

Advances in medicinal plant cultivation techniques for enhancing yield and quality – a review

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ABSTRACT

The cultivation of medicinal plants is undergoing a paradigm shift, driven by the dual demands of higher productivity. This review synthesizes recent advances in innovative cultivation systems, genetic improvement, and sustainable management practices aimed at enhancing yield, quality, and resource efficiency. Modern soilless systems such as hydroponics, aeroponics, and vertical farming are enabling precise control over growing environments, improving phytochemical content, nutrient uptake, and water-use efficiency. Tissue culture and bioreactor technologies are revolutionizing mass propagation, conservation, and targeted enhancement of bioactive compounds, while molecular breeding and CRISPR-based genome editing are unlocking new genetic potential. Concurrently, sustainable practices, including organic farming, integrated pest management, conservation tillage, cover cropping, and circular economy models, are reducing carbon footprints and safeguarding biodiversity. The review also examines future directions such as block chain-enabled traceability, life cycle assessment (LCA) for environmental benchmarking, and digital twin models for real-time cultivation optimization. These advancements collectively position medicinal plant cultivation to meet growing global demand for high-quality herbal products while aligning with ecological and regulatory imperatives.

Key words: Medicinal plant cultivation; Yield improvement; Phytochemical enhancement; hydroponics; Aeroponics; Tissue culture; Genome editing; Microbiome engineering; Sustainability; Precision agriculture

Medicinal plants have been an integral part of human healthcare for millennia, providing remedies that range from simple herbal preparations to highly refined pharmaceutical compounds. The World Health Organization (WHO) estimates that approximately 80% of the global population continues to rely on traditional plant-based medicines for primary healthcare (Beyene *et al.*, 2016), underscoring their enduring relevance to human health and cultural heritage. In recent decades, cultivation has expanded from small-scale gardens to large commercial operations, driven by rising global demand, advances in agricultural technology, and the urgent need to conserve threatened species. Successful medicinal plant production depends on an intricate interplay of factors, including the choice of species and genotypes, optimization of environmental conditions, integrated pest and disease management, and post-harvest handling. These parameters directly influence biomass accumulation, phytochemical content, and therapeutic efficacy. The last two decades have seen a notable shift towards science-based interventions that merge

traditional knowledge with cutting-edge cultivation and processing technologies.

Modern propagation techniques such as tissue culture and bioreactor-based production ensure uniform, disease-free planting material and facilitate rapid multiplication of elite genotypes. Precision agriculture enhanced by IoT-enabled sensors, unmanned aerial vehicles (UAVs), and AI-based environmental control allows growers to monitor and adjust crop conditions in real time for optimal growth and metabolite synthesis. Sustainable production systems, including organic farming, agroforestry, and conservation tillage, are being adopted to meet environmental and regulatory requirements while enhancing market value.

This review synthesizes current advances in medicinal plant cultivation, focusing on strategies to enhance yield, improve phytochemical quality, and ensure environmental sustainability. It covers innovations in soilless cultivation (hydroponics, aeroponics, vertical farming), genetic improvement (conventional breeding, molecular tools, and CRISPR-mediated genome editing), microbiome engineering, and sustainable agronomic practices. The discussion also addresses market and policy drivers, such as traceability systems and compliance with Good Agricultural and Collection Practices (GACP), which are increasingly critical in global herbal trade. By examining both technological advances and sustainability imperatives, this review aims to provide a holistic framework for the next generation of medicinal plant production systems.

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Enhancing yield and quality for sustainability

Meeting the rising global demand for safe and effective herbal products requires cultivation systems that simultaneously enhance yield, ensure and standardize quality, and minimize environmental impacts. These objectives are interdependent: practices that optimize resource utilization and stabilize growing conditions tend to improve both biomass production and phytochemical composition, while sustainable frameworks help secure long-term supply chains and strengthen market confidence.

Yield: Global demand for medicinal and aromatic plants necessitates improving productivity without exhausting resources. Precision agriculture, supported by IoT-enabled sensors, AI-assisted decision tools, and geospatial analysis, has shown potential to optimize irrigation, nutrient delivery, and site-specific crop management (Mansoor *et al.*, 2025; Kumar *et al.*, 2025). Machine learning-based suitability mapping has also been applied to identify optimal growing zones for medicinal crops under rainfed and climate-stressed conditions (Roopashree *et al.*, 2024; Sadeghfam *et al.*, 2024). These approaches enhance both yield and resource-use efficiency, providing a climate-resilient pathway for medicinal plant production.

Quality: The concentration and stability of bioactive metabolites, which vary with genotype, cultivation conditions, and post-harvest processing (Ambali *et al.*, 2024; Hasmi *et al.*, 2025). Controlled environment agriculture and Good Agricultural and Collection Practices (GACP) help in standardizing quality (WHO, 2003; Chen *et al.*, 2016). More recently, metabolomics has emerged as a powerful tool to fingerprint chemical profiles, monitor environmental and processing effects, and support multi-marker quality control systems (Ji *et al.*, 2024; Wang *et al.*, 2023). Comparative studies, such as those on gooseberries, highlight how harvest timing and environmental variation influence metabolite accumulation (Yao *et al.*, 2018). Together, these approaches ensure consistency, safety, and regulatory compliance in herbal products. Controlled environment agriculture and good agricultural practices have proven effective in optimizing active compound levels and improving medicinal plant quality (Saravanan and Das, 2024).

Sustainability: Unsustainable harvesting and habitat degradation threaten many medicinal species (Hamilton, 2004). Promoting sustainable cultivation through organic farming, agroforestry, and biodiversity conservation contributes not only to ecological health but also to improved yield and quality by maintaining soil fertility and ecosystem services (Marcelino *et al.*,

2023). Emerging approaches include circular economy models and life cycle assessments (LCAs), which help in identifying hotspots of energy and resource use in herbal value chains and propose pathways to reduce carbon footprints (Becerra *et al.*, 2022). Additionally, climate-focused strategies are needed to buffer medicinal plant resources against over-exploitation and environmental change (Mykhailenko *et al.*, 2024).

Traceability and market confidence:

Sustainability and quality assurance are increasingly linked to digital traceability. Block chain-based systems are being piloted to integrate GACP records, laboratory test results, and lot identity across supply chains, thereby reducing adulteration risks and improving consumer confidence (Wang *et al.*, 2021).

Innovative cultivation practices

The innovative cultivation of medicinal plants (Fig 1) is undergoing a paradigm shift with the adoption of controlled-environment technologies, precision nutrient delivery, and advanced propagation systems. These approaches not only enhance yield and phytochemical quality but also improve production consistency and reduce environmental burdens. By integrating hydroponics, aeroponics, tissue culture, and vertical farming, medicinal plant production is being redefined to meet the dual challenges of global demand and sustainability.

Hydroponics: enhancing phytochemical content, nutrient uptake, and water efficiency

Hydroponics-soilless cultivation with nutrient-rich aqueous solutions-has emerged as a highly efficient system for medicinal plant production. Beyond its water-use efficiency, hydroponics allows precise manipulation of nutrient regimes to modulate secondary metabolite accumulation. Studies have demonstrated significant gains in both biomass and phytochemical content compared to soil-based systems (Atherton, 2023). A recent experiment on *Withania somnifera* (ashwagandha) showed remarkable improvements under hydroponic conditions, including a 72% increase in wet biomass along with enhanced plant height and leaf number (Agrahari, 2025). Similarly, optimizing nitrogen forms, such as tailoring $\text{NH}_4^+:\text{NO}_3^-$ ratios, has been reported to elevate rosmarinic acid and other metabolites in *Melissa officinalis* (Safaei *et al.*, 2024). Such findings underscore hydroponics as a versatile tool for simultaneously enhancing productivity and therapeutic efficacy. Importantly, organ-targeted hydroponic designs-customized for roots, leaves, or flowers-are being developed to maximize yields of specific bioactive compounds (Atherton *et al.*, 2023).

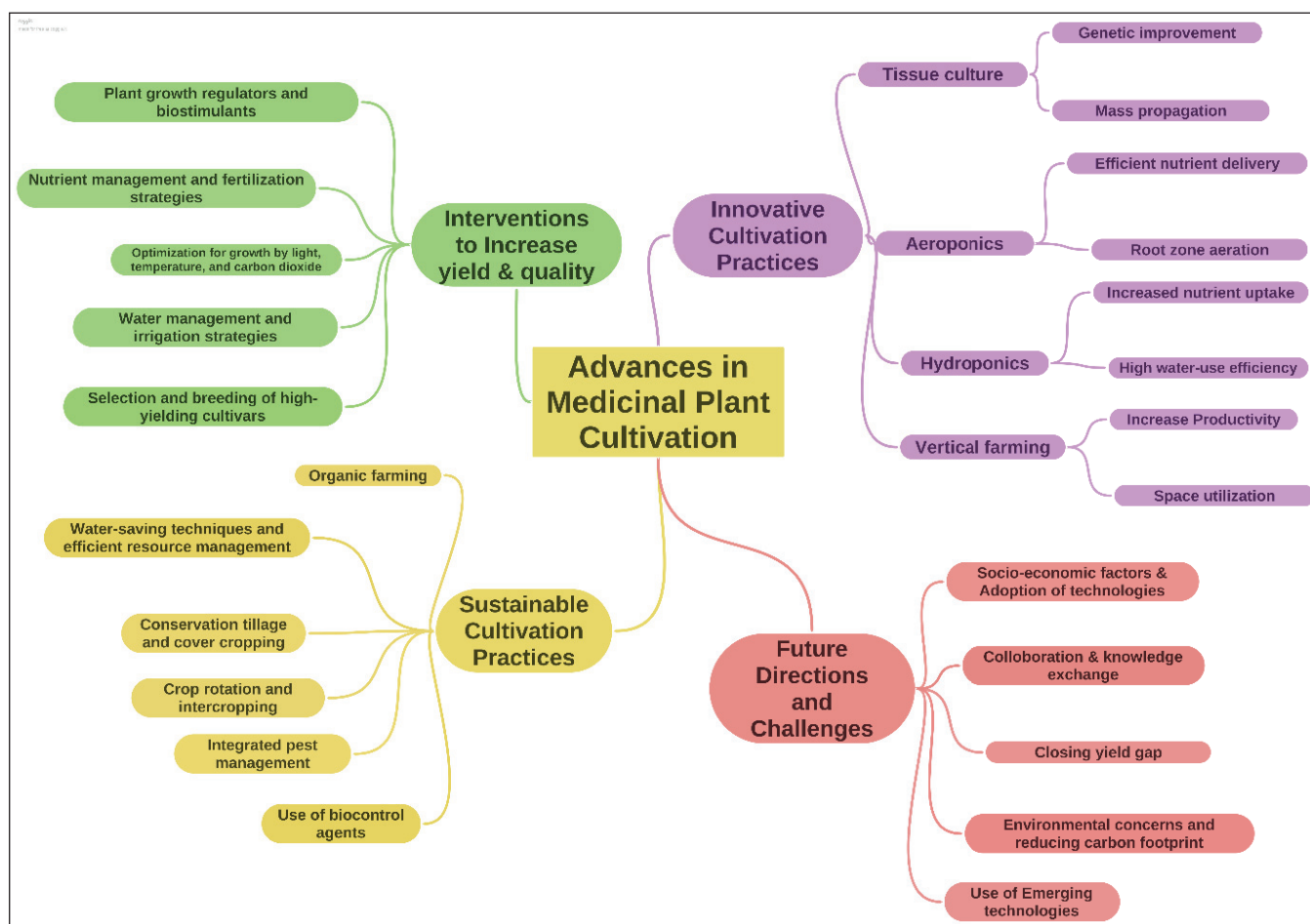


Fig. 1. Mind map of advances in medicinal plant cultivation

Aeroponics: optimizing root zone aeration and nutrient delivery

Aeroponic cultivation, where roots are suspended and intermittently misted with nutrient-enriched solutions, offers superior aeration and rapid nutrient uptake. This approach mitigates soil-borne pathogens while promoting root vigour and metabolite accumulation. With Industry 4.0 integration, aeroponic systems increasingly deploy sensors, automation, and AI-based controls to regulate mist frequency, nutrient concentration, and environmental parameters (Garzón *et al.*, 2023). Recent studies highlight innovative enhancements: electro stimulation treatments have improved root biomass and metabolite profiles in medicinal plants, while IoT-machine learning frameworks are being deployed for predictive irrigation scheduling and optimization of resource-use efficiency (Amjad *et al.*, 2025). These advances position aeroponics as an adaptable and high-precision system for medicinal species, especially those where root-derived compounds are commercially valuable.

Tissue culture: mass propagation, regeneration, and genetic improvement

Plant tissue culture remains a cornerstone of medicinal plant biotechnology. It enables mass propagation of genetically uniform, disease-free planting material while serving as a critical tool for conserving endangered species. Established protocols for somatic embryogenesis and de novo organogenesis have improved substantially in efficiency (Long *et al.*, 2022). Moreover, recent advances in nanoparticle-assisted culture media are being explored to mitigate contamination risks and enhance micropropagation success (Gunasena, 2024). Tissue culture platforms also provide avenues for targeted metabolite enhancement through precursor feeding, elicitor treatments, and even CRISPR-based metabolic engineering, linking propagation with biotechnological improvement of phytochemical profiles (Nazari *et al.*, 2023).

Vertical farming: maximizing space and controlled environments

Vertical farming offers a promising solution for high-density, year-round production of medicinal plants, particularly in urban or resource-limited settings. By stacking cultivation layers under controlled environments, vertical systems optimize space use while maintaining consistency in phytochemical quality (Dsouza *et al.*, 2025). Pharmaceutical crops such as *Digitalis purpurea* (foxglove) are now being cultivated indoors, ensuring uniform levels of cardiac glycosides (Bafort and Jijakli, 2024).

The integration of IoT sensors and AI platforms in vertical farms enables real-time disease monitoring, climate control, and predictive yield modelling (Rathor, 2024). Nonetheless, challenges remain-particularly in terms of high capital and energy demands (Reynolds, 2022). Recent research into renewable energy integration and closed-loop water and nutrient recycling is helping to mitigate these limitations, making vertical farming a viable long-term strategy for medicinal plant production in climate-uncertain futures.

Enhancing yield and quality

Selection and breeding

Breeding programs are foundation in enhancing both yield and phytochemical quality in medicinal plants. Traditional approaches-such as mass selection, hybridization, mutation breeding, and polyploidization-have led to cultivars rich in valuable metabolites like artemisinin from *Artemisia annua* (Delabays *et al.*, 2001) or oil in lemongrass from *Cymbopogon* spp. (Dutta *et al.*, 2017). For instance, mutation breeding has generated high-alkaloid cultivars through induced variability (Kolakar *et al.*, 2018), while cultivar selection in milk thistle (*Silybum marianum*) has achieved improved bioactive content (Alemardan *et al.*, 2013) and optimized herb and oil yield in chrysanthemum (Gajbhiye *et al.*, 2025).

While these methods remain essential, modern breeding integrates molecular and genomic tools to accelerate trait improvement with precision. Genomics-assisted breeding (GAB) and omics-assisted breeding (OAB) now allow rapid identification of quantitative trait loci (QTLs) and candidate genes tied to secondary metabolite pathways and stress resilience (Tyagi *et al.*, 2024). Advanced technologies like long-read sequencing have already produced over 400 medicinal plant genomes by early 2025, enabling robust gene annotation and identification of loci involved in secondary metabolism (Cheng *et al.*, 2025). Pre-sowing seed treatments have also been reported to boost germination vigour and expand

flavonoid diversity in butterfly pea accessions (Makasana *et al.*, 2016).

In addition, synthetic polyploidization-applying colchicine or other agents-has emerged as a powerful tool to enhance agronomic traits and metabolite production. For example, tetraploid chamomile strains now dominate globally, showing heightened chemical activity (Gupta, 2024). Yet, variability in metabolite profiles post-polyploidization suggests complex genomic effects that must be carefully managed.

The most recent and transformative advance is the application of CRISPR/Cas9 gene editing in medicinal plant improvement. This technology enables precise upregulation or knockout of key genes in secondary metabolism, directly improving bioactive compound synthesis. Reviews and case studies published in 2024–2025 document successful CRISPR applications targeting pathways in *Ocimum sanctum*, *Withania somnifera*, and *Artemisia annua*, including modifications to flowering regulators and metabolic genes that enhance metabolite yield and plant fitness (Gao *et al.*, 2025; Das *et al.*, 2024). Early outcomes show improved artemisinin levels and stress tolerance without compromising plant viability (Afridi *et al.*, 2025). Collectively, by combining classical selection with GAB/OAB, synthetic polyploidy, and genome editing, breeders can now pursue multi-trait improvement: high yield, enhanced metabolite profiles, and adaptability-closing the gap between cultivation and applied phytopharmaceutical production.

Environmental optimization for growth, manipulating light, temperature and CO₂

Verma *et al.* (2023) observed the plant growth characteristics, yield, oil composition, and dry herb production in different cultivars of *Ocimum sanctum*. Optimizing environmental parameters is critical to maximizing both biomass and bioactive compound accumulation in medicinal plants. Fine-tuning light spectra, temperature, and carbon dioxide (CO₂) levels enables targeted modulation of plant metabolism, resulting in higher yield and enhanced phytochemical quality (Saravanan *et al.* 2013; Shah *et al.*, 2010; Nair *et al.* 2024).

Light quality and photoreceptor pathways: Light spectral quality-particularly the balance of red, blue, and UV wavelengths-regulates secondary metabolism through photoreceptor signaling. Recent research highlights how specific wavelengths, via receptors like cryptochrome and phytochrome, activate transcription factors (e.g., HY5, MYBs) that govern phenolic and terpenoid biosynthesis (Wu, 2025). For instance, blue-red LED treatment has been shown to elevate monoterpene and sesquiterpene

production in aromatic medicinal species, enhancing fragrance and therapeutic profiles (Trivelliniet al., 2023). Spectral optimization under controlled-environment systems offers a precise, non-invasive strategy to enhance metabolite yield without growing cycle extension.

Light-driven metabolic regulation: LED applications have demonstrated remarkable efficacy in enhancing phytochemical content. A study of Bungala *et al.* (2024) showed that red + blue LED light significantly increases anthocyanins, phenolics, and glucosinolates in baby leaf pakchoi-indicating substantial antioxidant potential. Broadly, manipulating light quality within growth chambers or plant factories offers a robust tool to standardize metabolite profiles across production batches.

Elevated CO₂ effects and climate interactions: Increasing atmospheric CO₂ consistently boosts photosynthetic rate, plant height, and biomass across medicinal taxa (Jangkangi, 2025). However, the impact on secondary metabolites is species-specific and complex. For example, elevated CO₂ increased flavonoid levels in ragweed pollen (Bernauer *et al.*, 2024), whereas in *Hypericum perforatum*, elevated CO₂ reduced hypericin concentrations by over 20%, alongside faster phenological development (Hounsou, 2024). These results underline that CO₂ enrichment must be approached with caution: while yield may rise, critical phytochemical targets might decline if not carefully managed.

Integrated environment-controlled systems: Modern controlled-environment agriculture (CEA), including plant factories and growth chambers, is increasingly adopting AI- or sensor-based regulation for simultaneous adjustment of light spectrum, temperature, and CO₂. These systems aim to maintain steady-state metabolite profiles while adapting to dynamic plant responses. Such integration holds promise for stabilizing both yield and quality in medicinal plant production.

Nutrient management

Nutrient management remains a cornerstone of sustainable medicinal plant production, as both macro- and micronutrients directly influence growth, biomass accumulation, and secondary metabolite biosynthesis. Strategic combinations of organic, inorganic, and biofertilizer inputs not only improve plant health but also enhance soil fertility and microbial activity-factors critical for consistent yield and quality in medicinal crops.

Role of macronutrients (N, P, K): Nitrogen availability and its form (NH₄⁺ vs. NO₃⁻) are pivotal for alkaloid and phenolic accumulation. For instance, NO₃⁻-based fertilization in *Melissa officinalis* significantly

increased rosmarinic acid content, whereas NH₄ favoured leaf biomass (Fallah *et al.*, 2024). Potassium supplementation improves oil quality and enhances terpenoid production, as shown in rose-scented geranium where higher K doses elevated essential oil yield and citronellol-geraniol balance (Mazeed *et al.*, 2022). Phosphorus availability is also linked to root development and higher secondary metabolite flux, especially in root-harvested medicinal species like ashwagandha and ginseng.

Integrated nutrient management (INM): Combining organic manures, biofertilizers, and inorganic fertilizers has proven more effective than any single approach. Integrated practices improve soil microbial populations, nutrient mineralization, and enzymatic activities that support metabolite biosynthesis. For example, applying farmyard manure alongside NPK fertilizer increased both biomass and withanolide content in *Withania somnifera* (Basak *et al.*, 2020). Similarly, INM with organic amendments and beneficial microbes improved herb yield and essential oil content in French basil (Anwar *et al.*, 2005). Proper application of NPK fertilizers has been shown to enhance herb and oil yields while improving soil fertility (Mandal *et al.*, 2008).

Biofertilizers and plant-microbe interactions: Beneficial microbes such as Arbuscular Mycorrhizal Fungi (AMF), *Azotobacter*, and *Trichoderma* not only enhance nutrient uptake but also upregulate secondary metabolite pathways. AMF colonization has been shown to boost essential oil yield in *Ocimum basilicum* while simultaneously enhancing phosphorus acquisition efficiency (Khalediyan *et al.*, 2021). Microbial inoculants also promote stress resilience, making medicinal crops more tolerant to drought or salinity stress while sustaining phytochemical quality. The optimum use of nutrients and biofertilizer enhances *Pisum sativum* growth and quality metrics (Yadav *et al.*, 2025).

Organic sources and soil health: Organic amendments such as vermicompost, compost tea, and green manures improve soil structure, water retention, and nutrient cycling, creating favorable conditions for medicinal plant cultivation. Vermicompost extract application enhanced antioxidant capacity and phenolic content in *Drimiopsis maculata* (Dube *et al.*, 2018). Long-term use of organic inputs also supports soil microbial diversity, which correlates with higher consistency in metabolite production.

Precision fertigation and resource efficiency: Recent innovations in fertigation, including micro-sprinkler and drip systems, have optimized nutrient-water delivery in controlled cultivation. A study demonstrated that alternating fertigation with organic fertilizer inputs

enhanced both biomass and bioactive compound yield in greenhouse-grown medicinal herbs (Yue *et al.*, 2023). Precision fertigation systems integrated with IoT sensors now allow real-time monitoring of nutrient solution composition, thereby minimizing nutrient losses and improving sustainability (Ahmad *et al.*, 2022).

Plant growth regulators and biostimulants for yield enhancement

The application of plant growth regulators (PGRs) and bio-stimulants has demonstrated significant potential in improving both yield and quality traits of medicinal and aromatic plants. Their effectiveness lies in stimulating plant growth, modulating secondary metabolite pathways, and enhancing resilience to abiotic stresses, thereby supporting sustainable production systems.

Organic and soil-based biostimulants: Organic manures and compost-derived biostimulants are widely reported to enhance growth and biomass accumulation. For example, organic amendments improved root yield in *Withania somnifera* (ashwagandha) while also boosting phytochemical concentrations (Jat *et al.*, 2021). Seaweed-based formulations are also gaining traction: in organically grown sage, foliar seaweed extracts increased biomass and essential-oil output by up to 25 % (Farruggia *et al.*, 2024). Similarly, vermicompost leachate has been shown to improve growth performance, phytochemical content, and antioxidant potential in *Drimiopsis maculata* (Dube *et al.*, 2018). These soil-based inputs contribute to improved soil microbial activity, nutrient cycling, and long-term fertility.

Stress-responsive biostimulants: Under challenging environments, stress-modifying bio stimulants improve plant resilience and maintain productivity. For instance, foliar application of biostimulants enhanced vegetative growth, nutrient uptake, and antioxidant activity in garden thyme (*Thymus vulgaris*) under water stress (Rahimi *et al.*, 2022). Such inputs help mitigate oxidative damage, regulate osmolyte accumulation, and maintain higher photosynthetic activity during stress events.

Novel biostimulant sources: Recent advances highlight the role of chitin- and chitosan-based formulations, which stimulate plant regeneration, cell division, and secondary metabolite biosynthesis in medicinal herb cultures (Sun *et al.*, 2023). Similarly, microbial inoculants (e.g., *Trichoderma*, *Bacillus*, Arbuscular Mycorrhizal Fungi) and botanical extracts act as natural elicitors, promoting biomass accumulation and enhancing bioactive compound levels (Gins *et al.*, 2017; Kocira *et al.*, 2021). Multi-species microbial consortia

combining AMF, PGPR, and yeast enhanced both growth and phenolic content in greenhouse medicinal crops have been reported (Pérez-Moncada *et al.*, 2024).

Broad-spectrum benefits: Biostimulants and PGRs are now recognized as sustainable inputs for improving yield and the chemical composition of aromatic and medicinal plants (Shahrajabian *et al.*, 2022). They have proven effective not only under optimal conditions but also under abiotic stress scenarios, enhancing quality consistency across growing environments (Tadele and Zerssa, 2023). Recent reviews showed that vegetal protein hydrolysates stimulate root architecture and essential-oil yield in rosemary and sage through amino-acid signaling and improved nitrogen assimilation (Sun *et al.*, 2024). By maintaining balanced growth, nutrient assimilation, and phytochemical synthesis, these stimulants play a crucial role in ensuring marketable quality and therapeutic efficacy (Majkowska-Gadomska *et al.*, 2022).

Sustainable cultivation practices

Organic farming

Organic cultivation is increasingly recognized as a cornerstone of sustainable medicinal plant production. By eliminating the use of synthetic fertilizers, pesticides, and growth regulators, organic systems emphasize soil health, biodiversity, and the production of residue-free raw materials—thereby aligning with environmental objectives and the growing consumer demand for clean-label botanicals. **Ecosystem and soil benefits:** Long-term organic management enhances soil organic carbon, microbial biomass and enzymatic activities, all of which are critical for nutrient mineralisation and stable secondary-metabolite production (Raei and Alami-Milani, 2014). A recent synthesis of 140 field trials showed organic manures to increase essential-oil yield and antioxidant capacity across diverse medicinal crops by up to 28 % compared with mineral fertilisers (Rostaei and Fallah, 2024).

Phytochemical enhancement: Multiple studies confirm that organically managed plants often accumulate higher concentrations of phenolics, flavonoids or terpenoids, probably because mild nutrient stress and richer soil microbiomes up-regulate defence-related pathways (Tariyal *et al.*, 2021). Comparative work on sage, mint and chamomile grown under organic *versus* conventional regimes reported 10–35 % greater essential-oil content and elevated antioxidant activity in the organic plots (Todorova *et al.*, 2022).

Substrate and nutrient optimisation: Organic substrates (compost, vermicompost, green manures) improve water-holding capacity and cation-exchange

properties, leading to higher biomass in container or greenhouse culture of medicinal herbs (Herrera *et al.*, 1997). Recent guidelines recommend tailored compost blends that match crop-specific macro-/micronutrient needs while supporting beneficial microbes (Marcelino *et al.*, 2023).

Market and certification drivers: The premium price of certified-organic botanicals and the growing interest of phytopharmaceutical companies in traceable, low-residue raw material continue to expand organic acreage worldwide (Trisilawati *et al.*, 2020). For urban and peri-urban growers, organic practices dovetail with short supply chains and traditional-medicine markets, reinforcing local food-medicine systems (Madaleno, 2012).

Integrated pest-and-disease management and use of bio control agents

Integrated pest-and-disease management offers a holistic, low-residue strategy for medicinal-plant production. Cultural measures such as crop rotation, intercropping, sanitation and tolerant cultivars-lower initial pest pressure and pathogen inoculum enhances alkaloids (Marimuthu *et al.*, 2018).

Microbial biocontrol: Targeted antagonists such as *Trichoderma* spp. (soil-borne fungi) and *Bacillus thuringiensis* or *Beauveria bassiana* (insect pests) now form the backbone of many IPDM programmes, providing season-long suppression without compromising phytochemical profiles (Lahlali *et al.*, 2022).

Botanical products: Azadirachtin-rich neem oil, karanjin and pyrethrin extracts broaden protection while respecting organic and export residue standards (Sayed *et al.*, 2020; Isman, 2020).

Decision support: Economic-threshold-based spraying, pheromone trapping and routine residue testing restrict synthetic pesticides to a last-resort role, minimising environmental load and safeguarding herb quality (Kavitha *et al.*, 2011; Jat *et al.*, 2021).

Emerging tools: RNA-interference biopesticides and endophyte-mediated immunity are poised to strengthen IPDM over the next decade, offering species-specific control with minimal non-target effects (Ahmad *et al.*, 2025).

Together, these components preserve ecosystem health and ensure residue-safe raw material for high-quality phytopharmaceuticals.

Conservation tillage and cover cropping

Conservation tillage, mulching and cover-cropping are increasingly adopted to improve soil health, suppress weeds and stabilise yields in medicinal-plant systems.

Non-tillage strips planted with aromatic herbs such as thyme or rosemary have proved effective living mulches, reduced erosion while allowing inter-row production of companion medicinals (Durán-Zuazo and Pleguezuelo, 2008). In *Panax notoginseng*, reduced-tillage beds combined with straw mulch moderated soil temperature and curtailed root-rot incidence by shifting edaphic microbial communities (Guan *et al.*, 2011). Similarly, conservation tillage lowered weed pressure in rain-fed peppermint without compromising oil yield (Farahani *et al.*, 2009). That said, responses can be crop-specific: for *Solanum khasianum*, conventional tillage still delivered higher fruit yield than no-till, likely because the crop's early growth benefits from a finely-tilled seedbed (Sanwal *et al.*, 2016). Agroforestry models-e.g., eucalyptus interplanted with citronella-illustrate how reduced tillage under tree shade can sustain soil organic carbon and essential-oil output.

Cover crops provide complementary ecosystem services. Leguminous or grass covers boosted biomass of *Serjania marginata* (Tabaldi *et al.*, 2012) and acted as permanent ground covers in orchards/vineyards, where medicinal perennials supply both habitat and secondary income (Petzer, 2023). In *Crocus sativus*, aligning planting dates with winter cover-crop termination plus deficit irrigation increased stigma yield (Koocheki *et al.*, 2016).

Crop rotation and intercropping for sustainable systems

Crop rotation and intercropping remain cornerstone practices for ecological intensification of medicinal-plant production. Rotating medicinal or aromatic crops with cereals, pulses or oilseeds breaks pest and pathogen cycles, diversifies soil microbial communities and balances nutrient extraction, thereby sustaining long-term productivity and soil health (Pandey *et al.*, 2019). In resource-poor drylands, intercrops such as lemongrass-pigeon-pea or coleus-groundnut provide land-equivalent ratios (LER > 1.2) and steady cash flow, offering risk insurance for farmers (Pushpa *et al.*, 2018).

Multi-storey and alley systems-e.g., shade-tolerant turmeric beneath neem or moringa rows-maximise vertical light capture and organic-matter return, while living mulches suppress weeds and conserve moisture (Smitha, 2010). Integrating medicinal species into broader rotations has also been shown to restore soil organic carbon and microbial diversity depleted by continuous monocropping; combined with organic amendments, it mitigates microbiome vulnerability (Misra *et al.*, 2019).

Intercrops of rosemary or basil within orchards/vineyards generate complementary income and enhance

habitat for pollinators, exemplifying how medicinal plants can fit into diversified agro-ecosystem design (Kanene, 2016). Recent extension bulletins further highlight that pairing short-duration aromatics with staple crops improves labour use-efficiency and spreads input costs across seasons (Misra *et al.*, 2019).

Future Directions and Challenges

Emerging technologies and innovations

Cutting-edge technologies are rapidly reshaping medicinal-plant production. Plant-cell and hairy-root cultures have moved from benchtop flasks to continuous stainless-steel bioreactors equipped with on-line sensors, making it feasible to supply cosmetics and pharmaceutical industries with consistent, contaminant-free actives (Georgiev *et al.*, 2018). Parallel advances in nano-biotechnology now deliver phytochemicals in nanoscale carriers that increase solubility and bioavailability, while nano-encapsulated elicitors are boosting secondary-metabolite titres in vitro (Bernela *et al.*, 2023). At the cultivation scale, tissue culture and micropropagation provide uniform planting material for vertical plant factories where light, temperature and CO₂ are governed by sensor networks linked to AI-driven “digital twins,” allowing growers to model and optimise metabolite trajectories before implementing changes in real time (Tripathi, 2025). Untargeted metabolomics integrated with next-generation sequencing is accelerating chemovar authentication and lead-compound discovery (Zhang *et al.*, 2023), while green extraction platforms—super-critical CO₂, deep-eutectic solvents and Quality-by-Design protocols—minimise solvent use yet meet stringent GMP standards (Tegtmeier *et al.*, 2023). Collectively, these converging innovations promise higher efficiency, tighter quality control and a markedly smaller environmental footprint.

Yield improvement and crop uniformity

Raising productivity without sacrificing chemotype consistency remains a central breeding and agronomic goal. CRISPR/Cas edits targeting rate-limiting genes in terpene, alkaloid and withanolide pathways have already delivered demonstrable jumps in active-compound yield in *Artemisia* and *Withania* species (Bhojiya *et al.*, 2024). Genomics-assisted selection is likewise fast-tracking heat- and drought-tolerant chemotypes of *Ocimum* and *Mentha*, helping stabilise yields under climate volatility (Tyagi *et al.*, 2024). On the management side, UAV-based multispectral imaging and IoT-linked fertigation allow centimetre-scale correction of nutrient or water deficits, improving uniformity within commercial blocks and

lifting dry-matter yield by double-digit percentages (Sasmalet *et al.*, 2024). High-density vertical hydroponics and modular aeroponic towers exploit stacked space and uniform LED spectra to narrow chemotype variability while increasing land-equivalent output (Dsouza *et al.*, 2025). As datasets balloon, machine-learning models are becoming indispensable for integrating genotype, environment and management variables into real-time recommendations that bolster both yield and compositional uniformity.

Environmental concerns and carbon footprint reduction

Sustainability credentials are now as important as pharmacological efficacy. Updated WHO-GACP modules emphasise life-cycle assessments that capture water use, energy demand and greenhouse-gas emissions along the value chain (WHO, 2003). Recent LCAs of essential-oil production pinpoint steam distillation as the dominant CO₂ hotspot, prompting interest in solar-assisted distillers and waste-heat recovery (Becerra *et al.*, 2022). Circular bio-economy solutions, which convert spent herb biomass into biofertilizer or biochar, are gaining traction and can reduce net emissions and synthetic-fertilizer dependence (Marcelino *et al.*, 2023). Biodiversity concerns also remain pressing, as many source species are listed as threatened; therefore, on-farm refugia and sustainable wild-collection protocols are indispensable complements to ex-situ cultivation (Schippmann *et al.*, 2002; Alamgir, 2017). Soil-carbon-conserving practices such as reduced tillage and living mulches in aromatic alleys further shrink the production carbon footprint while preserving soil structure (Durán-Zuazo and Pleguezuelo, 2008). Embedding these low-impact strategies within digital monitoring and certification frameworks will be key to meeting both market expectations and planetary boundaries.

CONCLUSION

Recent advances in medicinal-plant science now span the entire value chain from genomics-enabled breeding and controlled-environment cultivation to green extraction and quality-by-design manufacturing. High-throughput propagation systems, precision farming, and sensor-driven climate control have significantly raised biomass and phytochemical yields while lowering water, nutrient, and energy footprints. Parallel progress in plant-cell culture, hairy-root bioreactors, and nano-biotechnology offers reliable, on-demand production of rare or highly valued compounds, easing pressure on wild populations. Equally important, life-cycle assessment, circular-bioeconomy strategies, and updated WHO-

GACP guidelines are embedding sustainability metrics and traceability into commercial practice, building consumer confidence in residue-safe, standardised herbal remedies. Continued integration of 'omics' platforms, artificial-intelligence decision tools, and eco-certification schemes will further align productivity with environmental stewardship. Realising the full potential of these innovations demands coordinated efforts: breeders and biotechnologists to deliver resilient, high-yielding chemotypes; growers to adopt precision, low-impact production systems; industry to invest in green processing technologies; and policymakers to create clear, science-based regulatory pathways. With sustained collaboration, medicinal-plant agriculture can supply consistent, high-quality botanicals supporting public health and rural livelihoods while conserving the biodiversity on which this ancient resource ultimately depends.

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