indicators of ambient water quality standards (Anonymous, 2026o).

Xu et al. (2024) reported that wastewater from aquaculture facilities is subjected to periodic testing to ensure that it does not harm the spawning and development periods—the most sensitive life stages—of fish and shellfish in the area where it is discharged.

SanPiN 2.1.3684-21 and SanPiN 1.2.3685-21 are the core regulations in the Russian Federation that entered into force as of March 1, 2021, governing wastewater discharge, water quality, soil protection, and sanitation processes for all industrial facilities, including aquaculture (land-based aquaculture) operations. Within the framework of the Action Plan for the Implementation of the Strategy for the Development of the Fisheries Sector of the Russian Federation until 2030, the system of legal regulations has been developed and integrated into the existing legislation. Best management practices are implemented for aquaculture operations; these practices include risk and benefit analyses of the impacts of aquaculture on water quality, encompassing organic pollution or eutrophication, as well as water pollution caused by drugs and chemicals used in aquaculture (Sinitsyna et al., 2022; Anonymous, 2026p).

In Peru, there are two distinct regulatory approaches for controlling inadequate wastewater from fish farms. The first is the implementation of a discharge licensing scheme that establishes the maximum permissible amounts of pollutants in wastewater from fish farms and provides for an associated sanction if these limits are exceeded. The second approach involves banning or restricting the use of certain drugs and chemicals known to have a detrimental effect on the quality of receiving waters and ecosystems. Discharge licensing systems, which incorporate water quality and/or water volume criteria, require regular monitoring at specified intervals to demonstrate compliance. This type of discharge licensing is suitable for large operations with one or more wastewater discharge points. The most effective system, however, is to use general discharge permits that require farmers to implement specific operational Best Management Practices (BMPs) and include minimum baseline monitoring requirements (Takoukam and Erikstein, 2013). Within its environmental policy framework, Peru established the Environmental Assessment and Enforcement Agency (OEFA) in 2008. OEFA directly oversees the enforcement of environmental regulations across different economic sectors, including fisheries and large-scale aquaculture. Fish farms must conduct periodic monitoring of their water quality (surface, mid-water, and bottom) and submit the results to OEFA; OEFA, in turn, monitors the compliance of water bodies with environmental quality standards (OECD, 2026).

In Chile, it has been reported that the maximum limits specified for the discharge of liquid wastes directly entering natural waters (lakes, lagoons) must not be exceeded. To enhance the environmental sustainability of the sector, a set of standards is implemented, and operations are encouraged to adopt the WWF-supported Aquaculture Stewardship Council (ASC) certification standards to protect local ecosystems and minimize pollution (Anonymous, 2021; 2023b).

Legal Regulations Regarding the Subject in Türkiye

Türkiye holds a leading position in aquaculture among European Union countries. In 2024, a total of 933,119 tons of fishery products were produced in our country. Of this production, a total of 355,995 tons was obtained through capture fisheries, with 322,388 tons from marine waters and 33,607 tons from inland waters. Through aquaculture, a total of 577,124 tons of fishery products was achieved, comprising 405,742 tons from marine environments and 171,382 tons from inland waters. According to 2024 data, there are 2,471 aquaculture facilities in our marine and inland waters with a total capacity of 859,973 tons/year (BSGM, 2026). If the discharge water from these facilities is not treated, the physical, chemical, and biological structure of the receiving environments will be adversely affected. In Türkiye, the effluent management of facilities

engaged in intensive inland fish farming in ponds is primarily carried out through a series of regulations based on the Fisheries Law (Anonymous, 1971) and the Environmental Law (Anonymous, 1983).

- **Regulation on water pollution control**

This regulation (Anonymous, 2004a) establishes the general principles and standards for all types of wastewater discharge into inland waters, stipulating that enterprises are obligated not to pollute water resources and must comply with discharge standards. In Table 20, presented under the section "Aquaculture Production Facilities" of the regulation, limit values regarding the quality parameters that the effluent from fish farms must meet before being discharged into the "receiving environment" (streams, rivers, etc.) are provided (Figure 1).

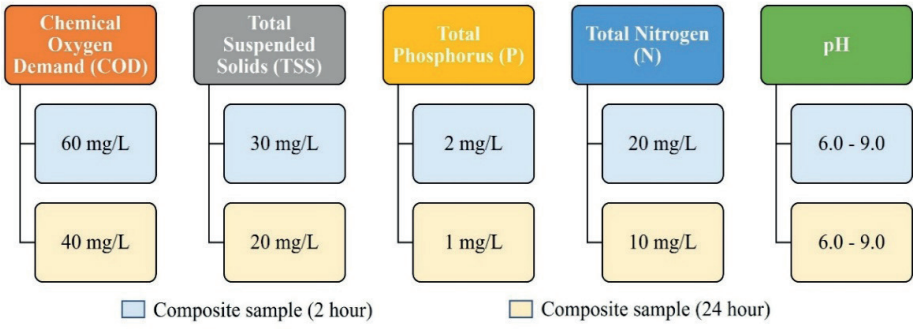


Figure 1. Maximum discharge limit values for effluents from aquaculture production facilities (Anonymous, 2004a)

- **Regulation on aquaculture**

Various legal regulations have been enacted in Türkiye to limit and reduce the environmental impacts of aquaculture. Article 22 of the Regulation on Aquaculture dated 29.06.2004 and numbered 25507 (Anonymous, 2004b) includes the following provisions:

Article 22 - The measures to be taken regarding environmental impact and protection in aquaculture facilities are specified below:

a) In aquaculture facility projects, compliance with the relevant provisions of the "Environmental Impact Assessment Regulation" is required.

b) Entrepreneurs are obliged to take measures to protect the environment during the construction and operation phases of aquaculture facilities. Within this framework, facility wastes shall not be discharged into the water body where

they are located; any materials and substances that may deteriorate water quality or cause harm to the environment, human health, and aquaculture health shall not be used.

c) *All necessary measures shall be taken to avoid causing visual pollution while carrying out aquaculture activities. Within this framework, in particular, feed bags and other wastes used in aquaculture shall be systematically removed from the facilities. Furthermore, land-based structures shall be designed in harmony with their surroundings, and their exterior facades shall be painted in a manner appropriate to the environment.*

d) *Necessary measures shall be taken to prevent the species produced in aquaculture facilities from escaping into nature.*

e) Waters discharged into the receiving environment by land-based aquaculture facilities and hatcheries must comply with the values specified in the Fisheries Regulation, and treatment systems capable of ensuring these conditions shall be established at the facilities.

f) Enterprises currently lacking a treatment system are obliged to make the necessary modifications to their layout plans and submit new layout plans—indicating the locations and technical specifications of these units—to the relevant Provincial Directorates for approval. The approval authority for the aforementioned modifications is the same authority that approved the initial project. The said facilities must fulfill this obligation within one year from the date of publication of this Regulation.

Article 22/e of the Aquaculture Regulation stipulates that the water discharged into receiving environments from land-based aquaculture facilities and hatcheries must comply with the limit values specified in the Fisheries Regulation. Additionally, this article encourages the installation of appropriate treatment systems to ensure that facilities can meet these quality criteria. Furthermore, Paragraph 2 of Article 17 of the Directive on Implementation Principles for the Aquaculture Regulation (Directive No: 2025/8) includes the provision: "*Facilities are obliged to install a system at their outlets to treat effluent using either a sedimentation pond with an area of at least five percent of the total pond area specified in their approved projects, or a drum filter, in a manner that ensures the removal of suspended solids*" (Anonymous, 2025).

- **Environmental Impact Assessment (EIA) regulation**

Within the scope of the Environmental Impact Assessment Regulation published in the Official Gazette dated 29.07.2022 and numbered 31907 (Anonymous, 2022), whether aquaculture facilities are subject to the environmental impact assessment process is determined by the annual

production capacity of the facilities. Accordingly, facilities with an annual production capacity of 1,000 tons and above are evaluated under the Annex-1 list, and it is mandatory to prepare an EIA report for these projects. On the other hand, facilities with an annual production capacity between 30 and 1,000 tons are included in the Annex-2 list, and the decision is made based on the evaluation conducted by the competent authority. On the other hand, aquaculture activities with an annual production capacity of less than 30 tons are generally excluded from the scope of the EIA; however, depending on the status of the project, an evaluation can be conducted within the framework of the relevant legislation.

Conclusion

Although Türkiye has largely aligned itself with the European Union (EU) environmental acquis regarding the effluent management of land-based aquaculture facilities, it maintains a structure that differs in practice compared to developed Western countries. Indeed, while facilities in Türkiye are predominantly inspected within the scope of the "Water Pollution Control Regulation," developed countries such as those in the European Union, Norway, and the USA implement the Water Framework Directive (WFD) and holistic river basin management plans. In Türkiye, as in most countries, specific concentration values regarding certain parameters are taken into consideration for effluent (Figure 1), whereas in countries such as Norway and the USA, the total nitrogen and phosphorus load (kg/day) discharged into the river or sea is calculated. Although sedimentation ponds are generally preferred for effluent management in our country, automatic drum filters, Recirculating Aquaculture Systems (RAS) technologies—which recycle up to 95% of water—and constructed wetlands are widely utilized in developed countries. Bottom sludge and suspended solids, which constitute the largest waste fraction of land-based facilities, are mostly precipitated in simple settling basins in Turkey; due to high initial investment costs, RAS systems are not yet widespread outside of hatcheries. Furthermore, the recovery and utilization of nutrient-rich effluents and waste sludge from aquaculture facilities in sectors such as agriculture are considered to be highly limited.

In conclusion, compared to EU countries, Norway, and China, Türkiye is close to the EU in terms of regulatory quality regarding the effluent management of land-based aquaculture facilities and has caught up with global standards in terms of legislative texts. However, since an inspection model based primarily on individual facility-based concentration limits is carried out, it is observed that the country lags behind in terms of technological transformation. In this context, the wider dissemination of environmentally friendly practices in the effluent management of enterprises will also contribute to the sustainability of aquaculture.

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