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Agronomic Practices Affecting Yield and Phytochemical Composition of *Thymus vulgaris*: A Comprehensive Review

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ABSTRACT
Thyme (*Thymus vulgaris*) is one of the most important medicinal and aromatic plants in the world, holding a special place in the pharmaceutical, food, and health industries due to its valuable bioactive compounds, including thymol and carvacrol. The quality and quantity of these compounds are significantly influenced by environmental conditions (light intensity, particularly in direct sunlight), agricultural management (suitable fertilization and irrigation techniques), and postharvest practices. This study examines the primary factors and agronomic practices that influence thyme yield and quality. This narrative review is based on a thorough search of numerous scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar, for relevant articles published up to November 2025. The search strategy included the terms “Thymus vulgaris,” “Garden thyme,” “Agronomic practices,” “Yield,” “Bioactive compounds,” “Essential oil,” “Thymol,” “Carvacrol,” “Environmental factors,” “Irrigation management,” “Fertilization,” “Harvest time,” and “Postharvest processing.” The results showed that light, temperature, climate, planting density and pattern, irrigation and plant nutrition, weed and pest control, and harvest timing are key factors in the yield and quality of phytochemicals. In addition, the use of organic and biological fertilizers, bio-stimulants, mycorrhiza, and endophytes, as well as foliar sprays of mineral elements and hormones, can increase production and maintain the quality of bioactive compounds. Overall, this research demonstrates that integrated and sustainable management approaches can significantly enhance the economic and medicinal value of garden thyme, providing farmers and the herbal industry with valuable insights to improve essential oil quality and yield.
Keywords: Garden thyme (*Thymus vulgaris*), Bioactive compounds, Essential oil, Agronomic management, Environmental conditions

INTRODUCTION
Thyme is a perennial plant with the scientific name Thymus vulgaris and belongs to the Lamiaceae family. Despite being native to the Mediterranean region, Thymus vulgaris is now widely grown in many different countries worldwide [1, 2]. The diverse properties of thyme, from its active compounds to its industrial applications, are all intertwined and demonstrate the importance of this plant for health, nutrition, and industry. This plant contains a variety of compounds, including primary metabolites (such as proteins, carbohydrates, minerals, and vitamins) and secondary metabolites (aromatic compounds, essential oils, carotenoids, phenolic antioxidants, flavonoids, and phenolic acids), which possess medicinal properties and play a crucial role in maintaining and promoting human health. Thyme essential oils are also rich in compounds such as thymol, carvacrol, eugenol, linalool, apigenin, Rosmarinus acid, and p-cymene [3, 4]. Figure 1 provides the structural representations of these major compounds, enabling readers to visualize their chemical frameworks and better understand the similarities and differences that underlie their biological activities and functional properties.

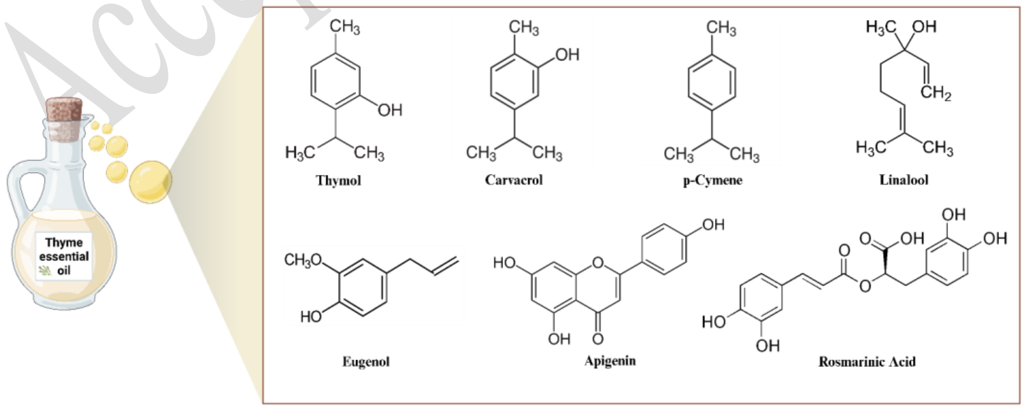

Fig. 1 Structural representation of the components of thyme essential oil (*Thymus vulgaris*)

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These compounds are responsible for many of the plant's biological properties, including antimicrobial [5-7], antifungal [8, 9], antiparasitic [10], antioxidant, anti-inflammatory [11, 12], and anticancer [13-15] effects. Various studies have shown that thyme is also effective for digestive problems [16], Parkinson's disease [17, 18], diabetes [18, 19], COVID-19 [20-22], asthma [23, 24], oral health [25], and the relief of cough and cold symptoms [5]. In addition to its medicinal uses, thyme is also utilized in the cosmetics and healthcare industries. Products such as shampoos, toothpastes, hair conditioners, perfumes, soaps, detergents, and creams often contain thyme extract or oil. Given the economic and medicinal value of garden thyme, optimizing agronomic practices is essential to enhance yield and improve the quality of its active constituents, particularly essential oils and phenolic compounds .By choosing appropriate methods of soil preparation, balanced nutrition, irrigation management, optimal planting density, and proper harvest timing, the quantity and quality of bioactive compounds can be maximized. These approaches not only promote economic productivity but also contribute to the sustainability of the ecosystem and improve the medicinal and industrial properties of the product [10, 24, 26].

Agronomic approaches intensified to boost yields may have a "dilution effect," reducing the levels of mineral micronutrients and antioxidants/phytochemicals in crops [27]. Due to thyme's sensitivity to environmental factors, the need to standardize product quality, and variations in the quantity of bioactive substances, optimizing agronomic practices is particularly crucial. A thorough investigation of the combined impact of ideal agronomic practices on thyme yield and bioactive components has not yet been conducted, despite substantial research on the individual effects of environmental and management factors on this plant.

Therefore, this review aims to address these gaps by summarizing and integrating current knowledge on the combined and interactive effects of improved agronomic practices on thyme yield and its principal bioactive compounds, particularly phenolics and essential oils. The review first analyzes critical environmental determinants of thyme production, then evaluates optimal and sustainable agronomic approaches, and finally synthesizes existing evidence on how these practices collectively influence both yield and phytochemical quality.

METHODS

The keywords "*Thymus vulgaris*," "Garden thyme," "Agronomic practices", "Essential oil yield", "Bioactive compounds", "Environmental factors", "Irrigation management", "Fertilization", "Harvest time," and "Postharvest processing" were used in a thorough search of scientific literature to gather information for the current review study. Publications up until November 2025 were found by searching the databases Web of Science, PubMed Central, Scopus, and Google Scholar. Initially, a single independent researcher (AHA) with a PhD compiled all publications on the physiology, cultivation, and biochemical characteristics of *Thymus vulgaris*. Pre-established inclusion and exclusion criteria were followed during the selection procedure. Conference abstracts, letters to the editor, review articles, and publications written in languages other than Persian or English were excluded; however, original research articles and full-text papers in both Persian and English were included. Lastly, eligible studies that directly examined the impact of environmental, agronomic, and postharvest factors on garden thyme yield and quality were included in this review for in-depth analysis. The included articles were critically evaluated for methodological soundness, data reliability, and relevance to the study's goals.

RESULTS

Factors and Agricultural Practices that Influence the Yield and Quality of Bioactive Compounds

Environmental and Climatic Conditions

Garden thyme is one of the most important medicinal and aromatic plants, and environmental factors strongly influence the quantity and quality of its active compounds. Factors such as light intensity and quality, temperature, humidity, growing season, and cultivation method play an essential role in determining the morphophysiological and chemical properties of this plant.

Light Intensity

With increasing light intensity, leaf number, biomass, and antioxidant enzyme activity increase, while thymol, carvacrol, phenols, and flavonoids increase, while stem and internode length decrease. The highest levels of chlorophyll, carotenoids, and medicinal compounds are observed at 70% light intensity, and the expression of key genes of the monoterpene biosynthetic pathway increases significantly in whole light [28]. Additional light accelerates seedling growth, increases biomass and stem length, and increases the content of carotenoids, anthocyanins, total antioxidant capacity, and flavonoids [29].

Growing garden thyme in full sunlight, especially in tropical climates and during warmer seasons, significantly increases dry weight and essential oil yield compared to growing under shade nets and also enhances the plant's antioxidant activity.

This effect was observed and reported in both spring and autumn, with 82.2% increases in dry weight and 639% increases in essential oil yield. The highest growth in dry weight was recorded in spring. On the other hand, thymol concentration increased in plants grown under shade nets, indicating that lower light intensity affects the biosynthetic pathways of this compound. However, plants under full sunlight exhibited higher antioxidant responses, despite a relative reduction in thymol, likely due to the activation of the plant defense system in response to light stress and increased free radical production [30].

A practical example is foil tunnel cultivation, which is designed to meet the plants' light requirements while also protecting them from damage. In temperate climates, cultivation in foil tunnels leads to a significant increase in fresh plant production compared to outdoor cultivation. This growing system allows for more uniform growth and higher yields by providing controlled conditions for temperature, humidity, and protection from unfavorable environmental factors. In addition, increasing the use of foil tunnels can reduce the risk of damage from wind, heavy rain, and temperature fluctuations, thereby improving plant quality and the content of active plant compounds, including essential oils and secondary metabolites [31].

Quality of Light

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Light quality is another factor that influences the performance of bioactive plant substances. Red light significantly increases dry weight, leaf area, and shoot number, but decreases fresh weight. The combination of red and blue light, especially a higher proportion of red light, results in more compact growth and increases in crown width, fresh weight, and dry weight. The most crucial essential oil components, such as para-cymene and γ-terpinene, also show the highest concentrations under white and blue light. The antioxidant activity and phenolic content reach their highest values under blue light, and a combination of red and blue light can act as a mild stressor for the plant [32].

The highest thymol concentrations are observed under white light and red-blue light combinations (R:25B75 and B:25R75). Other monoterpenoids, such as β-terpinene and perylene, are present in all treatments, but α-terpinene diepoxide is only observed in the red light and two-color treatments. The concentrations of the main essential oil molecules of thyme, especially thymol, vary significantly between the different light treatments, with thymol increasing in white light and in 75% red and 75% blue light treatments, indicating the influence of light quality on essential oil composition [33].

Red light leads to colorless plants with little chlorophyll, dry matter, and phenolic compounds, while blue light causes more compact growth and a higher accumulation of chlorophyll and dry matter. A 3:1 combination of blue and red light promotes compact growth and the accumulation of phenolic compounds [34]. LED illumination experiments show that a 4:1 ratio of red to blue light (R4B1) is the optimal light condition for increasing growth, fresh and dry weight, leaf area, and essential oil concentration in thyme compared to fluorescent light. Combined red and blue light, especially with a higher proportion of red light, improves the production of medicinal compounds, while blue light alone has a lesser effect [35].

The study by Tabbert et al. showed that using a broadband LED lighting system (360–760 nm) in a greenhouse increased the fresh and dry yields of garden thyme by 43% and 82%, respectively, compared to high-pressure sodium and fluorescent lamps. In addition, the LED system's energy consumption was 20–31% lower, resulting in significant cost savings. These results made LED an efficient and economical alternative to conventional greenhouse lighting systems, allowing for a longer growing season and greater product diversity [36].

Though blue light is still essential for optimizing antioxidant activity, the literature generally indicates that combined red and blue light treatments—often with a higher ratio of red light (e.g., R4B1) or specific white/mixed ratios (e.g., 75% Red/25% Blue or 25% Red/75% Blue)—are superior to monochromatic light in promoting overall biomass, compact growth, and the accumulation of critical medicinal compounds like thymol. Taken together, the reviewed studies demonstrate that mixed red–blue light regimes, frequently with a red-light bias, consistently outperform monochromatic treatments by simultaneously promoting biomass accumulation, improving morphological quality, and enhancing the concentration of principal medicinal compounds, particularly thymol.

Thermal Stress

Thermal stress significantly affects the content of secondary metabolites and chemical compounds in the essential oils of medicinal plants, including thyme. The antioxidant and antidiabetic activities of essential oils are strongly dependent on growth conditions. For example, samples cultivated under natural conditions exhibit the highest DPPH and ABTS radical-scavenging activities, as well as alpha-amylase inhibitory activity. In contrast, thermal stress has different effects on the FRAP assay and alpha-glucosidase inhibition [37].

Both heat and cold stress increase the content of monoterpenes and phenolic compounds, especially thymol and carvacrol, compared to natural conditions. Low temperatures (freezing) significantly increase thymol, while high temperatures (heat) significantly increase carvacrol. Additionally, heat stress reduces gamma-terpene production. Warmer regions are better suited to carvacrol production, while cooler areas are better suited to thymol production [38].

Heat stress significantly reduces thyme yield and growth. The simultaneous use of eucalyptus biochar and beta-sitosterol enhances plant heat tolerance and mitigates heat-stress effects by improving photosynthesis, antioxidant capacity, and nutrient uptake [39]. Under moderate heat stress, the content of compounds such as coumarin, saponin, tannins, alkaloids, and flavonoids in thyme increases, and the yield of essential oil reaches its highest level; however, these levels decrease as the stress intensifies [40].

In a 2023 study by Lotfollahi and colleagues, the effects of environmental stress, including elevated temperature and reduced water pressure, on the chemical composition of the essential oils and secondary metabolites of garden thyme were investigated. The results of this study indicate that in the second year, with a 50% increase in temperature and water pressure, the amount of secondary metabolites, including coumarin, saponins, tannins, alkaloids, and flavonoids, increases significantly. However, as stress worsens in the fourth year, these amounts decrease. The amounts of thymol and carvacrol change inversely, and hot, dry conditions increase their production [40]. These apparently contrasting findings reflect differences in stress intensity, duration, and the thyme chemotype studied, highlighting that the plant’s response to thermal stress is highly context-dependent and can range from enhanced accumulation of specific secondary metabolites to reduced overall growth and yield.

Climatic and Geographical Conditions

Climatic and geographical changes can impact the medicinal and aromatic properties of these plants, underscoring the need for further research to predict their effects on metabolites and the medicinal use of these species. The chemical composition of thyme essential oil, particularly the concentration of thymol and carvacrol, is influenced by climatic conditions, which may impact its medicinal properties and therapeutic applications [40].

A 2024 study by Hosseini et al. examined the impact of climate change on the distribution of three essential thyme species in Iran, utilizing MaxEnt models. The results of this study indicate that bioclimatic factors, including altitude, precipitation, solar radiation, slope gradient, and soil organic carbon content, play a crucial role in determining the suitable habitat for these species. These species are mainly distributed in mountainous areas with specific soil and altitude conditions [41].

In a 2021 study by Yousefzadeh and colleagues, the influence of geographical and environmental factors on the growth and quality of four thyme species in Iran was investigated for the first time. Their results showed that temperature was the most critical factor in the

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species' occurrence, followed by altitude and precipitation. Climate change had a greater influence on plant properties than soil characteristics [42]. A study by Capdevila and colleagues in 2025 also investigated the chemical composition of the essential oils of 13 thyme populations in Solsona, Catalonia. The diversity of compounds was influenced by geographical location and growing conditions, with linalool in particular being higher in the northwestern regions, indicating the influence of climate [43].

Other Important Factors

Other essential factors are humidity and growing season, which are crucial for the growth and adaptation of thyme species to different climatic conditions. The results of a 2024 study by Beiranvand et al. show that T. vulgaris grows better in humid years, while T. daenensis performs better in dry years with PSB fertilizer. Autumn sowing increased root growth and mycorrhizal colonization, which is crucial for establishment under dry conditions. Both species were grown in pots and transplanted to pastures. These results underscore the importance of transplanting seedlings and utilizing biofertilizers to promote plant survival and the sustainability of rainfed agriculture [44].

These results show that optimizing light, temperature, and humidity conditions, managing environmental stresses, and selecting appropriate cultivation methods are key to increasing the quality and quantity of garden thyme. These measures not only lead to the production of essential oils and active ingredients with higher medicinal and industrial value, but can also improve energy efficiency, plant resilience, and agricultural sustainability. Future studies should focus on identifying the optimal environmental and climatic conditions for various thyme species and populations, and on optimizing their industrial and therapeutic applications. The results of recent research in this field are collected in Table 1 [28–44].

Table 1 Overview of the effects of environmental factors on the growth and chemical/essential oil compounds of thyme *(Thymus vulgaris)*

Environmental factor	Main Effects on growth	Effects on chemical compounds/essential oils	References
Light intensity	↑ Leaf number, biomass, dry weight, growth in whole light ↓ , Stem, and internode length	↑ Chlorophyll, carotenoids, phenols, flavonoids, thymol, and carvacrol ↑ : Expression of monoterpene pathway genes	[28-31]
Light Quality	Red light: ↑ Leaf area, dry weight. Blue light: Compact growth, ↑ chlorophyll, Red + Blue combination: Compact growth, ↑ biomass, leaf area, fresh weight	Red light: ↓ Chlorophyll and phenols Blue light: ↑ Phenols and antioxidants White/Combined light: ↑ Thymol, para-cymene, γ-terpinene	[32-36]
Temperature stress	Heat stress: ↓ Yield and biomass; Cold stress: Alters growth structure.	Cold: ↑ Thymol Heat: ↑ Carvacrol Both: ↓ γ-Terpinene, ↑ Phenolic monoterpenes (thymol & carvacrol), Alterations (coumarin, saponin, tannin, alkaloid, flavonoid)	[37-40]
Climate & geographical conditions	Species distribution is dependent on temperature, altitude, and rainfall	Altered essential oil composition (↑ Thymol in cold regions, ↑ Carvacrol in the warm areas, ↑ Linalool in northwestern regions)	[40-43]
Other factors (humidity, planting season)	Better growth of *T. vulgaris* in high-rainfall years, *T. daenensis* performs better with PSB fertilizer under drought. Autumn planting: ↑ Root growth and mycorrhizal colonization	Improved survival and sustainability of rainfed agriculture through seedling grafting and biofertilizer	[44]

Planting Density and Cultivation Pattern

The choice of appropriate plant spacing plays an essential role in the growth, morphological development, and quality of garden thyme. The results of studies show that a planting distance of 30 x 30 cm increases plant height, the number of branches, and both fresh and dry weight, while also improving nutrient uptake by creating sufficient space for root and shoot development. This planting density not only reduces competition between plants, but also provides better conditions for photosynthesis and synthesis of active ingredients, ultimately leading to the highest percentage and quality of essential oil [45]. A plant spacing of 30 x 30 cm, combined with 50% aloe vera extract, has been recommended as the most effective method to improve the quantitative and qualitative characteristics of thyme [46].

Wider row spacing (40 cm) increases the overall yield of thyme, while narrower rows (30 cm) improve the chemical composition and essential oil and polyphenol content [47].

Increasing plant density to 111–222 thousand plants per hectare significantly increased dry matter yield, with the highest yield obtained using mineral fertilizer N180P180K180. Plant density also affected the ratios of leaves, flowers, and small branches, resulting in the highest raw-material contribution at lower densities [48]. This result indicates that optimal plant spacing, combined with auxiliary factors, can simultaneously improve growth, biomass production, essential oil yield, and the concentration of active plant compounds, making it an efficient strategy for growing and increasing thyme productivity.

Drought and Water Stress

Morphophysiological Responses of Thyme to Drought Stress

Drought stress in this plant results in a marked reduction in morphological characteristics such as leaf length and width, plant height and root length, as well as a decrease in the fresh weight and dry weight of shoots and roots, water content, and chlorophyll and carotenoid content [49]. Constant and severe drought stress (40% of usable soil moisture) leads to a significant reduction in stem and internode length, while leaf width, height, and chlorophyll content show no significant changes. In contrast, the content of rosmarinic acid, total phenolics, and antioxidant capacity increases, especially under prolonged drought conditions. Garden thyme responds to drought stress by increasing the production of phenolic and antioxidant compounds. Although this plant can tolerate a significant water deficit, regular irrigation during dry periods is recommended to maintain optimal yield [50].

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Strategies and Their Role in Modulating Drought Effects

The intensity and timing of water stress significantly influence the levels of volatile compounds, physiological indices, and yield in thyme plants [51]. Severe water stress leads to a significant decrease in chlorophyll and carotenoid content, reducing photosynthetic activity and yield. In contrast, mild stress can activate the plant's adaptive capacity and increase essential oil yield [52]. Shorter irrigation intervals (every 4 days) also increase plant biomass and overall yield, while water stress enhances oil content and increases the percentage of essential oil in the plant [53].

In a 2022 study by Azimi and colleagues, the effects of four drought levels on two thyme species, Thymus vulgaris (more drought-sensitive) and Thymus kotschyanus (more drought-tolerant), were investigated using physiological indices and gene expression related to stress response. The results showed that T. kotschyanus has a greater ability to conserve water and stabilize photosynthesis due to its morphological characteristics and faster activation of alternative metabolic pathways. At the same time, T. vulgaris is more sensitive and shows different changes in gene expression [54].

Therefore, the use of modern methods can play a crucial role in mitigating drought stress and optimizing irrigation. In a study conducted by Rahimi and his colleagues, the effects of stress modifiers, including zinc nanofertilizers, amino acids, algae, and humic acid, on vegetative growth, antioxidant activity, and nutrient content of garden thyme (T. vulgaris) under water-deficit stress conditions were investigated. The results show that water deficit stress reduced growth, relative leaf water content, chlorophyll, and nutrient uptake (NPK), but foliar application of modifiers significantly improved these values. Additionally, the water deficit increased the content of protective substances, including proline, flavonoids, phenols, soluble sugars, and essential oils. The most significant improvement in growth and increased activity of antioxidant enzymes, including catalase, superoxide dismutase, and ascorbate peroxidase, was observed in the humic acid and seaweed treatments, indicating the effective role of these compounds in improving thyme's response to water deficit [55].

Growth Regulators, Biological Agents, and Protective Compounds

Foliar application of kaolin at various concentrations significantly affects the growth, physiology, and chemical composition of garden thyme under drought stress. Kaolin increases the plant's resistance to drought by enhancing antioxidant responses and accelerating the recovery process after stress, making it an effective and efficient strategy to improve sustainable agriculture in arid regions [56]. Understanding these physiological reactions is therefore essential, as they directly influence the selection of efficient mitigation techniques to enhance drought tolerance and maintain the quality of bioactive chemicals.

Amino acids can improve the growth, yield, and quality of the essential oil of thyme (T. vulgaris). Under favorable irrigation conditions, aminofert and aspartic acid increased plant height, dry weight, leaf area, and essential oil yield, while also enhancing levels of physiological compounds, including chlorophyll, carotenoids, and antioxidant enzymes. Under water stress, proline and tyrosine were the most effective acids, significantly increasing growth and essential oil production. Targeting amino acids could be an effective strategy to improve the yield and quality of thyme essential oil, especially under water stress conditions [57].

Treatment with 100 μM melatonin restored growth and percentage of essential oils even at 40% of field capacity. In contrast, 150 μM produced the most significant increase in phenolic compounds, thymol, carvacrol, rosmarinic acid, and antioxidant capacity. Melatonin enhances plant drought tolerance by mitigating oxidative damage, regulating cell osmotic pressure, and activating protective enzymes [58].

Foliar application of salicylic acid (SA) can improve the growth, yield, and essential oil quality of garden thyme (T. vulgaris) and reduce the adverse effects of water deficit. Under full irrigation, 200 mg/L SA produced the highest dry matter. Under water deficit conditions, 100 mg/L SA produced the highest essential oil, and 200 mg/L SA produced the highest thymol. This simple, inexpensive, and environmentally friendly method is an effective means of improving the quality and active compounds of the plant under water deficit conditions [59]. Additionally, the combined use of SA and jasmonic acid (JA) mitigated the adverse effects of drought and enhanced antioxidant activity; therefore, the use of these two hormones is recommended to improve the quantitative and qualitative quality of thyme under water-deficit conditions [60].

Plant growth-promoting rhizobacteria (PGPR) can improve thyme (T. vulgaris) germination and growth and reduce water deficit stress. A study using Bacillus, Pseudomonas, and Azotobacter strains isolated from thyme rhizosphere soil showed that Pseudomonas 53P and Azotobacter 1A had the greatest positive effects on growth and germination indices and reduced the impact of drought stress by producing the enzyme ACC deaminase [61]. Irrigation after depletion of 50% of field capacity, in combination with mycorrhizae, not only saves water but also improves the quantity and quality of essential oil, increases overall plant performance, and contributes to sustainable productivity by enhancing nutrient uptake and increasing plant resistance to drought stress [62]. Inoculation of garden thyme with the endophytic fungus Aspergillus Niger, isolated from the plant Teucrium polium, can also reduce the adverse effects of drought stress and improve plant growth and quality.

This method has been suggested as an effective biological strategy to increase thyme resistance to water deficit and improve its yield, especially when applied as three foliar sprays over three weeks during the vegetative growth stage [63].

The simultaneous use of endophytes (bacteria and fungi) and FeNPs significantly enhanced the drought tolerance of T. vulgaris, increased plant growth and antioxidant activity, and increased the phenol and flavonoid content. The combination of FeNPs and endophytes partially compensated for the reduction in thymol and carvacrol under drought conditions, and the percentage and quality of the essential oil were also improved [64].

Nutritional Management and Organic Fertilizers

The application of organic fertilizers, especially vermicompost, can reduce the adverse effects of irrigation deficiency. These fertilizers improve the physiological status of garden thyme by increasing the absorption of vital nutrients, such as nitrogen, phosphorus, and potassium, and by maintaining leaf relative water content. Additionally, organic fertilizers play a crucial role in mitigating oxidative stress caused by drought by enhancing the activity of key antioxidant enzymes, including catalase, superoxide dismutase, and ascorbate

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peroxidase. These findings highlight the importance of carefully managing plant nutrition and using organic fertilizers as practical strategies to enhance growth, maintain physiological health, and increase medicinal plants' resistance to water stress [52].
Choosing the right time and amount of irrigation, along with the use of growth regulators, can help maintain yield, improve the quality of essential oil, and increase garden thyme's resistance to drought, making it an effective strategy for optimizing cultivation in water-scarce areas.

Soil Conditions and Plant Nutrition

The use of biofertilizers, organic fertilizers, and combined fertilizers has been considered as sustainable alternatives to chemical fertilizers. These studies examine the effects of different types of fertilizers on the growth, yield of essential oil, and bioactive compounds of thyme, providing strategies for optimizing plant nutrition. The key findings of these studies are reviewed below.
The application of Plant growth-Regulating Bacteria (PGRB) biofertilizers shows significant superiority over NPK and micronutrient fertilizers in all growth and quality indicators. Biofertilizers create optimal growth conditions by improving the activity of beneficial soil microorganisms, increasing plant access to nutrients, and improving soil structure. Using this type of fertilizer as part of an integrated plant nutrition management strategy can increase production sustainability and reduce the adverse effects of excessive chemical fertilizer use [45].
This study, conducted by AlBakry in 2022, examines the effects of organic, mineral, and biological fertilizers, especially vermicompost and Azotobacter bacteria, on the vegetative growth, chemical composition, and essential oil content of the garden thyme plant (T. vulgaris). The results show that the combination of 25% vermicompost with 75% NPK mineral fertilizer, along with the presence of Azotobacter bacteria, has the most significant effect on improving plant growth and increasing the content of chlorophyll, nitrogen, phosphorus, potassium, carbohydrates, protein, and essential oil. These effects are due to vermicompost's role as a rich source of nutrients and a stimulant of microbial activity, as well as to Azotobacter's ability to fix nitrogen and secrete plant growth hormones that increase nutrient absorption efficiency. Therefore, the balanced use of organic and mineral fertilizers along with biological fertilizers is an effective strategy for improving the quality and yield of thyme and producing a product with high nutritional and medicinal value [65].
In a 2024 study by Honorato, the effects of different sources and doses of organic fertilizers (quail, cow, and goat) and chemical fertilizers on the growth, chemical composition, and essential oil yield of garden thyme (T. vulgaris) were investigated. The results show that quail manure is more effective at lower doses than other fertilizers and, when combined with cow manure, causes the most significant increase in dry weight and accumulation of nutrients in the leaves. Essential oil yield, especially the amount of thymol, the main compound of thyme, improves with increasing doses of organic fertilizers, and the highest amount of essential oil is observed in plants fed with cow manure [66]. In contrast, the use of goat manure is associated with increased production of reactive oxygen species (ROS), leading to decreased leaf nutrient levels and reduced essential oil yield [66, 67]. Additionally, organic fertilization, comprising a mixture of cow, goat, and quail manure, significantly increased plant dry weight, chlorophyll content, leaf nutrients, antioxidant capacity, and essential oil and thymol production, while reducing oxidative stress indices [68].
Green manure (Crotalaria juncea), primarily when used in combination with cow manure, improves thyme growth and production, and essential oil and thymol respond positively to this combined fertilizer. This combination enhances the plant's antioxidant activity, and the highest yield and thymol percentage (65.42%) were obtained with 9 kg of cow manure and 3 kg of green manure. Simultaneous use of green and cow manure is an economical and sustainable solution to increase growth, essential oil, and thymol production, and reduce the need for chemical fertilizers in thyme cultivation [69]. In a study by Asghari et al., foliar spraying with 10 ml/L of wood vinegar, combined with the fungus Glomus mosseae, had the most significant effect on garden thyme, significantly increasing root weight, canopy diameter, root colonization, and carbohydrate, protein, and essential oil content [70].
The combination of nitrogen and cytokinin significantly affects plant height, branch number, biomass, and the percentage and yield of essential oil. The highest vegetative growth and biomass were observed with 100 kg nitrogen × 400 µM cytokinin; the highest rate of essential oil was observed with 50 kg nitrogen × 400 µM; and the highest yield of essential oil was observed with 100 kg nitrogen × 200 µM. These results indicate that balanced management of nitrogen and cytokinin can effectively improve the quantity and quality of thyme [69]. Additionally, foliar spraying of cytokinin (benzylaminopurine) at the first harvest significantly increases thyme vegetative growth and essential oil production. As the plant ages, the essential oil production also increases. It is recommended to use a 400 µM cytokinin solution at the first harvest to optimize plant yield [71].
Yadekari (2024) showed that foliar application of methyl jasmonate (1 mM), especially in combination with titanium dioxide nanoparticles (100 mg/L), had the most significant effect on improving THEO yield and quality [72]. In addition, a concentration of 0.1% CSNPs provided the best results in increasing biochemical responses and the quality of thyme under chromium toxicity, and is suggested as an effective method to reduce heavy metal toxicity and improve medicinal plant production in contaminated soils [73, 74].
Salinity stress can be used as a biostimulant to increase phenolic content and antioxidant capacity in thyme species, although plant yield and growth are reduced [75]. However, foliar sprays of potassium (K^+) and calcium (Ca^{2+}) can increase garden thyme's tolerance to salinity. These elements maintain photosynthetic performance and plant growth by improving K^+/Na^+ and Ca^{2+}/Na^+ ratios, reducing oxidative damage, and enhancing the activity of antioxidant enzymes and the ascorbate–glutathione cycle [76].
Nitrogen and potassium. The application of humic acid (HA) and arbuscular mycorrhizal fungi (AMF) has a positive effect on the growth, essential oil production, and chemical composition of *Thymus vulgaris*. Adding AMF to the soil increases growth parameters, chlorophyll content, carbohydrates, and the percentage of essential oil. The combination of AMF with HA at a concentration of 1% produces the most significant increase in fresh weight, chlorophyll a, carbohydrates, and oil yield. Simultaneous use of AMF and HA is an effective method to promote the growth and essential oil production of thyme and increase its commercial value .Fertilization significantly increased common thyme growth, with the most significant effect observed when 150 kg of urea and 100 kg of potassium sulfate were applied together [77]. Additionally, optimal adjustment of the calcium-to-magnesium ratio in hydroponic culture can

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improve both growth and phenolic compound production in garden thyme [78]. Using complementary methods can help optimize fertilizer use and increase its efficiency.

The effect of spent mushroom substrate (SMS), especially when combined with mineral NPK fertilizer, is a more effective method than manure for improving thyme yield and quality. In contrast, NPK alone increases production [47]. Additionally, optimization of fertilizer use using response surface methodology (RSM) reveals that applying 162 kg/ha of nitrogen, 12 kg/ha of potassium, and 4 L/ha of algae extract yields the highest biomass and essential oil production in thyme. This combination, while maintaining the quality of the main essential oil components such as thymol, reduces fertilizer use, especially synthetic nitrogen, and minimizes the risk of environmental pollution [79].

The addition of micronutrients, such as zinc, iron, and manganese, improves chlorophyll A and B content, increases carotenoid content, and improves thyme essential oil quality. These elements play a role in plant physiological and biosynthetic processes, increasing the concentration of bioactive compounds such as β-cymene, thymol, borneol, and carvacrol. Optimal micronutrient supply can directly improve this plant's medicinal and economic quality [45]. The optimal combination of mineral, organic, and biofertilizers enhances the productivity and yield of essential oil, reduces the use of chemical fertilizers, and limits negative environmental impacts. Table 2 summarizes several observations from various sources.

Table 2 Effect of fertilizers and feeding methods on growth and chemical/essential oil compounds of garden thyme *(Thymus vulgaris)*

Fertilizer Type / Method	Effects on growth	Effects on Chemical Compounds / Essential Oil	Key Points	Source
PGRB Biofertilizer	Increased growth and plant quality indices	–	Improves beneficial soil microorganism activity and reduces the adverse effects of chemical fertilizers	[45]
Vermicompost + NPK + Azotobacter	Increased vegetative growth, chlorophyll, and nutrients	Increased essential oils, carbohydrates, and protein	The combination of organic and biofertilizers yields the best performance	[65]
Organic (Quail, Cow, Goat) & Chemical Fertilizer	↑ Dry weight, ↑ Leaf nutrient accumulation	↑ Essential oil and thymol (highest with cow manure), Goat manure: ↑ ROS	Combined organic fertilization improves growth, antioxidant capacity, and reduces oxidative stress	[66, 80]
Green Manure (Crotalaria juncea) + Cow Manure	↑ growth and plant production	↑ Essential oil and thymol	Combining green and cow manure is an economical and sustainable strategy	[68]
Wood Vinegar Foliar Spray + Glomus mosseae	↑ Root weight, ↑ Canopy diameter, ↑ Root colonization	↑ Carbohydrates, ↑ Protein, ↑ Essential oil	Synergistic effect of the mycorrhizal fungus and wood vinegar	[70]
Nitrogen + Cytokinin	↑ Plant height, ↑ Branch number, ↑ Biomass	↑ Essential oil percentage and yield	Balanced management of nitrogen and cytokinin improves plant quantity and quality	[69, 71]
K^+ and Ca^{2+} Spray	↑ growth and yield	↑ Phenols, ↑ Antioxidant capacity	Increases salinity tolerance	[76]
Nitrogen and Potassium Fertilizer	↑ Thyme growth	–	Most excellent effect with 150 kg Urea + 100 kg Potassium Sulfate	[77]
Humic Acid (HA) + AMF	↑ growth parameters, ↑ Chlorophyll	↑ Carbohydrates, ↑ Essential oil	Adding AMF and HA is an effective method to increase the commercial value of thyme	[81]
Spent Mushroom Substrate (SMS) + NPK	↑ Yield and quality	–	More effective than manure; NPK alone only increases production	[47]
RSM Method (Nitrogen, Potassium, Algal Extract)	↑ Biomass	Maintained the quality of the main essential oil compounds (Thymol)	Reduces chemical fertilizer use and environmental pollution	[79]
Micronutrients (Zn, Fe, Mn)	↑ Chlorophyll A & B, ↑ Carotenoids	↑ β-Cymene, ↑ Thymol, ↑ Borneol, ↑ Carvacrol	Enhances the medicinal and economic quality of the plant	[45]
Methyl Jasmonate Foliar Spray + TiO_2 / CSNPs Nanoparticles	–	↑ Essential oil yield and quality, reduced heavy metal toxicity	A practical method to increase plant quality and environmental tolerance	[73, 74]

Weed and Pest Management

Weed control is an effective factor in increasing yield and the quality of bioactive compounds in common thyme. Thyme weed control with glufosinate ammonium at 13-16 days after planting is the most effective method, reducing weed density by 43% to 85%. Flame spraying is less effective, and its application increases the risk of damage to seedlings and their components [82]. Effective weed and pest control in garden thyme requires careful timing and the selection of an appropriate method; incorrect use can damage the plant and pose environmental hazards [83]. In a 4-year study, the efficacy of flame weeding on two dates was compared with glufosinate

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ammonium spraying for weed control in common thyme cultivated directly in the field. The results showed that, in the early stages of slow and sensitive thyme growth, glyphosate ammonium spray was the most effective control method, with 43 to 85 percent weed reduction after four weeks, while flame-throwing was less effective (up to 68 percent reduction); neither method left any residue in the soil [84].

Harvesting Time and Frequency

Harvest time and season significantly impact the essential oil content, bioactive compounds, and antioxidant activity of thyme. The highest yield of thyme essential oil is observed at 6:00 AM, and the lowest at 14:00. Thymol, gamma-terpinene, para-cymene, and carvacrol are the primary constituents of the essential oil, with slight variations in their proportions throughout the day. Thymol is most abundant in the early morning hours. Higher midday temperatures reduce essential oil content; therefore, harvesting between 6:00 AM and 10:00 AM is the best time to obtain the highest quantity and quality of thyme essential oil [85]. The spring harvest increases γ-terpinene, thymol, carvacrol, essential oil content, and TFC, whereas the autumn harvest yields the highest amounts of borneol, para-cymene, TPC, and antioxidant activity [86]. The highest plant fresh weight was obtained at 4 months of age, indicating active vegetative growth during this period, while the highest amount and yield of essential oil were observed at 6 months of age, suggesting increased synthesis of volatile compounds and essential oil production as the plant reached full maturity [53].

In addition, the essential oil content of thyme and the percentage of thymol decrease with successive harvests, while the amount of phenolic compounds increases [31]. The chemical composition and biological properties of thyme oil vary depending on the flowering phenophase stage and harvesting conditions (fresh or dried plant), such that essential oils extracted from fresh plants and at the beginning of the flowering period show the highest antibacterial and antibiofilm activity against bacteria such as Haemophilus influenzae, Haemophilus parainfluenzae, and Pseudomonas aeruginosa [5]. The highest amount of essential oil, phenol, and flavonoid content is observed in the pre-flowering stage. The main components of the essential oil include thymol, carvacrol, para-cymene, and gamma-terpinene, with thymol playing a particularly prominent role in antioxidant and antibacterial activities. The antimicrobial activity against the gram-negative bacterium Escherichia coli is more potent than that against S. aureus. The results show that harvest time and plant growth stage significantly affect the quality and biological properties of the essential oil, with the second harvest at the flowering stage yielding the highest activity [87]. The second harvest at flowering exhibits the highest biological activity, despite the pre-flowering stage offering the highest total essential oil and phenolic content. This is because the antimicrobial and antioxidant efficacy of thyme essential oil is determined by the relative composition of important compounds rather than the total amount alone. This distinction highlights that the functional activity of thyme essential oil is more closely linked to its qualitative chemical profile, particularly the balance among thymol, carvacrol, and related monoterpenes, than to the absolute concentration of total oil or phenolics. Therefore, the enhanced bioactivity at the flowering stage reflects a more favorable composition of active compounds, underscoring that phytochemical effectiveness is determined by compositional dynamics rather than total metabolite accumulation.

The results show that harvest time and season have a significant impact on the quality and effectiveness of the essential oil, and therefore, choosing the right harvest time is necessary for optimal use of the antimicrobial properties of thyme, especially in a situation where antibiotic resistance in microbes is increasing and essential oils are emerging as promising natural therapeutic options.

Postharvest Processing and Handling

The quality, chemical composition, and bioactive activity of the essential oils and extracts of garden thyme are strongly influenced by postharvest methods, drying conditions, and storage, so different drying methods can directly alter the bioactive compounds and antioxidant activity of the plant. The drying process of thyme increases its polyphenol content and antioxidant activity, although vitamin C and chlorophyll are reduced. The most significant increase in polyphenols and antioxidant capacity is observed in freeze-dried thyme, suggesting that the plant's dried extract is a rich and promising source for food and pharmaceutical applications [88]. Drying at room temperature (27°C) and at high temperature (100°C) results in differences in phytochemical composition: alkaloids are observed only at high temperature, while tannins are destroyed at these temperatures. High temperatures can alter the structure of compounds and reduce the presence of some volatile compounds, whereas low temperatures better preserve polyphenolic compounds and flavonoids.

Additionally, low temperatures are an effective trigger for the accumulation of certain phytochemicals. Furthermore, increasing temperatures can lead to loss of essential oils and changes in organoleptic properties, and the antibacterial activity of compounds such as thymol is more stable at room temperature [89]. Furthermore, storing essential oils at room temperature rather than refrigeration results in a sharp decrease in low-molecular-weight compounds, such as alpha-pinene and gamma-terpinene, due to evaporation and oxidation; however, it increases important therapeutic compounds, such as thymol and carvacrol [90].

A 2024 study by Mohammadian investigated changes in the composition of the essential oils of garden thyme (T. vulgaris) under various storage conditions, including room temperature, a refrigerator (4°C), and a freezer (-20°C), over 3 months. The results show that the key compound, thymol, remains stable for the first two months under all three temperature conditions, but decreases significantly in the third month. In contrast, the amount of para-cymene increases over the same period. In general, the key monoterpenes in essential oils are more stable and of higher quality at room temperature, making them more economically viable [91]. Although conventional practice favors cool storage to reduce microbial growth and slow degradation, several studies [89-91] indicate that room temperature storage can maintain thymol stability for key periods. This discrepancy likely arises because thymol, as a major monoterpene, is relatively volatile but chemically stable under moderate, dry conditions; thus, while refrigeration slows microbial spoilage, it may not always enhance the chemical stability of specific bioactive compounds like thymol. Drying at room temperature in the dark resulted in the most significant preservation of total phenolics and antioxidant activity in the methanolic extract. After 5 months of storage, the bioactive compounds remained at high concentrations. In terms of antimicrobial activity, oven drying was the most effective method at the end of the storage period, except for E. coli [92]. Shade drying resulted in a significant reduction in total essential oil content. In contrast, freeze drying resulted in a minor reduction but led to the loss of some more volatile compounds under vacuum [93].

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Vacuum drying at 40°C provides the most significant retention of chlorophyll, ascorbic acid, and bioactive compounds, as well as near-fresh color. In contrast, vacuum drying at 45°C is suitable for preserving nutritional components and producing teas, supplements, and beverages. Tray and rotary tray dryers at 45°C are used for bakery and food products, which exhibit good emulsification and foaming capacity [94].

According to a 2021 study by Karami et al. (2021), hybrid drying is the most effective method for drying thyme, as it preserves 24 major volatile compounds, including thymol and pinene, and extracts approximately 50% more essential oil than traditional and oven methods. This method is also faster and prevents loss of quality and volatile compounds, making it ideal for postharvest processing of thyme [95].

Freeze drying (FD) and microwave at 360 W (MW360) maintained higher levels of total phenolic content and linalool. Moreover, FD, oven drying at 40°C (OV40), and microwave drying at 720 W (MW720) produced the highest amounts of thymol, carvacrol, and TFC, whereas MW360, OV40, and FD produced the highest amounts of TPC and linalool [86]. The use of a carrier mixture of maltodextrin and whey protein concentrate (MD-WPC) during spray drying at 150°C provided the optimal conditions for stabilizing the antioxidant compounds in thyme extract. This method resulted in better retention of phenolic compounds and antioxidant activity, increased production yield, and improved microbial stability of the final product [96].

The use of thyme essential oil nanoemulsions stabilized with cellulose nanocrystals and composite films can maintain the stability and quality of bioactive compounds, increasing the shelf life and antimicrobial properties of products. These methods are a practical complement to optimizing agronomic practices to preserve thyme's medicinal properties [97]. Other novel methods include gamma irradiation under modified atmosphere packaging (MAP, 100% N_2), which can completely inactivate ground thyme microbial contamination and simultaneously improve some of its functional properties [98]. In general, the intended end use should be considered when selecting the best postharvest technique for thyme. For high-value pharmaceuticals and food items where the preservation of sensitive chemicals is crucial, FD yields the most effective results in maintaining the concentration of phenols and antioxidant compounds.

On the other hand, vacuum drying at regulated temperatures (40–45°C) strikes an outstanding balance between preserving active ingredients and maintaining color and sensory qualities that are suitable for making tea and beverages. Lastly, hybrid drying seems to be the most effective technique for procedures whose main objective is to extract as much essential oil as possible. Moderate heat-based methods, such as drying at room temperature, may be more cost-effective. Still, they always carry the risk of losing volatile chemicals or slightly altering the chemical profile. Therefore, selecting suitable postharvest and processing strategies enhances the shelf life and medicinal value of the product, while optimizing its economic and nutritional applications. Optimization of postharvest methods is emphasized to maintain the quality and valuable chemical composition of plant essential oils, especially thyme. Table 3 summarizes results from various sources. Figure 2 organizes and illustrates the study's key components.

In summary, the choice of drying and storage method should be guided by the intended end-use. Freeze-drying preserves phenolic compounds and antioxidant activity most effectively, making it ideal for pharmaceutical and nutraceutical applications. Hybrid drying maximizes essential oil yield and volatile retention, which is optimal for commercial essential oil production. Moderate heat-based methods, such as room temperature or vacuum drying at 40–45°C, offer a practical compromise between preserving bioactive compounds, maintaining color and organoleptic properties, and ensuring cost-effective processing. Therefore, a postharvest strategy should be selected based on both product value and target application to optimize quality, stability, and economic efficiency.

Table 3 Effect of postharvest and drying methods on the quality, chemical composition, and bioactive activity of garden thyme *(Thymus vulgaris)*

Postharvest / Drying Method	Effects on Chemical Compounds	Effects on Bioactive Activity	Key Points	Source
Freeze-Drying (Lyophilization)	↑ Polyphenols	↑ Antioxidant activity	A rich and stable source for food and pharmaceutical applications	[88]
Room Temperature (27°C) Drying	Preserves polyphenols and flavonoids	Increases the accumulation of bioactive compounds and antioxidant activity	Low temperature is effective for maintaining the chemical composition	[89, 90]
High-Temperature (100°C) Drying	↑ Alkaloids, ↓ Tannins, and volatile compounds	reduce antioxidant activity	High temperature can alter the chemical profile	[89, 90]
Drying in Darkness	Preserves total phenols and antioxidant activity	–	After 5 months of storage, bioactive compounds remain high	[92]
Vacuum Drying at 40–45°C	Preserves chlorophyll, vitamin C, and bioactive compounds	–	Suitable for producing tea, supplements, and food products	[94]
Hybrid Dryer	Preserves 24 volatile compounds, including thymol and pinene	–	Extracts 50% more essential oil, faster, and with higher quality	[95]
Freeze Drying and Microwave MW360	↑ TPC and linalool	↑ Total phenols	FD, OV40, and MW720 produced the most thymol and carvacrol	[86]
Spray Drying with MD-WPC carrier at 150°C	Preserves phenolic compounds	↑ Antioxidant activity, ↑ Microbial stability	Optimizing conditions for stabilizing antioxidants	[96]

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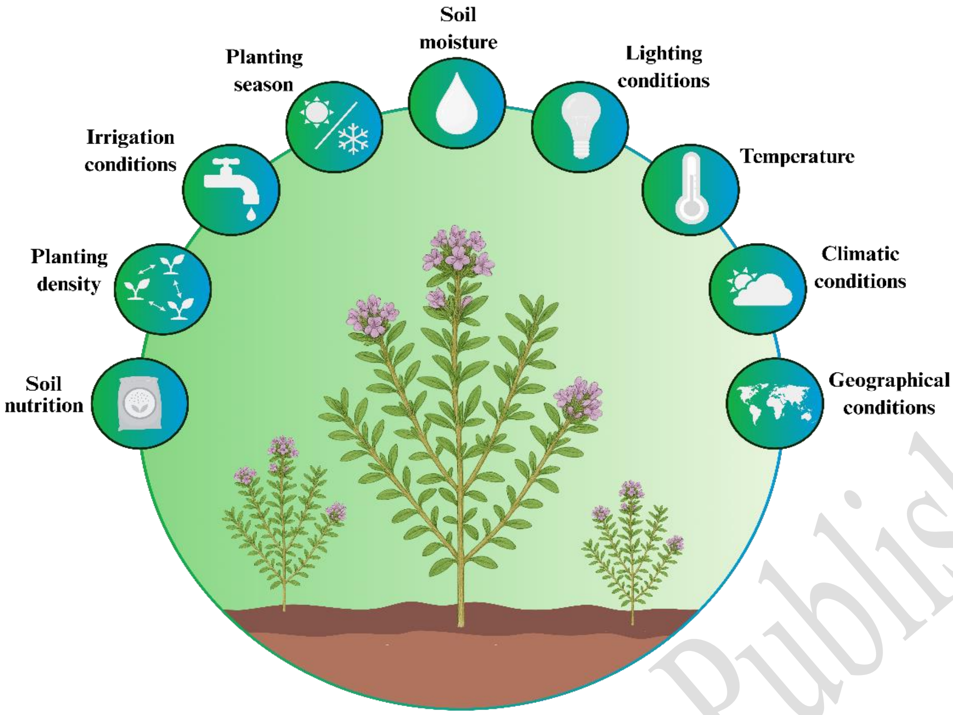

Fig. 2 Schematic of factors affecting the growth of garden thyme (*Thymus vulgaris*)

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New Thyme Cultivation Technologies and Approaches

The organic cultivation of garden thyme in Mediterranean climates has yielded promising results, with a notable increase in plant biomass over three years. In addition to enhancing growth and biomass production, this cultivation method can also positively impact the quality of active compounds and essential oils. It can improve environmental sustainability and soil health by limiting or eliminating the use of chemical fertilizers and synthetic pesticides. In addition, organic cultivation can increase plants' resistance to environmental stresses, such as drought, temperature changes, and pests, and enhance the economic and medicinal value of the resulting products. Adopting sustainable, organic cultivation methods, especially in regions with temperate and Mediterranean climates, can be an effective strategy to optimize the production and quality of garden thyme and pave the way for its broader use in the pharmaceutical, food, and cosmetic industries [99].

Navrátilová et al. (2021) presented an efficient protocol for in vitro polyploidization of garden thyme using oryzalin, yielding stable tetraploid lines that can be transferred to the field. Polyploid plants have a different essential oil composition than diploids and produce higher amounts of bioactive compounds, such as thymol, γ-terpinene, and 4-cymene. These lines increase thyme genetic diversity and are used in the food industry and in the production of plant pesticides [100]. Although more field comparative research is needed to assess effectiveness and sustainability on a broad scale before it can be commercially used, this approach is a formidable breeding tool with the potential to develop new generations of thyme with tailored chemical profiles.

Treatment of thyme seeds with a 50 mT magnetic field for 60 min accelerated germination, improved root and shoot growth, and more than doubled the essential oil content. These results indicate the potential of using magnetic fields as physical stimuli to improve thyme yield and quality in agriculture [101]. Enhanced UV-A radiation increases the production of critical phenolic compounds, such as thymol, carvacrol, and γ-terpinene [102]. Although UV-B radiation reduces the growth and yield of garden thyme, it increases its biochemical content and the percentage of essential oil. Silver nanoparticles (AgNPs) mitigate the adverse effects of UV-B radiation and enhance the quantitative and qualitative traits of plants. The simultaneous application of UV-B and AgNPs enhances plant growth, yield, and biochemical composition and is considered a practical approach to increase the quality and quantity of garden thyme [103]. Therefore, even though UV-B initially reduces growth, the synergistic interaction between UV-B and AgNPs eventually yields a net positive effect on the production of important bioactive compounds and the enhancement of both quantitative and qualitative traits, thereby satisfying the primary objective of contemporary cultivation strategies.

As an organic amendment, biochar improves soil properties, reduces sodium absorption, increases garden thyme resistance to salinity, and enhances growth, yield, and production of essential oils, including thymol, carvacrol, and Rosmarinus acid. Treatment with 3% biochar had the most significant positive effect. Overall, biochar is an effective and environmentally friendly solution for increasing thyme quality and yield in saline and low-yielding lands [104].

Cold plasma (DBD-CP) can be used as an effective pretreatment to increase the extraction efficiency of thyme essential oil. CP treatment increases the leaves' hydrophilicity, leading to tearing and creasing of the glandular hairs over time and with increasing voltage, thereby improving the extraction of essential oil. Therefore, DBD-CP can improve extraction efficiency without compromising essential oil quality. However, the choice of treatment time and intensity is vital to avoid damage to the leaf structure [105].

Various agronomic, biological, and physical approaches can significantly enhance growth, resistance to environmental stresses, and the quality of essential oils in garden thyme (T. vulgaris). These studies emphasize the importance of combining agronomic, biological, and postharvest strategies for sustainable, High-quality, and valuable thyme production, providing practical and effective solutions for organic, resilient, and economical agriculture.

Limitations and Future Research

Thyme is a species with a long history in Mediterranean culture and agriculture, and determining its natural or naturalized presence in areas affected by human activities is difficult. Ecological and biogeographical analyses indicate that the species is endemic in many places, whereas its associated plant communities are predominantly semi-natural and influenced by human activities. Natural succession processes or human pressures cause changes and fluctuations in population. This situation highlights the importance of monitoring, managing, and protecting primary and secondary habitats, along with careful planning of human interventions, to maintain biodiversity, ensure the sustainability of plant communities, and enhance the conservation of thyme. These findings offer practical guidance for improving management strategies and conserving plant species in human-dominated habitats [106].

There are significant gaps in the current garden thyme research landscape that can be broadly divided into three categories: a lack of research into the long-term applied effects of contemporary postharvest and novel compound treatments; a need for a deeper understanding of complex, simultaneous interactions; and, finally, difficulties with sustainability assessment and the practical integration/transfer of laboratory findings to agricultural practice. Despite significant advances in cultivating and optimizing garden thyme, essential limitations and scientific gaps remain that can guide future research. Many studies have focused on the effects of environmental stresses, bio-stimulants, and various fertilizers on the growth and quality of essential oils. However, knowledge of the simultaneous interactions among multiple ecological and management factors, especially under natural conditions, is limited. Additionally, the long-term effects of modern postharvest methods and nano- or biologically derived compounds on the stability of bioactive compounds, soil health, and agroecosystems have not been thoroughly investigated. Gaps in the genetics and genotypic diversity of thyme, particularly in the development of resistant, high-quality varieties, require further study. Finally, the integration of laboratory and field results, as well as the transfer of knowledge to farmers to support sustainable agriculture, has not yet been fully realized, offering an essential opportunity for future research.

Therefore, multifactorial field studies that assess the combined effects of environmental, agronomic, and postharvest factors under realistic production methods should be the primary focus of future studies. Lastly, the conversion of laboratory findings into practical management recommendations that support farmers and businesses in implementing high-yield, sustainable, and quality-focused *Thymus vulgaris* production in various agro-ecological locations.

CONCLUSION

The yield and quality of garden thyme are strongly influenced by a set of agronomic, environmental, biological, and postharvest factors. The use of integrated approaches, including sustainable agronomic management, optimal nutrition with organic and biological fertilizers, the use of bio stimulants, mycorrhiza, and endophytes, foliar spraying of hormones and mineral elements, and proper irrigation scheduling management can significantly increase plant growth, drought and salinity stress resistance, and the production of essential oils with bioactive compounds such as thymol and carvacrol. In addition, selecting optimal postharvest methods, including proper drying, storage at controlled temperatures, and the use of modern technologies to stabilize bioactive compounds, is vital for maintaining the quality, shelf life, and biological activity of essential oils. This review focuses on proven tactics. For instance, exposure to an R4B1 can significantly increase thymol content, and applying humic acid and mycorrhiza together is particularly effective in enhancing drought tolerance and essential oil yield. It has been demonstrated that, in situations of water scarcity, nutritional management based on sustainable methods, such as the concurrent application of organic fertilizers and biofertilizers (including mycorrhizal and bacterial inoculants), is an effective way to enhance production sustainability and mitigate the detrimental effects of chemical fertilizers.

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