RESILIENT AGROECOSYSTEMS: STRATEGIC CROPS AND FUNCTIONAL BIOACTIVES IN A CHANGING CLIMATE

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PREFACE

Global climate change, increasing population pressure, soil degradation, and the need for sustainable management of natural resources necessitate a comprehensive reevaluation of agricultural production systems. Today, agriculture is no longer considered solely from a yield-increase perspective; it is approached through a multidisciplinary lens encompassing environmental sustainability, soil health, functional food production, and the development of value-added plant products. This volume aims to provide a holistic scientific contribution by examining these transformations through three strategic plant species.

The first chapter focuses on the cultivation of safflower (*Carthamus tinctorius* L.) in marginal and saline-stressed soils. The limiting effects of salinity on agricultural production are analyzed within the framework of plant–soil interactions and ion flow dynamics. The tolerance mechanisms, physiological adaptation processes, and bioremediation potential of safflower are discussed based on scientific evidence, presenting innovative approaches for the sustainable management of salinity-affected lands.

The second chapter addresses sustainable flax (*Linum usitatissimum* L.) production and fertilization strategies. The relationships between plant nutrition management, soil fertility conservation, balanced macro- and micronutrient application, and the reduction of environmental impacts are evaluated from a holistic perspective. The economic significance of flax as a fiber and oil crop is highlighted, and its role within sustainable production systems is analyzed based on empirical findings.

The third chapter examines the phytochemical properties of true cinnamon (*Cinnamomum verum* J. Presl) and its innovative applications in functional foods. The secondary metabolite profile, bioactive components, and antioxidant capacity are assessed, and its potential in food technology and functional product development is discussed. This analysis illustrates the interdisciplinary connections between agricultural production and human health.

This book serves as a scientific reference for researchers, academics, and graduate students in the fields of plant physiology, soil science, plant nutrition, agricultural biotechnology, and food science. Additionally, it provides a theoretical and practical framework for practitioners and policymakers aiming to develop sustainable production models.

03.03.2026

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TABLE OF CONTENTS

CHAPTER 1

SAFFLOWER (Carthamus tinctorius L.) CULTIVATION IN MARGINAL SALINE SOILS: BIOREMEDIATION OF SOIL SALINITY AND SUSTAINABLE MANAGEMENT OF ION FLUX DYNAMICS

PhD Candidate Suat CUN

INTRODUCTION

Climate change is currently regarded as one of the most critical challenges faced by farmers and the agricultural sector worldwide (Zaman et al., 2016). This global challenge, combined with exponential population growth, has become increasingly complex due to the adverse impacts of unpredictable climate variations associated with global warming, thereby posing a serious threat to agricultural sustainability. The effects of global warming have intensified the occurrence of severe environmental stresses such as extreme temperatures, salinity, drought, and flooding, leading to substantial declines in crop productivity, yield quantity, and quality (Kissoudis et al., 2014).

Among these stress factors, soil salinity is considered one of the most significant global constraints due to its detrimental effects on crop production (El-Ramady et al., 2024). The primary causes of salt accumulation in soils include primary salinization resulting from rock weathering and seawater intrusion in coastal regions, as well as secondary salinization associated with anthropogenic activities such as excessive fertilizer use, irrigation with low-quality water, waterlogging, and the discharge or leakage of industrial saline effluents (Sahab et al., 2021). As a consequence of these processes, soil salinity is not only a limiting factor for plant production but is also recognized as a form of soil degradation that disrupts the integrity of soil ecosystems. Soil degradation adversely affects not only plant growth but also soil microbial properties, soil functionality (e.g., biochemical cycling), and other ecosystem services provided by soils (Stavi et al., 2021).

From a plant-centered perspective, salinity stress is defined as a major abiotic stress arising from salt accumulation in the root zone, which physiologically weakens plants and renders them unsuitable for productive cultivation (Munns, 2005). Therefore, salinity significantly compromises global food security (Ortas et al., 2020). Approximately 20% of irrigated agricultural lands worldwide are affected by salt accumulation, which disrupts plant water uptake and nutrient availability, thereby limiting production potential (Hailu and Mehari, 2021). Under such adverse conditions, yield reductions ranging from 20% to 50% have been reported in salt-affected regions (Eswar et al., 2021). Excessive salt concentrations restrict water and nutrient absorption, induce plant stress, and ultimately reduce overall productivity. Consequently, salinity exerts negative impacts on both soil and plant health (Shin et al., 2022) and poses a severe threat to agricultural sustainability, particularly in marginal lands characterized by nutrient deficiency, contamination, low or absent rainfall, and overall unsuitability for conventional agriculture (Ramakrishna et al., 2020).

Safflower (*Carthamus tinctorius* L.), which exhibits high tolerance to abiotic stresses such as salinity, is regarded as a sustainable model crop for the utilization of salt-affected marginal lands due to its deep-rooted system and its ability to activate biological processes within the rhizosphere. However, the realization of this potential is directly linked to a comprehensive understanding of the pressures exerted by climate change on agricultural production.

Plant–Microbial Approaches for the Rehabilitation of Saline Marginal Lands

Marginal land is defined as land with low productivity that can be restored for agricultural use if it is economically feasible (Ramakrishna et al., 2020). Such lands typically include soils that are nutrient-poor, contaminated, subject to low or no rainfall, and therefore unsuitable for conventional agricultural practices. This category encompasses arid regions, wetlands, salt-affected areas, metal-contaminated sites, infertile rocky terrains, and high-altitude mountainous regions. These lands generally possess little or no agricultural value due to unfavorable soil conditions such as salinization, acidification, desertification, contamination, and low nutrient availability (Tilman et al., 2006). In addition, harsh climatic conditions, including drought and cold stress, along with inadequate agricultural infrastructure, further constrain crop growth in these environments (Qaseem and Wu, 2021).

From a global perspective, approximately 45% of lands exhibiting these characteristics consist of arid and semi-arid regions, accounting for nearly 40% of the Earth’s terrestrial surface, with a predominant distribution across Africa and Asia (Shahid and Al-Shankiti, 2013). Salt-affected marginal lands alone cover approximately 950 million hectares worldwide, and their extent is reported to be increasing annually by 1–2% due to climate change, inappropriate irrigation practices, and unsustainable agricultural management (Wong et al., 2010). This increasing trend necessitates the reassessment of marginal lands within sustainable agricultural systems and the development of site-specific rehabilitation strategies.

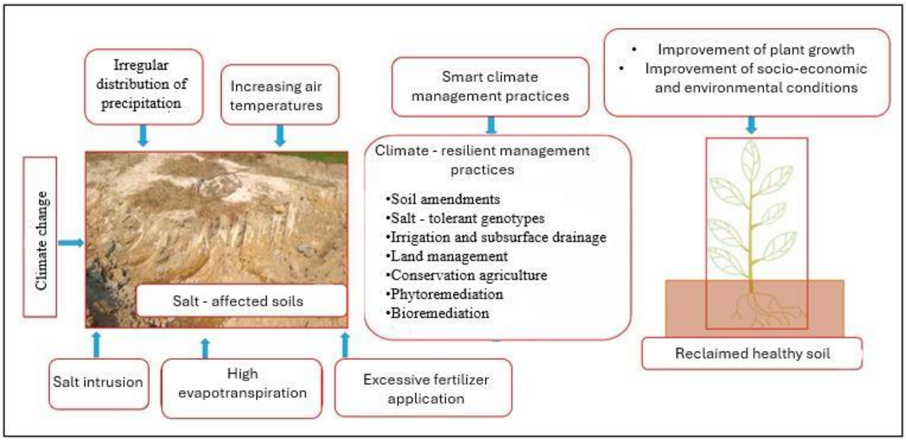

Figure 1. Schematic representation of the formation of salt-affected soils and their rehabilitation through climate-resilient management practices (Mukhopadhyay et al., 2021).

Bioremediation refers to the removal or mitigation of soil contamination through biological processes (Divya et al., 2015). The growing interest in the use of microorganisms as bioremediation agents offers potentially sustainable tools for the biological restoration of soils under various forms of degradation (Pollmann et al., 2018). Since saline soils impose abiotic stress conditions, physical and chemical remediation methods are often not cost-effective. Moreover, the availability of chemical amendments remains limited. In this context, the utilization of halophilic bacteria represents a promising strategy for improving saline soils by promoting vegetation growth (Arora et al., 2014) and enhancing soil properties such as water retention, aggregation, and the regulation of carbon source diffusion through the production of exopolysaccharides and biofilm formation.

In the case of bacteria, these microorganisms improve plant nutrient uptake, produce plant growth-promoting compounds, and simultaneously contribute to the restoration of soil quality (Grover et al., 2011). The application of halophilic bacteria in the remediation of saline soils through plant–microbe interactions is based on three fundamental principles (Arora et al., 2014):

1. Microbial activity in saline soils can support the growth of salt-tolerant plant species.
2. Bacteria can serve as biological indicators in saline wells, signaling that well water is of acceptable quality rather than excessively saline.
3. Through genetic manipulation, wild-type plants can be adapted to grow under saline soil conditions (Arora and Vanza, 2017).

The success of these biotic remediation approaches depends not only on the selection of appropriate microorganisms but also on the identification of suitable plant species capable of interacting effectively with these microbes. Plants intended for use in salt-affected marginal lands must exhibit tolerance to high salinity levels, regulate ion accumulation within the root zone, and support microbial activity in the rhizosphere. In this context, industrial crops with non-food applications emerge as sustainable alternatives for the utilization and rehabilitation of marginal lands.

Tolerance Mechanisms of Safflower Against Salinity Stress

Safflower (*Carthamus tinctorius* L.), belonging to the family Asteraceae, is cultivated worldwide due to its oil and flowers, which are used in the food, cosmetic, and dye industries. Owing to its tolerance to drought and salinity, safflower is considered a suitable crop for cultivation in semi-arid and saline soils where other oilseed crops cannot be grown economically (Önder et al., 2022). Although it is classified as a temperate climate plant, its tolerance to cold, drought, and salinity enables its cultivation in arid and semi-arid regions (Janmohammadi, 2016). Compared to other oilseed crops, safflower has remained a secondary (minor) crop; however, it is cultivated in more than 20 countries worldwide over an area exceeding 1,000,000 hectares (FAO, 2019). Safflower is recognized as a drought- and salinity-tolerant oilseed crop capable of producing reasonable seed yields under semi-arid climatic conditions (Lovelli et al., 2007).

Physiological Effects of Salinity Stress on Safflower

Under environmental stress conditions, increased production of reactive oxygen species (ROS) leads to the peroxidation of membrane lipids and pigments, as well as modifications in membrane permeability and functionality, thereby threatening the physiological integrity of plants (Wahid, 2007). In safflower, this process negatively affects numerous biological functions and results in the activation or suppression of genes encoding defense-related enzymes, transcription factors, and structural proteins (Jiao et al., 2021; Liu et al., 2021).

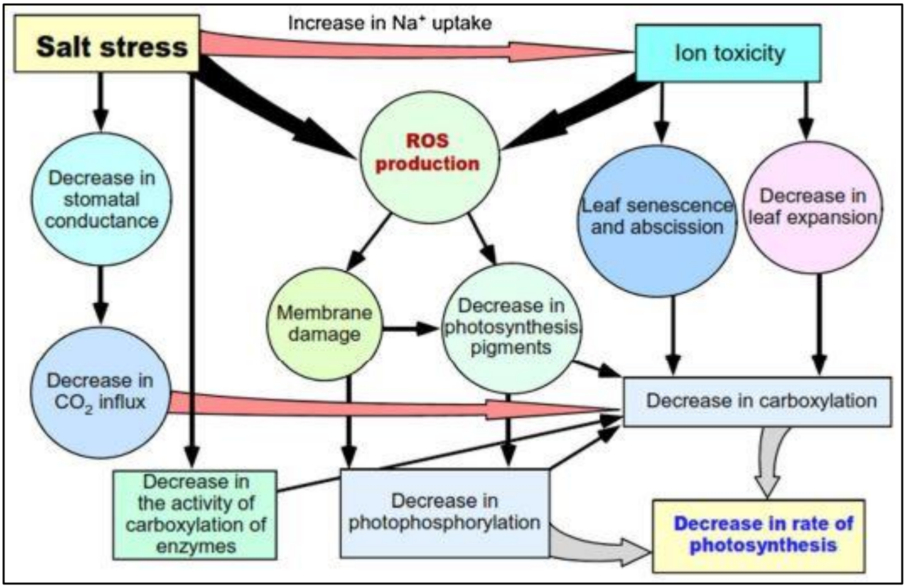

Figure 2. Physiological and biochemical effects of salinity stress on plants (Hussain et al., 2016).

Although safflower exhibits moderate tolerance to abiotic stresses, exceeding its tolerance threshold can lead to pronounced physiological impairments in growth and developmental processes (Salehi et al., 2023). Plant growth and development are significantly influenced by various environmental stress factors, particularly salinity, drought, and extreme temperatures. These stress conditions induce oxidative stress in plant cells by increasing the accumulation of reactive oxygen species (ROS), thereby exerting pressure on cellular metabolism.

Salinity stress resulting from increased NaCl concentrations in the soil adversely affects the growth and development of safflower, as it not only reduces water uptake from the soil but also restricts nutrient absorption (Pessarakli and Szabolcs, 2019). Consequently, plant water relations are disrupted, cellular turgor decreases, and both shoot and root growth are ultimately suppressed.

Ion Homeostasis Under Salinity Stress and Regulation of Na^+/K^+ Balance in Safflower

Specific ion toxicity resulting from the excessive uptake of certain ions is considered one of the primary causes of growth inhibition in plants under salt stress conditions (Chinnusamy et al., 2005). In salt-affected soils, the main ions responsible for toxicity are typically sodium (Na^+), chloride (Cl^-), and sulfate (SO_4^{2-}). Excessive accumulation of these ions in plant tissues induces ion toxicity, leading to severe disruptions in plant metabolism (Munns and Tester, 2008).

In salt-affected soils, excessive accumulation of Na^+ and Cl^- ions in the rhizosphere causes pronounced nutrient imbalances in safflower due to strong interactions with other essential mineral nutrients such as potassium (K), calcium (Ca), nitrogen (N), phosphorus (P), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) (Siddiqi et al., 2011). Under such nutrient imbalance conditions, the negative effects of salinity stress on safflower performance are further exacerbated (Hu and Schmidhalter, 1998).

Salt stress suppresses leaf water relation parameters, including relative leaf water content, water potential, osmotic potential, and turgor potential, ultimately reducing fresh biomass and inhibiting plant growth in safflower (Jabeen and Ahmad, 2012).

Numerous physiological studies have demonstrated that Na^+ toxicity arises not only from the direct toxic effects of Na^+ in the cytoplasm but also from the disruption of K^+ homeostasis due to the ability of Na^+ ions to compete for K^+ binding sites (Hussain et al., 2016). Sodium is the primary toxic ion in safflower that inhibits potassium uptake and translocation, leading to impaired stomatal regulation, increased water loss, and tissue necrosis (Siddiqi et al., 2011). Under salinity stress, competition between potassium and sodium significantly reduces potassium content in both the leaves and roots of safflower plants (Kaya et al., 2011).

Oxidative Stress and Antioxidant Defense Systems in Safflower Under Salinity Stress

Soil salinity is a major abiotic stress factor that affects plant growth, development, and yield by altering morphological, physiobiochemical, and molecular processes (Malhi et al., 2021; Imran et al., 2022). Under stress conditions, plants are exposed to severe adverse effects due to disruptions in cellular osmotic balance, restricted nutrient uptake, and reduced photosynthetic efficiency (Arif et al., 2020). Salinity stress induces nutrient ion imbalances, decreases stomatal conductance (Gholizadeh et al., 2017), causes morphological alterations, and triggers changes in secondary metabolite profiles (Munns and Tester, 2008). As a consequence of both osmotic and ionic stress, the production and accumulation of reactive oxygen species (ROS) increase, leading to oxidative damage. Elevated ROS levels result in lipid peroxidation, membrane disruption, and denaturation of biomolecules such as DNA, proteins, and lipids (Arif et al., 2020).

Secondary stress factors induced by salinity, such as oxidative stress, are primarily associated with excessive accumulation of ROS, including hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), hydroxyl radicals ($\bullet OH$), and superoxide radicals ($O_2\bullet^-$). These highly reactive and harmful ROS promote lipid peroxidation, thereby increasing membrane fluidity and permeability (Sharma et al., 2012), causing denaturation of functional and structural proteins, degradation of photosynthetic pigments (Nkomo et al., 2019), and inducing adverse effects on nucleic acids through base modifications (Jena, 2012).

The primary effects of ROS include peroxidation of membrane lipids and pigments, as well as modifications in membrane permeability and functionality (Wahid et al., 2007). Malondialdehyde (MDA) is the final product of the peroxidation of polyunsaturated fatty acids in cells. The level of lipid peroxidation is widely used as a reliable indicator of free radical-mediated damage to cellular membranes under stress conditions (Pistelli et al., 2019).

To survive oxidative stress induced by salinity and to maintain metabolic homeostasis, safflower plants have developed multiple adaptive strategies. One of the key stress defense mechanisms is the antioxidant defense system, which includes both antioxidant enzymes and low-molecular-weight antioxidants (Foyer and Noctor, 2005). Under stress conditions, plant cells mitigate the harmful effects of ROS through enzymatic antioxidants—such as catalase (CAT), glutathione reductase (GR), superoxide dismutase (SOD), and ascorbate peroxidase

(APX)—and non-enzymatic antioxidants, including carotenoids, α-tocopherol, reduced glutathione (GSH), ascorbic acid (AA), phenolics, and proline (Mansoor et al., 2022). Superoxide dismutase converts superoxide radicals ($O_2{\bullet}^-$) into hydrogen peroxide (H_2O_2), while catalase decomposes H_2O_2 into water and oxygen. In the presence of $O_2{\bullet}^-$ and H_2O_2, trace amounts of transition metals may lead to the formation of highly toxic hydroxyl radicals (•OH).

The non-enzymatic antioxidant system includes flavonoids, alkaloids, phenolic compounds, tocopherols, and carotenoids, all of which can donate electrons to the glutathione–ascorbate cycle, in which oxidized glutathione is regenerated to its reduced form (Gratão et al., 2005).

CONCLUSION

Globally, soil salinity is an abiotic stress factor that threatens arable land and crop production, thereby negatively affecting food security. In arid and semi-arid regions of the world, salinity stress not only restricts the expansion of plant production but also adversely impacts cellular metabolism, growth and developmental processes, and productivity through osmotic imbalance, ionic toxicity, and water deficiency. In this context, safflower, which has the potential to be cultivated in semi-arid and marginal lands, emerges as an alternative and strategic oilseed crop due to its inherent stress tolerance traits.

Understanding the physiological, biochemical, and molecular adaptation mechanisms exhibited by safflower under salinity and other abiotic stress conditions is of great importance for both fundamental plant physiology and applied agricultural and breeding studies. Plants exhibit a wide range of morphological and physiological changes, including alterations in plant phenotypes, micro- and ultrastructural organization, lipid peroxidation, and ion imbalance. Moreover, they initiate protective adaptations against salt-induced damage, such as osmolyte-mediated osmoregulation, ROS scavenging, photosynthetic adjustments, hormonal regulation, ion homeostasis, and gene regulation. The effectiveness of these mechanisms in coping with salinity stress plays a decisive role in determining whether a plant species is salt-tolerant or salt-sensitive.

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CHAPTER 2

FLAX (Linum usitatissimum L.) PRODUCTION AND FERTILIZATION STRATEGIES IN SUSTAINABLE AGRICULTURE

PhD Candidate Suat CUN

INTRODUCTION

Flax (*Linum usitatissimum* L.) is one of the 150 species belonging to the Linaceae family and is a crop with considerable potential due to its versatile uses and high adaptability (Jhala and Hall, 2010; Kiryluk and Kostecka, 2020). Although it originated in the Mediterranean region and Southwest Asia (Bilalis et al., 2018), its ability to adapt to a wide range of climatic conditions has led to its cultivation spreading across the Middle East, India, Canada, and several European countries (Kiryluk and Kostecka, 2020). Among these, Canada is recognized as the leading producer of flax worldwide (Madhusudhan, 2009). Flax is cultivated either for its fiber or for its seeds and the oil derived from them (Kiryluk and Kostecka, 2020). In fact, flax cultivars can be classified as oilseed or fiber types (Millam et al., 2005). The oil obtained from oilseed flax cultivars was initially used as a raw material in the production of varnish, paint, ink, and soap (Laza and Pop, 2012); however, it is now incorporated into human nutrition (Zhang et al., 2011).

Flax ranks fourth among commercial natural fiber crops worldwide (Bolton, 1995). Due to its more crystalline cellulose polymer structure, flax fiber is stronger, more brittle, and more difficult to process. This fiber wrinkles more easily and has been found to be comfortable to wear in hot climates because it rapidly absorbs and releases moisture (FAO, 2009). Flax fiber is soft, lustrous, and flexible, with fiber bundles resembling blond hair. Although flax fiber is less elastic than cotton fiber, it is stronger than cotton (Namrata et al., 2015). In addition to upholstery applications, flax is also used to reinforce composite materials (Le Duigou et al., 2016). Flax fiber has been referred to as a "plant muscle" because it performs a fundamental function by strengthening plant tissues and enhancing their mechanical resistance (Baley et al., 2018).

Global Production of Flax

Despite a substantial decline in the harvested areas of both oilseed and fiber flax worldwide, intensive breeding efforts have been undertaken, preventing a significant reduction in total global production. Indeed, according to FAOSTAT (2022) data, a dramatic increase (733%) in fiber flax yield per hectare was observed when comparing the 10-year average of the period 1961–1970 with that of 2011–2020. Similarly, for oilseed flax, a sharp increase (112%) in flaxseed yield per hectare was recorded between the 10-year average of 1961–1970 and that of 2011–2020.

Globally, the yield potential of fiber flax per unit area has shown considerable variation among countries. Belgium, the Netherlands, France, and China (4808–5490 kg ha^{-1}) exhibited significantly higher yields compared with other major fiber flax-producing countries such as the United Kingdom, Great Britain, Ireland, Chile, Belarus, the Russian Federation, Argentina, and Egypt (866–1443 kg ha^{-1}) (FAOSTAT, 2022).

Differences in the yield potential of oilseed flax among countries have also been observed worldwide; however, these differences were not as pronounced as those recorded for fiber flax. The United Kingdom, Great Britain, and Ireland (1868 kg ha^{-1}) had the highest oilseed flax yield potential, followed by France (1841 kg ha^{-1}), Canada (1477 kg ha^{-1}), the United States (1339 kg ha^{-1}), China (1273 kg ha^{-1}), Ethiopia (1053 kg ha^{-1}), and other countries (FAOSTAT, 2022).

Figure 1. Images of the Flax plant (*Linum usitatissimum* L.)

Flax Production in Türkiye

Flax is known in Türkiye by several local names, including bezir, bızıktan, cimit, siyelek, and zeyrek (Koçak et al., 2023). In Türkiye, the cultivation of flax for fiber production has shown continuous fluctuations in sown areas throughout the Republican period. As illustrated in Figure 2, it is not possible to refer to a stable development between 1928 and 2018. Flax cultivation was first recorded in 1928 on an area of 3.900 ha; shortly thereafter, the sown area expanded to 20,600 ha, but declined again to 7.718 ha in 1933. In the following years, although the cultivation area expanded for short periods, flax was grown on 41.431 ha in 1941; however, by 1945, the cultivated area had sharply decreased to 15.091 ha.

In 1948, flax reached the largest cultivation area in its history, covering 79.879 ha. Subsequently, a rapid contraction period began, and the cultivated area declined to 28.000 ha in 1955, 29.000 ha in 1962, and 13.000 ha in 1970. Although a short-term expansion in flax cultivation area was observed from the second half of the 1980s, the area did not exceed 5.000 ha after 1990, decreasing to 745 ha in 1993, 320 ha in 2000, 10 ha in 2010, 1.5 ha in 2015, and only 5 ha in 2018 (Afyonkarahisar–Çay).

The very limited cultivation recorded in the Çay district in 2018 was not commercial in nature but consisted solely of experimental plantings. Although these areas were reflected in the Farmer Registration System (ÇKS), no actual commercial initiative was realized. By 2019, flax cultivation was carried out on only 2.5 ha, with the reduction in cultivated area largely attributed to the inability to deplete existing stocks, particularly of fiber flax, from previous production years. In 2020, however, the cultivated area increased to 11.3 ha, representing the largest flax cultivation area recorded in recent years (TÜİK, 2022).

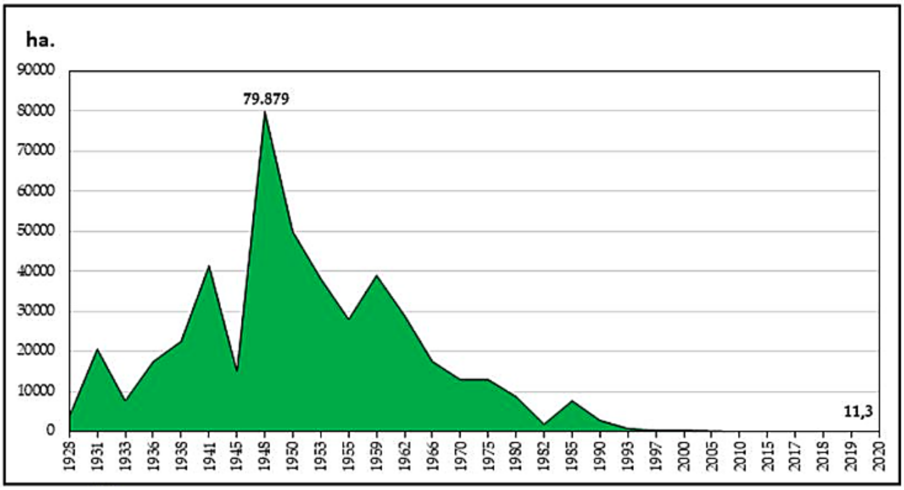

Figure 2. Changes in Flax Cultivation Areas in Türkiye (ha) (TÜİK, 2022)

Maintaining Soil Fertility in Flax Production

Intensive efforts are required to improve the physical and biological properties of soil as well as its fertility (Helmy and Ramadan, 2009). Soil fertility and plant nutrition are among the key components of crop production. The productive capacity of soils requires the provision of adequate and balanced amounts of nutrients to ensure proper plant growth. In reality, in most agricultural systems, soil nutrient status is severely constrained due to the limited use of inorganic and organic fertilizers and nutrient losses mainly caused by erosion and leaching (Tulema et al., 2007). Fertilizers improve soil structure, stimulate soil biological activity, increase the solubility of phosphorus applied to the soil as fertilizer, and play a critical role in enhancing soil fertility (Hailu et al., 2008).

Figure 3. Images of soils classified as unproductive in terms of crop production

Effects of Organic and Inorganic Fertilizers in Terms of Sustainable Agriculture

Chemical fertilizers play a crucial role in correcting nutrient deficiencies in soils. Nevertheless, their high cost and limited availability, particularly for small-scale farmers, represent major barriers to widespread use. Furthermore, the ongoing energy crisis, escalating fertilizer prices, and inefficiencies in the supply chain for inorganic fertilizers have highlighted the need to improve the use efficiency of organic fertilizers, green manures, crop residues, and other organic inputs alongside inorganic fertilizers in order to sustain crop yields (Sathish et al., 2011).

The prolonged and exclusive reliance on inorganic fertilizers adversely affects soil chemical and physical characteristics as well as biological activity, ultimately leading to a decline in overall soil health (Mahajan et al., 2008). Although the exclusive application of chemical fertilizers may result in short-term yield increases, such practices often lead to a gradual reduction in productivity and are not sustainable in the long term (Mahajan et al., 2008; Satyanarayana et al., 2002). In addition, excessive use of ammonium-based nitrogen fertilizers can induce soil acidification, further constraining soil fertility (Vanlauwe and Giller, 2006). In contrast, organic amendments release nutrients more slowly than mineral fertilizers but contribute significantly to the accumulation of soil organic matter (Pinitpaitoon et al., 2011). While Vanlauwe and Giller (2006) emphasized that organic nutrient sources alone cannot fully meet crop nutrient requirements, increases in soil organic matter, stimulation of microbial activity, and improvements in soil physical properties collectively enhance soil productivity (Watson et al., 2002).

Consequently, the combined application of inorganic and organic fertilizers is considered the most effective strategy for sustainable soil fertility management. Inorganic fertilizers supply nutrients in readily available forms, whereas organic inputs mainly improve soil organic matter content, structural stability, and buffering capacity (Alemu, 2015). This combined approach, commonly described as integrated nutrient management, has been widely acknowledged as an efficient method for improving crop yield while maintaining long-term soil productivity (Mahajan et al., 2008). Numerous studies (Singh and Agarwal, 2001; Mahajan et al., 2008; Farah et al., 2014) have reported that integrated nutrient management effectively alleviates both macro- and micronutrient deficiencies. Therefore, identifying the optimum rates of integrated nutrient application is essential to ensure sufficient nutrient availability and to achieve sustainable yield enhancement.

Optimization of Nutrient Uptake in Flax

Flax fertilization strategies have been extensively investigated, with numerous studies highlighting the crop's responsiveness to nutrient management. Among essential nutrients, nitrogen (N) plays a key role in stimulating vegetative development, improving canopy architecture, and ultimately enhancing yield performance in flax (Herzog et al., 2017; Kakabouki et al., 2021; Cui et al., 2022).

Consequently, a broad spectrum of N application rates, ranging from 20 to 150 kg N ha^{-1}, has been evaluated and recommended across different growing conditions (Kakabouki et al., 2021; Cui et al., 2022). The determination of an optimal N rate is largely influenced by soil properties and cultivar-specific characteristics (Kakabouki et al., 2021). However, in fiber flax production, excessive nitrogen supply has been reported to adversely affect yield by extending the vegetative phase, increasing susceptibility to lodging, and promoting disease development (Franzen, 2004).

Evidence from Herzog et al. (2017) further indicates that increasing nitrogen inputs may compromise flaxseed quality, as higher N rates were associated with a reduction in the α-linolenic acid concentration of flaxseed oil. In contrast, appropriate phosphorus (P) management has been shown to enhance oil quality parameters (Xie et al., 2014). In addition to quality improvements, P fertilization contributes to greater dry matter accumulation, higher seed and fiber yields, and improved yield components in flax (Xie et al., 2014; Xie et al., 2020). Potassium (K) nutrition has also been linked to increases in plant biomass and grain yield (Sun et al., 2015); however, similar to phosphorus, potassium fertilization does not appear to significantly influence flax oil content, composition, or overall oil yield (Berti et al., 2009).

According to a comprehensive review by Cui et al. (2022), the application of organic fertilizers in flax cultivation markedly improves grain quality, although their effects on yield remain inconsistent. Based on available literature, the authors proposed optimal fertilization ranges of 75–150 kg N ha^{-1}, 35–75 kg P_2O_5 ha^{-1}, and 35–52.5 kg K_2O ha^{-1} for flax production. Moreover, the integrated use of organic and inorganic nutrient sources has produced favorable outcomes by enhancing agronomic performance while preserving soil fertility and improving nutrient use efficiency (Xu et al., 2008; Yang et al., 2016).

Relationship Between Environmental Stress Factors and Fertilization in Flax Cultivation

The relationship between soil water availability and plant growth is strongly regulated by prevailing climatic conditions, particularly the frequency and intensity of extreme events such as droughts and heat waves (Hasanuzzaman et al., 2013). Insufficient water supply during the crop growth cycle restricts plant growth, results in reduced organ size, and disrupts key reproductive processes, including flowering and grain development (Farooq et al., 2009).

Within the group of abiotic stresses—defined as constraints imposed by unfavorable non-living environmental factors—drought represents one of the most severe limitations to crop productivity. In addition to drought, plants are adversely affected by other abiotic stressors such as soil salinity, temperature extremes, and various environmental anomalies, all of which can significantly impair plant performance and yield formation (Kaloki et al., 2019).

a. Drought Stress and Fertilization Interaction

Drought stress is a major environmental constraint characterized by limited water availability, which adversely influences plant growth, developmental processes, and productivity, particularly under arid and semi-arid climatic conditions (Battipaglia et al., 2014). Water deficit conditions disrupt multiple physiological and biochemical functions in plants, including biomass production, photosynthetic pigment concentration, water and nitrogen use efficiency, cellular organization, and the activity of essential metabolic enzymes (He et al., 2016; Chen et al., 2019). Furthermore, drought stress promotes the excessive generation of reactive oxygen species (ROS), resulting in oxidative stress at the cellular level. This oxidative imbalance suppresses photosynthetic performance, triggers stomatal closure, and modifies enzyme activities. Elevated ROS levels pose a serious threat to cellular integrity by inducing electron leakage, lipid peroxidation with subsequent membrane damage, and structural injury to nucleic acids and proteins (Maksup et al., 2014).

Flax is particularly vulnerable to drought and elevated temperature conditions, with the most pronounced adverse effects occurring during the seedling, flowering, and early seed-filling stages. Early investigations by Martin and Leonard (1967) demonstrated that water limitation toward the later stages of the growth period significantly reduces seed yield in flax, a conclusion that was subsequently confirmed by Casa et al. (1999).

b. Salinity Stress and Nutrient Management

Soil salinity has increased markedly in recent decades as a result of multiple interacting factors, including excessive irrigation practices, mineral weathering of parent materials, insufficient rainfall, ion exchange processes, high rates of surface evaporation, and inappropriate agricultural management (Dubey et al., 2020; Singh et al., 2021; Tao et al., 2021). Projections by Shrivastava and Kumar (2015) suggest that salinization may affect more than half of the world's arable land by approximately 2050. At present, saline conditions are estimated to impact nearly 33% of irrigated agricultural lands and about 20% of the total cultivated area globally. In flax, soil salinity and alkalinity have been reported to delay germination and seedling emergence, decrease seedling survival, disrupt uniform crop growth, and ultimately lead to yield losses (Dubey et al., 2020).

A number of studies have focused on screening flax germplasm for tolerance to salinity–alkalinity stress and have identified salt-tolerant genotypes based on traits such as germination performance, seedling vigor, biomass accumulation, and favorable K^+/Na^+ ratios (Nasri et al., 2017; El-Afry et al., 2018). In addition, Khan (2022) reported the identification of specific genes in flax that contribute to salt tolerance by promoting root elongation, maintaining membrane stability, and regulating ion distribution within plant tissues. Owing to its capacity to tolerate soil pH values of up to 9, flax can be successfully cultivated in marginal agricultural lands where many other crops fail to grow.

CONCLUSION

Flax (*Linum usitatissimum* L.) is a strategically important crop in both agricultural and industrial contexts due to its fiber and oilseed characteristics and represents a valuable alternative that should be reconsidered within sustainable agricultural systems. The conservation and improvement of soil fertility constitute fundamental components of sustainable flax production. Long-term production systems based solely on the use of inorganic fertilizers have been shown to exert negative effects on soil health, whereas the combined use of organic and inorganic fertilizers clearly supports soil physical, chemical, and biological properties.

The integrated nutrient management approach optimizes nutrient uptake in flax while increasing soil organic matter content and contributing to the long-term sustainability of production systems. Strengthening the role of flax within sustainable agricultural systems depends on the adoption of appropriate soil management practices, balanced and integrated fertilization strategies, and production approaches that take environmental stress factors into account.

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CHAPTER 3

TRUE CINNAMON (*Cinnamomum verum*): PHYTOCHEMICAL CHARACTERISTICS and INNOVATIVE FUNCTIONAL FOOD APPLICATIONS

Ibrahim CANBEY

INTRODUCTION

The genus *Cinnamomum* encompasses a diverse group of plant species that have been extensively utilized for centuries as foods, food additives, and culinary spices (Sharifi-Rad *et al.*, 2021). Cinnamon species are widely distributed across different regions of the world and hold significant economic and cultural importance. Among these species, true cinnamon, also referred to as Ceylon cinnamon (*Cinnamomum verum*), a member of Lauraceae family, is regarded as the most authentic representative of the genus (Wijesinghe *et al.*, 2020a). This species is indigenous to Sri Lanka, with its natural habitat extending to southern India. In addition to its native regions, *C. verum* is currently cultivated and distributed across several Asian, Caribbean, Australian, and African countries (Singh *et al.*, 2021). The species is also known by the botanical synonym *Cinnamomum zeylanicum* Blume, a name derived from the former designation of Sri Lanka, Ceylon, reflecting its historical and geographical origin (Thakur, 2023).

C. zeylanicum is an evergreen tree that typically attains a height ranging from 10 to 15 meters (Jakhetia *et al.*, 2010). *C. verum* thrives in humid environments characterized by well-drained soils, which provide favorable conditions for its optimal growth and development

(Wijesinghe *et al.*, 2020a). The plant is characterized by small, greenish flowers arranged in panicle-type inflorescences, which emit a distinctive aromatic odor. Its fruit is a purple, berry-like drupe approximately one centimeter in diameter, enclosing a single seed (Jakhetia *et al.*, 2010).

C. zeylanicum Blume has achieved worldwide recognition due to its notable therapeutic properties and its characteristic spicy aroma, both of which are closely associated with its distinctive chemical profile (Madhushika *et al.*, 2024). The sensory attributes of cinnamon are primarily derived from its aromatic essential oil (EO) fraction, which constitutes approximately 0.5%–1% of the plant material (Jakhetia *et al.*, 2010). EOs represent one of the most prominent classes of SMs, and are largely responsible for the characteristic fragrance of aromatic plants (Canbey *et al.*, 2025). Owing to these properties, *C. verum* has been extensively employed for centuries in both medicinal practices and culinary applications across diverse cultures (Singh *et al.*, 2021).

The nutritional profile of cinnamon indicates that it is a rich source of essential vitamins and minerals, while its biological activity is primarily associated with key biologically active constituents, notably polyphenols and cinnamaldehyde. The concentration and composition of these bioactive phytochemicals are influenced by multiple factors, including plant variety, anatomical part, edaphoclimatic conditions, post-harvest processing, drying practices, as well as extraction and analytical techniques. Owing to its wide range of biological properties, cinnamon has attracted considerable interest for direct incorporation into food products and for use as a functional component in active food packaging systems (Ribeiro-Santos *et al.*, 2017). In addition to its applications in food formulations, cinnamon is extensively utilized in various industrial products, such as confectionery items, chewing gums, mouthwashes, and toothpaste, reflecting its broad functional versatility (Singh *et al.*, 2021).

In this section, the phytochemical composition of true cinnamon and its innovative applications in the food industry are comprehensively examined in light of current scientific evidence. This chapter aims to serve as a thorough scientific resource that may contribute to and support future research endeavors in this field.

1. The Chemical Composition of Cinnamon

Spices represent valuable dietary sources of essential nutrients, including vitamins, proteins, dietary fiber, and minerals, such as calcium, magnesium, iron, and zinc, all of which contribute significantly to various biological functions. Within this framework, spices, like cinnamon are distinguished by their rich content of functional constituents, particularly phenolic compounds (PhCs) and volatile components, which underpin their nutritional and functional properties (Kumar *et al.*, 2025).

EOs are natural secondary metabolites (SMs) that differ structurally from edible oils, as they are not composed of triglycerides. They are generally characterized by a lower density than water, insolubility in aqueous media, and may appear colorless or slightly colored, ranging from pale yellow to light yellow. These compounds are responsible for the characteristic aroma of plants, and are known for their intense fragrance and pungent sensory properties (Canbey & Gürbüz, 2026). As volatile, natural, and chemically complex substances, EOs are biosynthesized by aromatic plants as SMs, and occur as mixtures of diverse bioactive compounds (Canbey, 2025a). Although distillation is the most commonly employed method for obtaining EOs, alternative extraction techniques may also be applied depending on the plant material and targeted compounds (Canbey, 2025b).

In this context, the phytochemicals present in cinnamon can be extracted from different plant parts using distillation or solvent-based extraction methods (Muhammad & Dewettinck, 2017). Nearly all organs of aromatic plants, including buds, flowers, seeds, fruits, leaves, stems, and roots, are known to contain EOs, which predominantly accumulate in specialized structures, such as secretory cells and epidermal tissues (Canbey, 2025c). Similarly, various anatomical parts of the cinnamon plant, including the bark, leaves, twigs, roots, wood, and fruits, can be effectively utilized for the production of EOs through distillation processes (Muhammad & Dewettinck, 2017). However, it is important to note that the chemical composition and relative abundance of EO constituents may vary considerably among different plant parts, reflecting physiological, biochemical, and environmental influences (Canbey, 2025c).

The leaves and bark of the cinnamon plant are commonly utilized as primary sources for the extraction of cinnamon EO (Ribeiro-Santos *et al.*, 2017). The EO yield of cinnamon generally ranges between 1% and 4%, with its chemical profile predominantly characterized by compounds, such as cinnamaldehyde, eugenol, and trans-cinnamic acid (Baser, 2012). In addition to these constituents, other studies have reported cinnamaldehyde, eugenol, caryophyllene, cinnamyl acetate, and cinnamic acid as the major components of cinnamon EO, highlighting the compositional complexity of this aromatic extract (Singh *et al.*, 2021).

Cinnamon EO, derived from species of the *Cinnamomum* genus, is considered one of the most valuable EOs for the food industry due to its distinctive aroma and functional properties. The oil can be obtained from different anatomical parts of the plant, including the roots, bark, and leaves, each of which exhibits a characteristic chemical composition. Notably, EO extracted from cinnamon bark is particularly rich in cinnamaldehyde, whereas leaf-derived oil is dominated by eugenol, and root EO is characterized by a higher camphor content (Feltes *et al.*, 2023).

Numerous studies have been conducted on EOs, and within this context, in a study, it was demonstrated that the EO composition obtained from the flowers and leaves of *C. verum* differs quantitatively. The findings revealed notable variations in the relative proportions of major constituents between flower-derived and leaf-derived EOs, indicating that the anatomical origin of the plant material significantly influences EO profiles (Table 1). (Narayanankutty *et al.*, 2021).

Table 1. GC–MS profiling of selected major constituents identified in the EOs extracted from the leaves and flowers of *C. verum* (Narayanankutty *et al.*, 2021)

Compounds	Leaf EO (%)	Flower EO (%)
(E)-Cinnamaldehyde	35.6	42.88
Eugenol	18.69	21.33
Linalool	18.92	15.62
(E)-Cinnamyl acetate	12.5	8.26
p-Cymene	1.88	2.68
Myrcene	1.54	1.99
Eugenyl acetate	1.38	0.74

In a comparable study, the phytochemical composition of EOs obtained from the bark and leaves of *C. verum* was analyzed using GC–FID and GC–MS techniques. The results indicated that the predominant constituents of *C. verum* EOs included (E)-cinnamaldehyde, trans-cinnamic acid, cinnamyl acetate, and benzaldehyde. Furthermore, the study revealed that both the qualitative profile and relative abundance of EO components varied depending on the geographical origin of the plant material, as well as the specific plant part used for extraction (Phu *et al.*, 2022).

Moreover, in another study, the EO isolated from the petiole of *C. verum* was characterized using GC–MS techniques. The analysis revealed that (E)-cinnamaldehyde was the dominant constituent (33.04%), followed by eugenol (17.32%), linalool (16.85%), and (E)-

cinnamyl acetate (11.78%) as major components of the EO (Rao *et al.*, 2007). In addition, the EO constituents of *C. verum* petiole were classified into distinct chemical groups, as summarized in Table 2.

Tablo 2. Classification of EO constituents identified in the petiole of *C. verum* (Rao *et al.*, 2007)

Grouped components	Percentage in EO
Aromatic aldehydes	33.04
Phenols and phenolic ethers	18.62
Aliphatic alcohols	16.90
Aromatic esters	12.01
Monoterpenes	3.01
Monoterpene esters	2.25
Cyclic alcohols	0.74
Oxides	0.46
Cyclic terpene ketons	0.16
Aromatic alcohols	0.09
Sesquiterpenes	0.03

In addition to these findings, several scientific studies have examined the EO constituents present in the leaves and bark of *C. zeylanicum* (*C. verum*), and selected results from these investigations are presented in Table 3.

Table 3. Major EO constituents identified in the leaves and bark of *C. verum* (*C. zeylanicum*)

EOs from plant parts	Main EO compounds (%)	References
The EO obtained from fresh leaves of *C. zeylanicum*	Eugenol (89.1%), linalool (4.3%), benzyl benzoate	Jazet Dongmo *et al.*, 2007

	(3.1%), and cinnamaldehyde (1.5%)	
C. verum leaf EO	Eugenol (77.22%), benzyl benzoate (4.53%), trans caryophyllene (3.39%), acetyl eugenol (2.75%), linalool (2.11%), trans-cinnamaldehyde (1.69%), and acetic acid cinnamyl ester (1.49%)	Wijesinghe *et al.*, 2020b
EO of *C. verum* bark	Trans-cinnamaldehyde (72.81%), benzyl alcohol (12.5%), and eugenol (6.57%)	Yap *et al.*, 2015
EO of *C. zeylanicum* bark	(E)-cinnamaldehyde, constituting 77.93%, followed by eugenol (4.34%), E-caryophyllene (3.68%), and linalool (2.79%)	Živković *et al.*, 2025

Furthermore, cinnamon bark is known to contain a diverse range of PhCs, particularly condensed tannins, such as catechins and proanthocyanidins, which constitute approximately 4%–10% of its composition. In addition to these PhCs, bark cinnamon also comprises gum, mucilage, resinous substances, starch, sugars, and trace amounts of coumarins (Baser, 2012).

Within this framework, phytochemical investigations have demonstrated that methanolic extracts of *C. zeylanicum* exhibit a pronounced presence of bioactive constituents, including alkaloids, flavonoids, tannins, PhCs, and saponins. Notably, fatty acids were detected exclusively in methanolic extracts derived from the stem bark (Mazimba *et al.*, 2015). Moreover, in another study, methanolic bark extracts were analyzed using GC–MS, UV–visible spectroscopy, and thin-layer chromatography to assess and elucidate the structure of proanthocyanidins present in *C. zeylanicum* bark. The phytochemical findings confirmed the presence of a proanthocyanidin compound, identified as procyanidin B_2 (Varalakshmi *et al.*, 2017).

In addition to these studies, numerous investigations have focused on the phytochemical constituents of extracts obtained from *C. verum* (*C. zeylanicum*), and selected findings from the literature are summarized in Table 4.

Table 4. The phytochemical compounds identified in the extracts of *C. verum* (*C. zeylanicum*)

Extracts from plant	Chemical composition	References
C. zeylanicum bark extract	Alkaloids, fixed oils, flavonoids, glycosides, gums, proteins, resins, steroids, and tannins	Aloraby *et al.*, 2024
C. zeylanicum bark powder extract	Alkaloids, carbohydrates, flavones, glycosides, saponins, phenols, resins, steroids, tannins, and terpenoids	Moses & Sasikala, 2021
Methanolic aqoueous and acetone extracts of *C. verum* bark	Alkaloids, anthrocyanin, coumarin, flavonoids, glycoside, PhCs, saponin, tannins, and terpenoids	Ahmed *et al.*, 2020
C. verum extract	Alkaloids, flavonoids, sterols, tannins, and triterpens	Abdalla & Abdelgadir, 2016

2. The Comprehensive Applications of Cinnamon in Food Industry

Spices are a class of food additives that have been utilized for millennia to enhance the sensory attributes of food. Beyond their role in flavoring, spices find applications in the production of botanicals, beverages, preservatives, pharmaceuticals, and other industries. They are aromatic plant-derived substances, used in whole, broken, or powdered forms, whose primary function in food is to provide seasoning rather than nutritional value (Bhagya *et al.*, 2017). Cinnamon, in particular, is employed both as a spice and as an aromatic plant (Ribeiro-Santos *et al.*, 2017). It may be utilized in the form of quills (whole or broken), dried ground powder, or, within the food industry, as an EO for flavoring purposes (Spence, 2024). Figure 1 illustrates the bark and powdered forms of cinnamon.

Figure 1. Cinnamon in bark form (left) and powdered form (right)

C. verum is an evergreen tree extensively utilized as a source of cinnamon spice (Mazimba *et al.*, 2015). Nearly all parts of the cinnamon tree, particularly the bark and leaves, possess culinary or medicinal applications (Wijesinghe *et al.*, 2020a). In this regard, the bark and leaves of *Cinnamomum* are commonly employed as spices and flavoring agents in various foods (Valizadeh *et al.*, 2015). The distinctive aroma and pungency of cinnamon are primarily attributed to the presence of cinnamaldehyde and eugenol (Figure 2) (Banu & Lunghar, 2023).

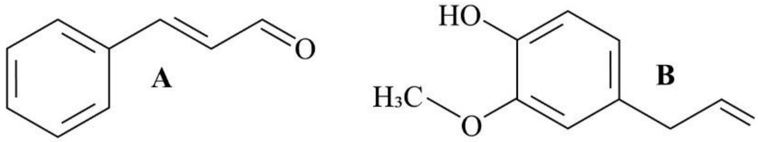

Figure 2. The chemical structures of cinnamaldehyde (A, inspired by Peng *et al.*, 2024) and eugenol (B, inspired by Haro-González *et al.*, 2021).

Commercial cinnamon consists of the dried inner stem bark of *C. verum* Bercht. & Presl., which is widely used as a spice (Rao *et al.*, 2007). *C. verum* is recognized for its delicate and complex flavor profile. Its characteristic sweet and mildly citrusy aroma is largely due to the high content of cinnamaldehyde, contributing to sweetness, while compounds, such as linalool, limonene, and geranial (Figure 3) are responsible for the subtle citrus notes (Spence, 2024).

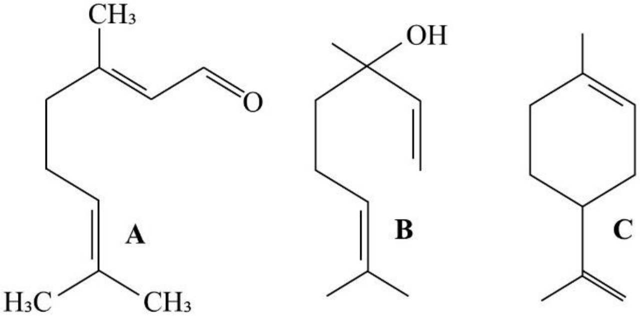

Figure 3. The chemical structures of geranial (A, inspired by Canbey, 2025c), linalool, and limonene (B and C, respectively; inspired by Canbey, 2025d).

Cinnamon is widely used as an ingredient in a broad range of confectionery products due to its characteristic flavor and aroma (Jeewanthi *et al.*, 2021). In Turkiye, the ground form of cinnamon is commonly consumed by sprinkling it over milk-based desserts, reflecting its traditional culinary use. In addition, powdered cinnamon is incorporated into the formulations of various confectionery products, such as traditional hard candies, as well as different types of cookies and baked goods. Selected food categories in which cinnamon is commonly used or added are illustrated in Figure 4.

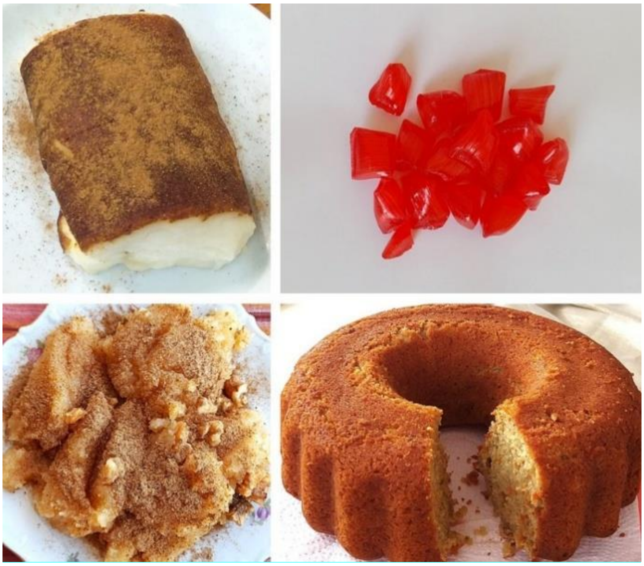

Figure 4. Selected food products containing added powdered cinnamon

In a study on cinnamon, the effects of incorporating varying amounts of cinnamon powder into bakery products, such as bread, cakes, and biscuits were evaluated in terms of microbial growth during storage at room temperature, as well as its potential as a natural preservative. The results indicated that cinnamon powder is rich in protein, dietary fiber, and carotenoids, while its methanolic extract exhibited significant antioxidant and antimicrobial activities. Products containing higher levels of cinnamon powder effectively suppressed microbial growth throughout storage, supporting its use as a natural antimicrobial agent. Furthermore, all bakery products with different cinnamon concentrations were found to be acceptable in terms of sensory quality (Saber, 2019).

In another investigation, it was found that cinnamon bark powder and clove buds can serve as valuable sources of carbohydrates and potassium in food, while also contributing to extended shelf life through the inhibition of foodborne bacteria (Lartey *et al.*, 2023).

Moreover, several noteworthy studies have explored the utilization of cinnamon extracts within the food industry, with a selection of these investigations summarized in Table 5.

Table 5. Selected innovative applications of cinnamon extract in the food industry

Extracts	Effects and Results	References
Cinnamon extract	Incorporating a 3% cinnamon extract into butter not only enriches its antioxidant content but also functions as a natural preservative, thereby enhancing the product's shelf life and quality during preparation	Vidanagamage *et al.*, 2016
Cinnamon extract	Cinnamon extract was shown to effectively reduce lipid oxidation in palm oil, and may be successfully applied as a natural alternative to synthetic antioxidants in food formulations	Shahid *et al.*, 2018
Cinnamon and turmeric nanoparticle extracts	The addition of cinnamon and turmeric nanoparticle extracts to ground beef during cold storage significantly improved antioxidant efficacy, as indicated by lower thiobarbituric acid values, while also enhancing pH, water-holding capacity, and reducing drip loss	Al-Salmany & Al-Rubeii, 2020

Cinnamon extract	Cinnamon extract obtained by ultrasound-assisted extraction effectively inhibited oxidative and microbial deterioration in hamburger meat during refrigerated storage, indicating its potential use as a natural antioxidant and antimicrobial agent in the food industry	Sohrabpour *et al.*, 2020
Cinnamon ethanol extract	A mixture of freeze-dried garlic powder, cinnamon ethanol extract, and xanthan gum can effectively inhibit the formation of white colonies on the surface of kimchi, thereby prolonging its shelf life	Kim *et al.*, 2021
Aqueous extract of *C. zeylanicum*	An aqueous extract of *C. zeylanicum*, due to its antioxidant properties, can be utilized as a functional additive to improve the quality of oil cakes	Lomer & Ghannadias, 2025

In addition, spice-based beverages are considered valuable natural products due to their inherent antioxidant and antimicrobial properties, which contribute to extended shelf life and support their use as functional health drinks. Cinnamon, along with other spices such as black pepper, ginger, mint, cumin, and curry leaves, has found wide application in the beverage industry (Bhagya *et al.*, 2017). Within this sector, cinnamon is commonly incorporated into teas, as well as alcoholic and ready-to-drink beverages. Cinnamon-flavored beverages, including cocktails, wine, tequila, and beer, are particularly popular and represent a significant market segment (Jeewanthi *et al.*, 2021).

2.1. The applications of cinnamon essential oil

EOs, which find applications across a wide range of fields, also exhibit considerable potential for use in the food industry for various purposes, including flavor enhancement and natural preservation (Canbey, 2025a). This potential is largely attributed to their pronounced antimicrobial and antibacterial activities against pathogenic and spoilage microorganisms in foods (Canbey *et al.*, 2025). In this context, similar to cinnamon itself, cinnamon EO has been widely utilized in diverse applications. For instance, EOs extracted from the leaves and bark of *C. verum* are extensively employed as flavoring agents (Rao *et al.*, 2007). While EOs are primarily responsible for aroma and flavor, oleoresins contribute to pungency (Bhagya *et al.*, 2017). Owing to its characteristic sweet and spicy sensory profile, cinnamon EO is commonly used in culinary preparations, and is also widely incorporated as a flavoring agent in products such as chewing gum (Feltes *et al.*, 2023).

Moreover, owing to its pronounced antioxidant and antibacterial properties, cinnamon EO is regarded as a promising natural preservative (Zhang *et al.*, 202323). Previous studies have demonstrated that *Cinnamomum* EO exhibits strong antibacterial and antifungal activities. These findings suggest that the EO of *Cinnamomum* possesses considerable potential for application in food preservation (Valizadeh *et al.*, 2015).

Active packaging systems contribute to the preservation of food quality, extension of shelf life, and improvement of food safety through controlled interactions between packaging materials and the food matrix. In this framework, the incorporation of EOs, particularly cinnamon EO, as active components has attracted increasing interest as a natural alternative to synthetic additives (Alonso *et al.*, 2024). Nevertheless, the practical application of cinnamon EO in food systems is limited by its low water solubility and susceptibility to degradation. Consequently, various encapsulation and delivery strategies have been developed to enhance the stability and effectiveness of cinnamon EO in food preservation applications (Zhang *et al.*, 2023).

In this context, a study aimed to encapsulate cinnamon EO within cyclodextrin nanosponges, and to assess the antimicrobial effectiveness of the resulting systems against foodborne pathogens. The results demonstrated that cyclodextrin nanosponges function as efficient encapsulation carriers, highlighting their potential applicability in active food packaging technologies (Simionato *et al.*, 2019).

Another research demonstrated that ultrasonication-assisted microencapsulation represents a promising approach for the effective and controlled utilization of cinnamon aroma in bakery products (Gong *et al.*, 2020).

Moreover, the use of edible coatings has increased rapidly in the preservation of fruits and vegetables due to their environmental friendliness and consumer safety. Edible coatings incorporating EOs represent an effective strategy to extend shelf life and maintain the nutritional quality of fresh produce (Rashid *et al.*, 2020). In this regard, the incorporation of cinnamon EO into active packaging materials, including films and coatings, has been shown to enhance optical, mechanical, and water vapor barrier properties. Cinnamon EO exhibits a chemically diverse profile, with cinnamaldehyde as a major component responsible for antimicrobial activity, while PhCs contribute substantially to its antioxidant potential. Its efficacy in inhibiting microbial growth and reducing lipid oxidation in food products has been widely reported. Nevertheless, despite these promising outcomes, comprehensive regulatory frameworks are still required to facilitate the industrial-scale implementation of EO-based active packaging systems (Alonso *et al.*, 2024).

Controlled release of EOs through nanoemulsions, coatings, and film-based packaging systems has emerged as a promising strategy. Within this framework, the use of edible coatings containing encapsulated *C. zeylanicum* EO has been highlighted as an effective approach for achieving controlled release and enhanced preservation performance (Gheorghe-Irimia *et al.*, 2024).

Several significant studies examining the application of cinnamon EO in food systems are summarized in Table 6.

Table 6. Selected key applications of cinnamon EO in the food industry

Plant Materials	Effects and Results	References
Cinnamon bark oil	Mozzarella cheese wrapped with chicken bone gelatin film incorporating 1% cinnamon bark oil exhibited a significant reduction in *L. monocytogenes* counts after 20 days of storage, demonstrating the potential of this active packaging material to enhance the microbiological safety of cheese	Kim *et al.*, 2018

Cinnamon EO	It can act as natural inhibitors of bacterial adhesion, contributing to shelf-life extension and sensory quality improvement in foods	Ferreira *et al.*, 2019
Cinnamon EO	Edible coatings formulated with cinnamon EO effectively inhibited spoilage and preserved the nutritional quality of fresh apples	Rashid *et al.*, 2020
Cinnamon EO	Optimized cinnamon EO enriched Persian gum coatings significantly improved the shelf life, marketability, and nutritional quality of pomegranate arils	Jokar *et al.*, 2021
Cinnamon EO	The findings highlight the potential of EOs as effective agents for extending the shelf life of bakery product	Valková *et al.*, 2022
Cinnamon EO	The results indicate that the newly developed curdlan/bacterial cellulose film incorporating cinnamon EO, characterized by enhanced mechanical strength and barrier performance, represents a promising natural material for advanced food packaging applications	Zhou *et al.*, 2022
Cinnamon EO	Encapsulation strategies (including spray drying, emulsion-based systems, complex coacervation, ionic gelation, liposomes, inclusion complexes, and electrospinning) have been shown to enhance the stability, controlled release, and shelf-life extension efficacy of cinnamon EO in food systems	Zhang *et al.*, 2023
Cinnamon EO	Cinnamon EO based micelles and 1-methylcyclopropene fibers effectively delayed postharvest senescence, preserved fruit quality, and enhanced the antioxidant capacity of apricots	Luo *et al.*, 2024

Cinnamon EO	The packaging film effectively maintained shrimp freshness under refrigerated conditions for up to 7 days, offering a novel approach to limiting cinnamon EO volatilization during film fabrication for improved food preservation	Yang *et al.*, 2025
Cinnamon EO	The cinnamon EO - incorporated film demonstrates improved mechanical and barrier performance alongside strong bioactivity, effectively reducing weight loss, limiting oxidative deterioration, and preserving the sensory quality of grapes, thereby highlighting a structure-based strategy for active food packaging	Liu *et al.*, 2026
Cinnamon EO	By integrating humidity control with bioactive functionality, the polyacrylonitrile-based composite membrane incorporating cinnamon EO extended the shelf life of cherry tomatoes at 25 °C from 6 to 18 days compared with conventional polyethylene wrapping	Tian *et al.*, 2026

In conclusion, spices are fundamental components of the human diet, serving roles that extend beyond flavor enhancement (Bhagya *et al.*, 2017). In this context, cinnamon can be used in various forms, including quills (whole or fragmented), dried ground powder, and, in food industry applications, as an EO for flavoring purposes (Spence, 2024)

Although its application in innovative functional foods is technologically achievable, successful development requires long-term, multidisciplinary research integrating natural product chemistry, biological evaluations, and clinical validation. Such coordinated efforts are essential to ensure scientifically sound and health-promoting functional food products (Muhammad & Dewettinck, 2017).

3. Results and Recommendations

True cinnamon (*Cinnamomum verum* or *C. zeylanicum* Blume) is an important aromatic plant belonging to the Lauraceae family. The plant is primarily valued for its EO, which is generally obtained from different plant parts through distillation. The major constituents of cinnamon EO are typically cinnamaldehyde and eugenol, accompanied by other volatile compounds, such as linalool, limonene, geranial, camphor, etc. In addition to volatile components, several studies have demonstrated that cinnamon extracts contain a wide range of bioactive compounds and nutritional constituents, including alkaloids, coumarins, fixed oils, glycosides, gums, PhCs (such as flavonoids, flavanones, tannins, etc.), proteins, resins, terpenoids, etc.

Cinnamon is predominantly used as a spice to impart flavor and aroma to foods. For this purpose, the bark is commonly dried and rolled into quills or ground into powder. Cinnamon is incorporated into a wide variety of desserts and beverages, with its characteristic aroma mainly attributed to its EO content. Beyond its sensory properties, cinnamon EO has been shown to possess notable antimicrobial and antioxidant activities, which make it a promising natural agent for food preservation and shelf-life extension. Similarly, scientific evidence supports the potential use of cinnamon extracts for comparable applications in food systems. These properties highlight cinnamon as a promising bioresource that can be utilized as a natural alternative to synthetic preservatives

Nevertheless, in order to enable the use of cinnamon not only as a spice but also as a natural preservative, comprehensive laboratory and clinical studies are required. In this context, the development of innovative extraction techniques that allow the isolation of EO constituents with minimal or no degradation is of particular significance. Furthermore, the determination of appropriate usage doses and the establishment of standardized quality criteria for the extracted compounds are essential. Such scientific advancements can only be achieved through well-designed multidisciplinary approaches.

The expansion of multidisciplinary research efforts and the consequent increase in the large-scale utilization of cinnamon EO are expected to enhance the demand for cinnamon trees, thereby contributing to the national economy at both agricultural and industrial levels. In this framework, cultivated cinnamon trees may be utilized not only for spice production but also for EO extraction, leading to the emergence of a distinct industrial sector. Establishing EO production facilities in close proximity to regions where cinnamon cultivation is widespread could further support this development. Such initiatives would also promote employment opportunities and contribute positively to regional socio-economic development.

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