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Enhancing Medicinal Plant Yield through Optimization in Greenhouses and Controlled Environments: A Review

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Review Article

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ABSTRACT

The use of medicinal plants has played an important role in maintaining health and producing herbal medicines throughout history. The increasing global demand for these plants has led to unprincipled exploitation and overharvesting of natural resources. The development of controlled cultivation methods has been proposed as an effective solution to produce high-quality products, to preserve natural ecosystems and to meet market needs. These methods not only increase the yield and quality of the product by optimizing the factors affecting growth, but are also quite effective in producing the active compounds of medicinal plants, and in this regard, they obtain more valuable plants. Along with the various advantages of these systems, the existence of several challenges has still prevented their significant expansion, which, of course, is expected to overcome recent advances. In order to achieve the full potential of these methods as a sustainable solution, more research is needed to provide useful solutions in this field.

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Introduction

Throughout history, medicinal plants have held a significant role in healthcare, hygiene, and traditional herbal medicine practices. Today, they continue to serve as essential resources for health and well-being across many countries, where a large proportion of the population relies on these plants for preventive and therapeutic purposes (Asafo-Agiye et al., 2023). Medicinal and aromatic plants occupy a critical position not only within global healthcare systems but also in economic development, acting as catalysts for rural employment and income generation (Taghouti et al., 2022). However, the rising global demand for these valuable plant resources poses serious concerns regarding the overharvesting of wild populations and the consequent threats to biodiversity and natural ecosystems. This increasing pressure underlines the urgency of developing innovative, sustainable, and eco-friendly cultivation methods that can meet demand without compromising environmental integrity (Marcelino et al., 2023). The expanding herbal medicine market has transformed medicinal plants into significant economic commodities, offering valuable income opportunities for farmers and local producers. In this context, the controlled and sustainable cultivation of medicinal plants emerges as a strategic approach to prevent environmental degradation, enhance employment, and support economic growth within the agricultural sector (Motokeng et al., 2022). Nevertheless, unsustainable harvesting practices driven by market pressures have intensified stress on natural ecosystems, disrupting species population structures, impairing reproductive success, limiting natural dispersal, and in some cases, leading to local extinctions (Sharma and Kala, 2018). Given the broader environmental implications of agricultural activities—such as biodiversity loss, climate change, and water pollution—there is a pressing need to implement sustainable agricultural strategies that balance productivity with ecological preservation (Yu and Mu, 2022). Integrating sustainable practices into medicinal plant production can further contribute to environmental conservation by reducing energy use, limiting the spread of harmful microorganisms, and mitigating the release of greenhouse gases and other pollutants that accelerate ecosystem degradation (Trabelsi et al., 2019; Freitas et al., 2021).

Research has shown that controllable environmental factors and conditions such as light spectrum, ambient temperature, root zone temperature, nutrient composition, and microbial presence significantly affect plant growth and the synthesis of secondary metabolites of medicinal plants (Suksawat and Panichayupakaranant, 2024). By optimizing these factors, producers can cultivate medicinal plants regardless of fluctuations in weather conditions and improve yield and quality (Pant et al., 2021). Severe climate change, water scarcity, limited arable land, nematode contamination, pathogens, and the use of pesticides and chemicals are some of the disadvantages and limitations of traditional soil-based cultivation of medicinal plants (Barman et al., 2016; Surendran et al., 2017). The controlled cultivation of medicinal plants presents a strategic approach to enhancing the quality, purity, and biomass yield of plant-derived raw materials, thereby addressing one of the major bottlenecks in phytopharmaceutical production—namely, the limited availability of high-quality starting materials. For instance, the cultivation of *Pelargonium sidoides* under optimized irrigation regimes has been shown to significantly increase total biomass production without negatively affecting the concentration of its pharmacologically active constituents (Mofokeng et al., 2020).

Studies have shown that various soilless cultivation systems can improve the production of bioactive compounds in plants. High-quality medicinal plants rich in bioactive compounds have been successfully cultivated using hydroponics (Gaja et al., 2023). The hydroponic cultivation system, in which the plant is grown in nutrient solutions, is one of the practical methods for producing medicinal plants in controlled environments such as greenhouses (Ahmed et al., 2020). Another soilless cultivation method in controlled environments such as greenhouses is aeroponics, in which the plant roots are nourished in a dark chamber with nutrient solutions sprayed on them. A notable advantage of aeroponics over other cultivation methods is excellent root aeration, which increases plant performance, especially in root medicinal plants. Other advantages include crop size control, optimal water consumption, easy harvesting, nutrient solution recycling, and precise nutrition control (Movahedi and Rostami, 2020).

In recent years, aquaponics—a soilless cultivation system—has garnered considerable interest from both the scientific community and commercial producers (Yep et al., 2019). This integrated system synergistically combines aquaculture and hydroponics by utilizing fish excreta, which is converted into bioavailable nutrients for plants through the action of nitrifying bacteria within a closed-loop system. One of the primary advantages of aquaponics lies in its capacity to reduce dependency on synthetic fertilizers and chemical pesticides, while simultaneously enabling the production of both plant and aquatic organisms (König et al., 2018; Palm et al., 2018). Given the ongoing depletion of wild medicinal plant populations due to overharvesting and environmental pressures, the greenhouse cultivation of medicinal plants has been increasingly recommended as a viable and sustainable alternative. Experts in traditional medicine, stakeholders in the medicinal plant trade, and commercial producers largely support the cultivation of these species under controlled greenhouse conditions as a means of ensuring consistent quality and supply (Nefhere, 2019). Controlled environment agriculture (CEA) offers a promising strategy to alleviate pressure on natural plant reserves while addressing growing consumer and pharmaceutical demands.

Accordingly, this review aims to highlight the significance and diverse applications of medicinal plants, and to evaluate the potential for their cultivation within greenhouses and other controlled environments. Particular emphasis is placed on the key environmental and agronomic factors influencing production efficiency, sustainability, and plant quality in such systems.

2. Understanding medicinal plants and the importance of their use

Medicinal plants are defined as plant species that contain bioactive compounds, particularly secondary metabolites, which are widely utilized in both traditional medicine systems and modern pharmaceutical applications. The global demand for these plants in therapeutic contexts has been steadily rising in recent years. As the trade of medicinal plants represents a sector of considerable economic value, their systematic and planned cultivation is considered essential not only for reducing the unsustainable exploitation of wild resources but also for generating employment and supporting rural economies (Motokeng et al., 2022). According to projections by the International Trade Center, the global medicinal plant market is anticipated to grow at an annual rate of approximately 10–12% (Chandra and Sharma, 2019). Particularly in developing countries, the demand for herbal medicines is increasing at a rapid pace, driven by their perceived health benefits and affordability compared to synthetic pharmaceuticals. In this context, the World Health Organization (WHO) reports that nearly 75–80% of the global population relies on medicinal plants to meet primary healthcare needs (Bareeseng, 2022). Market analyses conducted in 2022 estimated the total value of the global herbal medicine sector at approximately 170 billion USD, with forecasts suggesting this figure may rise to 600 billion USD by 2023, reflecting a compound annual growth rate (CAGR) of 15%. Similarly, the global value of dried herbs such as oregano, rosemary, mint, and thyme reached 5.8 billion USD in 2022, projected to grow to 6.17 billion USD in 2023, and expected to attain 7.93 billion USD by 2027, with a CAGR of 6.3%. Furthermore, processed herbal products—including capsules, tablets, and extracts—are predicted to reach a market value of 117 billion USD by 2029, growing at a CAGR of 7.3% (Silveira and Boylan, 2023). These trends underscore the rapidly expanding global herbal medicine market, which is likely to intensify the demand for medicinal plants. Consequently, the strategic expansion of cultivation efforts is expected to play a crucial role in ensuring future supply and in capitalizing on emerging economic opportunities within this sector.

Secondary metabolites are specialized compounds that play a vital role in enabling plants to adapt to and defend themselves against a variety of biotic and abiotic stresses. Among these, *phytoalexins*, known for their antimicrobial properties, serve not only as protective agents for plants but also possess promising therapeutic potential for human health (Pagare et al., 2015; Chae et al., 2012; Mahmudali, 2013). Medicinal plants are characterized by their ability to biosynthesize a diverse range of secondary metabolites—such as flavonoids, tannins, steroids, saponins, and alkaloids—many of which have demonstrated pharmacological efficacy in the treatment of various diseases, thereby rendering these plants highly valuable resources in both traditional and modern medicine (Davies and Espley, 2013; Khazir et al., 2014). Numerous examples highlight the pharmaceutical importance of such compounds. For instance, cardiotonic drugs derived from *Digitalis lanata*, and anticancer agents extracted from *Catharanthus roseus*, have been well documented in the scientific literature (Bhusare et al., 2018; Rai et al., 2014). Likewise, curcumin, a bioactive compound found in *Curcuma longa* (turmeric), has shown therapeutic potential in the development of stroke medications (Almutairi et al., 2022). Additionally, artemisinin, obtained from *Artemisia annua*, is recognized globally as an effective antimalarial agent, while ellipticin, derived from *Ochrosia elliptica Labill*, has been employed in the formulation of anticancer drugs (Isah, 2019). Moreover, the antimicrobial, anti-inflammatory, and immunomodulatory properties of many medicinal plants suggest their potential role in addressing viral infections, including global pandemics such as COVID-19. Certain plant species have demonstrated antiviral activity and the capacity to regulate immune responses, thereby reducing disease severity and supporting recovery (Lim et al., 2021). These findings collectively underscore the therapeutic value of medicinal plants and reaffirm their relevance in both preventive and curative healthcare strategies.

3. Various Environmental Control Methods for Cultivating Medicinal Plants

The precise and efficient optimization of environmental parameters that influence the biosynthesis of plant-derived bioactive compounds represents a promising strategy for enhancing the qualitative and quantitative output of secondary metabolites. In this context, various environmental stimuli are known to act as elicitors, triggering the plant’s defensive metabolic pathways, especially in medicinal plants, where secondary metabolites often accumulate in response to biotic, abiotic, or chemical stress factors (Thakur et al., 2019). Under controlled cultivation systems, such as greenhouses, these defense responses can be artificially stimulated by mimicking environmental stressors—a process referred to as elicitation. Among the most influential environmental parameters in this regard is light, which is a highly adjustable factor in greenhouse-based production systems. Manipulation of light intensity, duration, and wavelength spectrum has been shown to significantly impact the biosynthesis of key secondary metabolites such as flavonoids and alkaloids (Holopainen et al., 2018). Specific light wavelengths can modulate plant metabolism and promote the accumulation of targeted bioactive compounds. For example, controlled UV-B irradiation was found to elevate stigmasterol and sarcasapogenin concentrations in *Chlorophytum borivilianum* (Jaiswal et al., 2023). Similarly, elevated light intensity at particular growth stages enhanced the flavonoid and polysaccharide content in *Dendrobium officinale* (Li et al., 2023). Experimental evidence also indicates that blue light increased artemisinin accumulation in *A. annua* and vinblastine levels in *C. roseus* (Zhang et al., 2018; Nagy et al., 2023). In *H. perforatum*, blue light exposure resulted in a higher concentration of bioactive compounds in flowers compared to red or white light treatments (Karimi et al., 2022). Notably, while red light may primarily influence plant morphology and overall physiological traits, blue light has consistently been associated with increased biosynthesis of photoprotective secondary metabolites, without detrimentally affecting plant development (Landi et al., 2020). These findings underscore the potential of elicitation techniques in enhancing the pharmacological value of medicinal plants by activating their inherent defense systems through carefully calibrated stimuli (Agathokleous et al., 2019; Godínez-Mendoza et al., 2023). However, the effectiveness of light spectrum manipulation in inducing secondary metabolite production is species-dependent and can vary according to developmental stage and interactions with other environmental variables. Therefore, further research is essential to elucidate the species-specific response mechanisms that govern the optimal application of light-based elicitation strategies (Taulavari et al., 2018).

Developing strategies to enhance photosynthetic efficiency in greenhouse cultivation offers a promising route to boost the biosynthesis of secondary metabolites in medicinal plants. Photosynthesis is the primary source of carbon for plants and leads initially to the production of primary metabolites, many of which serve as precursors for specialized metabolic pathways. Pathways such as shikimate, phenylpropanoid, mevalonate, and methylerythritol phosphate (MEP) are fundamentally dependent on the carbon fixed during photosynthesis. For instance, the shikimate pathway—crucial for the biosynthesis of aromatic amino acids and specialized metabolites such as indole derivatives and phenolics—utilizes over 30% of photosynthetically fixed carbon (Maeda and Dudareva, 2012). Supporting this, Abadie et al. (2024) reported that carbon derived from photosynthesis is channeled through the shikimate pathway to fuel phenylpropanoid metabolism. Additionally, elevated CO_2 concentrations and high light intensity can enhance the synthesis of specialized metabolites by increasing the production of intermediates like 3-phosphoglyceric acid, a key precursor in sugar and polysaccharide biosynthesis (Pan et al., 2020).

An emerging approach in optimizing secondary metabolite production is chronoculture, which aligns agricultural practices with the plant's circadian clock—the internal time-keeping mechanism that synchronizes physiological processes with diurnal environmental cues such as light and temperature. Chronoculture involves scheduling agronomic interventions (e.g., irrigation, nutrient supply, elicitor application) in accordance with the plant's biological rhythms to maximize growth and metabolite output (Steed et al., 2021). Plants have been shown to exhibit differential sensitivity to environmental stressors like drought or temperature based on the time of day. Thus, timing the application of elicitors or stimuli in harmony with circadian-regulated metabolic peaks can optimize the synthesis of medicinally valuable compounds (Kerwin et al., 2011; Wang et al., 2021; Horak and Farré, 2015; Grinevich et al., 2019; Liebelt et al., 2019). Adjustments to environmental parameters such as light quality, CO_2 levels, temperature, humidity, and water availability, when synchronized with circadian rhythms, have been shown to improve biomass accumulation and phytochemical production. For example, Hotta (2021) demonstrated that applying stimuli at specific circadian time points significantly enhanced metabolite yields. In summary, chronoculture in controlled environments offers an effective strategy for fine-tuning secondary metabolism through the temporal coordination of external stimuli, although a deeper understanding of circadian regulation mechanisms is still required (Dsouza et al., 2025).

Another critical advantage of controlled greenhouse cultivation—particularly within hydroponic systems—is the ability to precisely manipulate root zone conditions, including temperature, nutrient composition, and even root zone illumination. Such manipulations have been associated with significant improvements in secondary metabolite biosynthesis in various medicinal plant species (Paponov et al., 2023). Modifying the ratios of macronutrients (e.g., nitrogen, phosphorus, potassium) and micronutrients directly influences enzyme activity, precursor availability, and metabolic fluxes within biosynthetic pathways (Abdalla et al., 2021; Corrado et al., 2021a). For instance, tailored nutrient formulations have been reported to enhance secondary metabolite concentrations in mint (*Mentha* spp.) (Zeljković et al., 2022) and *Echinacea purpurea* (Ahmadi et al., 2021). Moreover, a root zone temperature of 15°C was found to increase both net photosynthesis and the expression of regulatory genes in the phenylpropanoid pathway in *Nicotiana benthamiana* (Son et al., 2023). Furthermore, exposing plant roots to white, blue, or red light increased the accumulation of artemisinin in *A. annua* and coumaroylquinic acid in *H. perforatum*, indicating that root zone illumination is a novel and effective elicitation technique (Paponov et al., 2023).

In addition to abiotic manipulation, the use of biotic elicitors—particularly microbial stimuli—in hydroponic systems has demonstrated potential in enhancing secondary metabolite production. Research suggests that combinations of multiple elicitors are generally more effective than single treatments (Mubeen et al., 2022; Aremu et al., 2016; Partap et al., 2020). Collectively, these findings highlight the capacity of precise environmental control in soilless systems to significantly improve the phytochemical profile of medicinal plants. However, it is important to note that the efficacy of these strategies is often species-dependent, necessitating further targeted studies (Zeljković et al., 2022). A summary of various soilless cultivation techniques and their documented impacts on secondary metabolite production in medicinal plants is provided in Table 1.

Table 1. Medicinal Plants Cultivated in soilless cultivation (DFT: Deep Flow Technique. NFT: Nutrient Film Technique. FRS: Floating Raft System. CF-DWC: Continuous Flow Deep Water Culture)

Scientific Name	Cultivation Technique	Effect of Cultivation Technique	Reference
Agastache rugosa	DFT	Increased antioxidant and phenolic compounds such as: Rosmarinic Acid, Tilianin and Acacetin.	Lam et al., 2020
Cannabis sativa	Substrate-based Hydroponics (Peat moss) and Aquaponic	Hydroponics increases inflorescence biomass. Aquaponic Enhanced production of medicinal compounds such as: 1. Cannabinoids: - THCA (Tetrahydrocannabinolic Acid) - CBDA (Cannabidiolic Acid) 2. Terpenes: - Pinene - Limonene	Yep et al., 2020
Datura stramonium And *Datura tatula*	Aeroponic	Increased Production of medicinal alkaloids such as: Atropine, hyoscyamine and scopolamine.	Rahmoune et al., 2017
Ocimum basilicum	FRS	Increased accumulation of phenolic compounds such as: rosmarinic acid, caffeic acid, chicoric acid and ferulic acid. Increased volatile compounds such as: Linalool, eucalyptol, eugenol and alpha-bergamotene.	Ciriello et al., 2021
Hyssopus officinalis	Cultivated in separate pots and fed in solution. Similar to DWC but without continuous rotation.	Increased phenolic compounds and antioxidant activity such as: Rosmarinic Acid, Chlorogenic Acid, Hydroxycinnamic Acids and Protocatechuic Acid. Increasing essential oils	Skrypnik et al., 2022
Agastache rugosa	CF-DWC	Increased antioxidant and phenolic compounds such as: Tilianin and Acacetin	Kim et al., 2017

4. Various factors affecting the growth of medicinal plants cultivated in hydroponics

4.1 Temperature

The influence of temperature on growth parameters of medicinal plants cultivated hydroponically has been investigated in several studies. For instance, research conducted on basil (*Ocimum basilicum*) utilizing the nutrient film technique (NFT) revealed that maintaining the root zone temperature at 23°C significantly enhanced root and stem fresh and dry biomass, as well as leaf width and average leaf area. In contrast, a temperature of 27°C was found to promote overall plant growth (Hendrickson et al., 2022). Similarly, in a study on *Ophiorrhiza pumila* grown via the nutrient solution-filled container method, a root zone temperature of 20°C was optimal, resulting in the greatest leaf area, fresh and dry biomass accumulation, and maximal camptothecin concentration in roots (Lee et al., 2020). Furthermore, investigations on coriander using the deep flow technique (DFT) demonstrated that root zone temperatures of either 15°C or 35°C increased the accumulation of phenolic compounds, ascorbic acid, carotenoids, and chlorogenic acid (Nguyen et al., 2020).

4.2 Nutrients

In *Lavandula angustifolia* cultivated using the pot method, appropriate potassium supplementation was found to enhance root development as well as the accumulation of phenolic and flavonoid compounds in the leaves (Chrysargyris et al., 2017a, b, c). In *Mentha spicata* grown in a nutrient solution-based container system, specific nitrogen concentrations promoted the biosynthesis of key secondary metabolites such as carvone, limonene, 1,8-cineole, germacrene D, and β-compounds (Chrysargyris et al., 2017a, b, c). Additionally, phosphorus application under deep flow technique (DFT) cultivation increased rosmarinic acid content in the aerial parts of the plant (Chrysargyris et al., 2019). In another study on *L. angustifolia* grown in pots, a balanced application of nitrogen and phosphorus was shown to elevate cineole levels (Chrysargyris et al., 2016). Similarly, in *Salvia officinalis* cultivated in a nutrient solution system, nitrogen supplementation led to increased levels of carotenoids, proline, total phenolic compounds, and oxygenated monoterpenes in the foliage (Khammar et al., 2021). For *Prunella vulgaris* grown in a plastic hydroponic setup, phosphorus treatment significantly enhanced the concentrations of oleanolic and ursolic acids (Yu et al., 2016). Furthermore, a recent study reported that the combined application of humic acid and zinc sulfate improved both growth performance and alkaloid accumulation in the roots and leaves of *Physalis alkekengi* (Kazemi et al., 2023). Another related experiment demonstrated that this nutrient combination increased micronutrient uptake, particularly zinc and iron, which was associated with enhanced root biomass, chlorophyll content, antioxidant capacity, and phenolic compound production. These findings suggest that the combined use of humic acid and zinc sulfate may serve as an effective strategy to improve biomass yield and stimulate secondary metabolite biosynthesis in medicinal plants cultivated under hydroponic or controlled environment systems (Kazemi et al., 2024).

4.3. Nanoparticles

Various studies have investigated the effect of nanoparticles on secondary metabolites in medicinal plants cultivated hydroponically. For example, adding silver nanoparticles to the nutrient solution of milk thistle (floatation method) increased the phenolic and flavonoid content in the leaves (Mobin et al., 2022). In another study, silver nanoparticles in a hydroponic system based on Hoagland solution increased carnosic acid in rosemary leaves (Hadi Soltanabad et al., 2020). Conversely, zinc and copper nanoparticles increased plant height, fresh and dry weight in *Corydalis hybridus* but had no effect on secondary metabolites (Francis et al., 2022). Nanoparticles at high concentrations can have phytotoxic effects and damage plant cells through the production of reactive oxygen species (ROS) (Rastogi et al., 2017; Marslin et al., 2017). Silver and copper oxide nanoparticles at certain concentrations can cause oxidative stress and reduced plant growth (Jasim et al., 2017; Lala, 2020). Copper oxide and zinc oxide nanoparticles can also have cytotoxic and genotoxic effects, including DNA damage and cell cycle disruption (Ahmed et al., 2018; Youssef et al., 2020). The effect of nanoparticles on plant secondary metabolism is often hormetic, acting as stimulators at low concentrations and inhibitors at high concentrations (Spinoso-Castillo et al., 2017). In addition, important concerns include the accumulation of nanoparticles in plants and the possibility of their entry into the food chain, posing a threat to human health and the environment, which requires careful assessment for their consumption (Rajput et al., 2020. Rico et al., 2011).

4.4. pH

In *Taraxacum officinale* grown in nutrient-filled containers, leaf number and stem diameter were maximal at pH 5.5, while phenolics, carotenoids, and chlorophyll were maximal at pH 4 (Alexopoulos et al., 2021). Similarly, in *Reichardia picroides*, leaf number and stem diameter were maximal at pH 5.5, while phenolics and carotenoids were maximal at pH 4 (Alexopoulos et al., 2021). In *Stevia rebaudiana* grown in Styrofoam boxes with nutrient solution, aerial biomass was maximal at pH 6, while steviol glycosides were maximal at pH 7 (Kafle et al., 2017).

4.5. EC

In *Centella asiatica* grown by Floating technique, increasing the electrical conductivity (EC) up to a certain level increased asiaticoside, asiatic acid, madecassoside and madecassis acid in leaves (Shawon et al., 2023). In *Acmella oleracea* (Pot Technique), EC close to 3.5 mS/cm increased caryophyllene and spilanthol isomers (Carmo et al., 2024). High EC (8.5 dS/m) reduced phenolic and flavonoid content in Pelargonium graveolens (Pot Technique) (Chrysargyris et al., 2021), this negative effect was also observed in *Verbena officinalis* (Chrysargyris et al., 2021).

4.6. Light

Red light (600 nm) increased catharanthine and vindoline in leaves of *Catharanthus roseus* (plastic container containing nutrient solution) (Fukuyama et al., 2015). In NFT, the combination of red light (660 nm) and blue light (470 nm) increased growth parameters (number of branches/leaf, number of flowers, root volume) in *Hypericum perforatum*, while blue light increased proline. However, their results indicate that this is cultivar-dependent (Karimi et al., 2022). In pot technique, white, red (680 nm) and blue (460 nm) light improved the performance of *Ocimum basilicum* (Rahman et al., 2021). Red light (660 nm) reduced fresh/dry weight in *Geranium thunbergii* (NFT) but maximized geranium content (Watanabe et al., 2011). In another experiment, LED lights were used on the medicinal plant *Panax ginseng*, and different light spectra were observed to have different effects on growth and physiology. White light increased root biomass by increasing the net photosynthesis rate and decreasing the intracellular CO_2 partial pressure. Red and yellow light significantly increased stem biomass, while blue light had the least effect on the growth of this plant. Yellow light also increased stomatal conductance and transpiration rate, indicating the response of this shade-loving plant to low light conditions. These findings suggest that optimizing the light spectrum in controlled environments can improve the production of medicinal parts of *Panax ginseng* (Kim et al., 2023). Full LED light in floating hydroponic culture increased carvacrol content, height, leaf length/width, number of branches, crown diameter, and leaf dry weight in *Lippia palmeri* (Bringas-Burgos et al., 2023). Red light (660 nm) and far-red light (738 nm) increased chlorogenic, caffeic, and chicoric acid in *Crepidiastrum denticulatum* in a pot experiment (Bae et al., 2017). A study investigated the effects of different LED light spectra on physiological traits of lettuce growth in a greenhouse. The results showed that the red/blue light combination was the most effective treatment for improving stomatal traits and vegetative growth, while red light produced the highest substomatal CO_2 concentration and white and blue lights produced the highest CO_2 uptake. These findings highlight the importance of selecting the appropriate light spectrum in plant cultivation for lettuce (Soufi et al., 2024). Another study showed that blue and red light increased nutrient uptake, photosynthetic performance, and growth in strawberry plants, while white/yellow light had no significant effect. However, more research is needed on the effects of LEDs on different species (Malekzadeh and Roosta, 2024). In a recent study to evaluate the performance of silver vanadate nanorods in smart windows, a sample coated with nanorods was fabricated and its effect on the growth of wheat, barley, millet, and beet plants was investigated. The results showed that these nanostructures significantly improved the phytochemical properties of plants by converting green light to higher wavelengths. This research shows the high potential of silver vanadate nanorods in the development of smart agricultural windows, although further studies are needed (Bagiyan et al., 2024).

From a financial and economic efficiency point of view for producers, the use of LEDs in controlled environment agriculture can be cost-effective, because its unique features such as precise light regulation and the use of specific wavelengths (such as red and infrared light) lead to reduced electricity costs, improved product quality, and better control of plant growth and flowering. These benefits have been confirmed in various studies on a variety of plants under controlled cultivation conditions. Of course, for LED to be cost-effective, photoperiod management using longer and lower intensity exposure to increase light efficiency, monitoring plant physiological responses such as quantum yield and electron transfer rate, developing intelligent algorithms to automatically control light based on environmental conditions, and determining the amount of light each plant needs should be investigated. These solutions will be effective in addition to reducing initial investment costs (such as installing fewer lights) (Van Iersel., 2016-2021).

4.7. Living organisms

Natural microorganisms have both beneficial and detrimental effects on plant growth. Few studies have investigated their effects on secondary metabolites in medicinal plants. However, in *Rhinacanthus nasutus* (hydroponic system with Trichoderma harzianum), rhinacanthus content in roots increased (Suksawat and Panichayupakaranant, 2024). In Silybum marianum (flotation technique), Aspergillus niger increased phenolic and flavonoid content (Mubeen et al., 2022). Furthermore, Aspergillus niger treatment in a nutrient-rich container system increased flavonolignans (apigenin 7-D glucoside, silybin A/B, isosilybin A/B) in *Silybum marianum* (Mubeen et al., 2021).

4.8. Phytohormones

Phytohormones have diverse roles in plant cultivation. In black cumin (hydroponic plastic box), 100 µM methyl jasmonate (7-day treatment) significantly increased the production of triterpenoid saponin (Calopanax saponin) in leaves (Scholz et al., 2009). In milk thistle (floatation method), 100 mM methyl jasmonate maximized phenol and flavonoid synthesis (Mubeen et al., 2022). Similarly, in *Allium tuberosum* (hydroponic boxes), methyl jasmonate increased the content of phenol, protocatechuic acid, and chlorogenic acid in leaves (Wang et al., 2022). Salicylic acid (200 mM) increased flavonolignans in milk thistle fruits (NFT) (Ahmed et al., 2020).

5. Examples of aeroponic and aquaponic cultivation of medicinal plants

Cultivation of root medicinal plants has traditionally been costly and time-consuming due to manual mechanical harvesting. In recent years, aeroponic systems have emerged as a modern agricultural technology that is widely used for the production of various crops, including medicinal plants, especially root species (Penzkofer et al., 2014; Buckseth et al., 2016). Aeroponic cultivation, with excellent aeration of the roots, enables rapid propagation of medicinal plants. This method reduces water and fertilizer consumption and improves plant growth by accurately transferring nutrients and eliminating soil. It also allows cultivation in adverse environments and provides complete control over the growth conditions of medicinal plants (Lopez-Valdez et al., 2022).

In a study comparing two types of soil and aeroponic cultivation systems for medicinal plants (Cichorium, Withania, and Echinacea) in a greenhouse, it was shown that the aeroponic cultivation system performed better than soil in increasing morphological traits and photosynthetic pigment content. Therefore, aeroponic systems were recommended for greenhouse cultivation of these plants (Movahedi and Rostami, 2020). Also, research on aeroponic cultivation of the medicinal plants *Zingiber officinale* and *Urtica dioica* in a greenhouse showed increased yield and root biomass, along with the production of cleaner products compared to field cultivation (Honary et al., 2011; Crosby and Craker, 2007). Another study investigated the effect of aeroponics on four medicinal plants, including valerian (*Valeriana officinalis*), chicory (*Cichorium intybus*), cow parsley (*Withania coagulans Dunal*), and *echinacea purpurea*, using salicylic acid (SA) at concentrations of 0, 50, 100, and 150 mg/L. The results showed that aeroponics combined with SA treatment, especially at a concentration of 150 mg/L, significantly improved morphological traits and photosynthetic pigments in all plants. An increase in plant height, root length, leaf number, root and shoot biomass, and chlorophyll and carotenoid content were observed, indicating the effectiveness of the aeroponics system in optimizing growth conditions for these medicinal plants (Rabary et al., 2020). Also, in another experiment, the aeroponic method was used to evaluate the propagation of three endangered medicinal plants, Carallumaedulis, Leptadeniareticulata and Tylophoraindica, and its appropriate efficiency was reported.

Another study showed that aquaponics performed better than hydroponics in cultivating medicinal cannabis. The presence of microorganisms and organic matter in aquaponics, especially in low light conditions, probably improves its efficiency. Aquaponics also has a lower environmental impact compared to hydroponics (Subah and Mirkouei., 2025).

Various medicinal plants have been cultivated in aquaponics, including: peppermint (*Mentha piperita*), spearmint (*Mentha spicata*), basil (*Ocimum basilicum*), oregano (*Origanum vulgare*), coriander (*Coriandrum sativum*), rosemary (*Rosmarinus officinalis*), thyme (*Thymus vulgaris*), parsley (*Petroselinum crispum*), and dill (*Anethum graveolens*). These plants are considered suitable options for cultivation in this system due to their compatibility with the aquaponics system and low nutrient requirements (Stoyanova et al., 2024).

In aquaponic systems, various combinations of medicinal plants have been used with fish species. Basil (*Ocimum basilicum*) and coriander (*Coriandrum sativum*) have been cultivated with Nile tilapia (*Oreochromis niloticus*) and catfish (*Clarias gariepinus*) (Love et al., 2015; Nishanth., 2023). Coriander, parsley (*Petroselinum crispum*), mint (*Mentha spicata*), thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), dill (*Anethum graveolens*), and basil have also been cultivated with Nile tilapia (Valdez et al., 2020).

Mint, basil, and peppermint (*Mentha piperita*) have also been used with Nile tilapia and common carp (*Cyprinus carpio*) (Knaus and Palm, 2017; Knaus et al., 2020). Other combinations such as basil and coriander have been grown with Nile tilapia and catfish (Nishanth., 2023), as well as basil, rosemary (*Salvia rosmarinus*), oregano, and thyme have been grown with Nile tilapia (Espinosa et al., 2018). Mint and basil have also been used alone with Nile tilapia in aquaponic systems (Valdez et al., 2020). These combinations represent a significant diversity in aquaponic systems that allows for the simultaneous production of valuable medicinal plants and different fish species. The selection of these compounds was based on the compatibility of plants and fish in terms of nutritional needs and growth conditions. Figure 1 and Figure 2 shows a comparison between aeroponically and soil-grown medical plants after several months.

Figure 1. Comparison of root development in aeroponic cultivation (right side) versus soil cultivation (left side) after 4 months in *Chicory* plants (Movahedi and Rostami, 2020).

Figure 2. Comparison of root development in aeroponic cultivation (right side) versus soil cultivation (left side) after 4 months in *Withania* plants (Movahedi and Rostami, 2020).

6. Limitations of Soilless Cultivation

One of the main challenges that can prevent the expansion and optimal productivity of these systems is the high initial costs for setup, which include equipment, infrastructure, and environmental control technologies (Lakhiar et al., 2025; Gruda et al., 2023). Energy consumption, especially in indoor systems such as vertical farms and controlled greenhouses, is usually very high due to the need for artificial lighting, heating, and cooling, which increases operating costs (Paris et al., 2022).

Soilless cultivation systems require careful monitoring of environmental conditions and nutrient solutions. The issue of excess nitrate in plant leaves is also a major challenge in these systems (Colla et al., 2018). The dependence of these systems on technical expertise to precisely manage parameters such as pH, electrical conductivity (EC), and nutrient concentrations in solutions is another challenge facing these systems (Savvas and Gruda, 2018; Shareef et al., 2024). In the discussion of nutritional management, one of the main problems is the management of the electrical conductivity (EC) of the nutrient solution, which has a direct impact on plant growth and the accumulation of bioactive compounds. Very low EC (0.5 $dS \bullet m^{-1}$) can lead to nutrient deficiency and reduced plant growth, while very high EC (8.0 $dS \bullet m^{-1}$) causes salt stress, ion toxicity, and reduced water and nutrient uptake (Ding et al., 2018). Changes in the composition of secondary metabolites such as phenolic acids and aromatic compounds under the influence of pre-harvest factors indicate the complexity of managing these systems to achieve uniform quality (Filip, 2017). Some potential limitations include the need for precise control of growth conditions (e.g. pH and conductivity of the nutrient solution) and the dependence on nutrient supply, especially for trace elements. Also, the difference in the uptake of elements through nutrient solutions compared to other methods such as foliar spraying can be a challenge (Skrypnik et al., 2021). In addition, adjusting the optimal concentration of elements to avoid toxicity or deficiency requires further research (Hasanuzzaman et al., 2020).

Another challenge of soilless cultivation is the limitation in the diversity of cultivable plants. These systems are mainly suitable for plants with short growth cycles and high economic value (Gruda, 2021; Zhou et al., 2024). Microbial contamination in hydroponic systems, due to the absence of soil as a protective medium, can lead to health problems and reduced product quality, which must be taken into account (Saldinger et al., 2023; Thomas et al., 2024).

It is important to note that waste management in high-density systems is important because the accumulation of some substances, such as sodium, can negatively affect plant health (Chowdhury and Asiabanpour, 2024). Also, the need for high-quality, contaminant-free water to prepare nutrient solutions is problematic in areas with limited water resources (Sridhar et al., 2023). Scalability of soilless culture systems in developing countries is difficult due to the lack of appropriate infrastructure, limited access to technology, and lack of supportive policies (Gumisiriza et al., 2022; Bahri et al., 2022).

Conclusion

Conflict of This review examined the importance and applications of medicinal plants and assessed the feasibility of their controlled cultivation in greenhouse environments and soilless systems. The findings indicate that controlled cultivation of medicinal plants, including hydroponic, aeroponic, and aquaponic methods, can not only meet market needs but also help conserve natural resources and reduce pressure on ecosystems. In particular, the regulation of environmental factors such as light, temperature, pH, and nutrient solutions is effective in increasing the production of secondary metabolites and the concentration of medicinal compounds such as alkaloids, flavonoids, and terpenes, improving the quality and quantity of products. However, challenges such as high initial costs, the need for management and accurate knowledge of growing conditions, and the limitation in the diversity of cultivable plants require further attention and the development of sustainable solutions. Overall, controlled cultivation of medicinal plants is proposed as a promising solution for the sustainable supply of these plants and achieving economic and environmental goals. To advance the development of these systems, future research topics in this field include further study on optimizing cultivation conditions, investigating the effect of beneficial microorganisms, reducing overall costs in these systems, evaluating the long-term effects of soilless cultivation systems on the environment and human health, and increasing the diversity of cultivable species in controlled environments.

Interest

The authors declare no conflict of interest

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