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Article

The Role of Phytofungi in Enhancing The Quality of Active Compounds of Medicinal Plants in Polluted Environments

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Abstract: Medicinal and aromatic plants represent an important source of bioactive compounds that have various applications in medicine, pharmacy, and nutrition. However, their production is increasingly challenged by the rising problems with environmental pollution, poor soil fertility, and abiotic stresses that impinge negatively on the growth of the plant and its capacity for producing secondary compounds with therapeutic value. In such a scenario, symbiotic mycorrhizal fungi, particularly shrubby mycorrhizal fungi (AMF), have emerged as a potentially sustainable natural alternative capable of improving medicinal plant growth along with biochemical productivity both under optimum and stressful conditions. These fungi establish a network of hyphae beyond the root zone, thereby improving efficiency in the uptake of water and nutrients, especially phosphorus, iron, zinc, and trace elements, within the plant's rhizosphere. Generally, plants associated with AMF have greater resistance to drought and salinity and heavy metals due to the enhanced nutrient and water balance, induction of defense mechanisms, antioxidants, and better soil structuring through metabolites such as glomalin, which improves cohesion and stability in the soil. The effects of AMF extend to influencing secondary compound production, such as flavonoids, terpenoids, phenols, and alkaloids, through direct or indirect means, including increased biomass, enhanced photosynthesis, modulation of plant hormones, and induction of enzymes involved in biosynthetic pathways like PAL and CHS. A wide array of works reported on species like Salvia miltiorrhiza, Hypericum perforatum, and licorice presented that AMF inoculation positively and significantly enhances the active content, especially when multiple fungal species rather than a single one are used

Keywords: Arbuscular Mycorrhizal Fungi (AMF), Medicinal and Aromatic Plants, Environmental Stress and Pollution, Secondary Metabolites, Sustainable Agriculture and Soil Rehabilitation

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1. Introduction

Medicinal and aromatic plants form a crucial natural reservoir of bioactive compounds that have traditionally been used for many centuries in medicine and are still of great importance today in the modern pharmaceutical, cosmetic, and nutrientdrug industries [1]. These plants synthesize numerous types of bioactive metabolites, including flavonoids, alkaloids, glycosides, essential oils, and other secondary metabolites that possess therapeutic properties, antioxidant, antimicrobial, and healthpromoting effects. This gives medicinal plants strategic value as renewable resources for healing, health maintenance, and also the development of natural products [2]. However, environmental changes and human influences increasingly pose serious challenges to the sustainable production of medicinal plants. Soil and water pollution with heavy metals, industrial pollutants, chemical fertilizers, and pesticides, degradation of soil fertility and structure, salinity, drought, among other abiotic stressors, may hinder plant growth, nutrient uptake, and physiological functions. Consequently, this might deteriorate the capabilities of medicinal plants for the synthesis of high-value bioactive compounds and hence negatively affect yield and medicinal value [3].

In this context, beneficial soil microorganisms, symbiotic fungi especially those that colonize the roots, have emerged as an effective, natural, and sustainable method for overcoming environmental stress and restoring the productivity of plants [4]. Of these, shrubby rhizosphere fungi, AMFs are those that form an extensive symbiotic relationship with the roots of a large number of vascular plants, including medicinal ones. Fungal hyphae extend into the soil beyond the root zone, enhancing the ability of a plant to access water and mineral nutrients, especially phosphorus and micronutrients, while the plant provides the fungi with nutrients for photosynthesis [5].

Importantly, there is already a growing body of scientific data to support the fact that the inoculation of medicinal plants with AMFs can support not just basic growth but also significantly enhance the biosynthesis and accumulation of active secondary metabolites. The symbiosis may enhance the productivity of these bioactive compounds, such as flavonoids, terpenoids, phenols, and other valuable pharmaceutical ingredients, not only through direct mechanisms like increased biomass and improved nutrient and water uptake but also through indirect metabolic influences such as the stimulation of biosynthetic pathways, modulating plant hormones, and enhancing photosynthetic capacity [**6**,7].

The present article, therefore, opens a new window toward sustainable cultivation strategies that ensure not only quantity-biomass production but also quality-concentration of active compounds of medicinal plants, even in suboptimal soils. Furthermore, such symbiotic approaches do not offer potential only for improved medicinal plant production but also for contributing to soil reclamation and environmental restoration efforts. A systematic, literature-based study of the potential of mycorrhizal fungi and similar root fungi to support medicinal plants against environmental stress is, therefore, both timely and necessary. The review has aimed to explore the available evidence, underlining the basic mechanisms and highlighting the prospects and limitations of applying these biological symbioses for improving quality and dependability in medicinal plant resources under challenging environments.

The most common and ecologically important fungal symbionts in the environment are rhizomatous fungi, usually referred to as mycorrhizae. In this association, the fungal hyphae grow from the roots of a plant into the surrounding soil, developing an extensive network that greatly increases the volume of soil the plant can draw upon for water and nutrients. The plant provides the fungi with carbohydrates and organic compounds, products of photosynthesis, thus making it a mutualistic association. [8]

According to [9], rhizomas are generally classified into the following main types based on how the fungal partner interacts with the plant roots:

- Shrubby Rhizomatous (AMF) - Endomycetes (Inner Mycorrhizae): AMF species largely belong to phylum Glomeromycotina. In the process of colonization, the fungal hyphae penetrate the cortical cells of the plant root. Internal to those cells, highly branched, specialized structures in the form of dendritic cells begin to form. These become the crucial sites for nutrient exchange between the fungus and the plant. . AMF also often forms storage structures called vesicles within root cells. AMF symbiosis is widespread: It is estimated that around 80% of terrestrial plant species form associations with AMF. Through the external fungal network, AMF fungi can access phosphorus, micronutrients, and water from soil regions beyond the root surface, thus improving nutrient uptake efficiency.
- Ectopic Root Fungi (ECM) - External Fungi: ECM fungi generally belong to phyla such as Basidiomycota and Ascomycetes. Instead of penetrating individual root cells, ECM fungi form a dense sheath (cap) around the root tips. From this sheath, fungal hyphae grow into the intercellular spaces of the root cortex, forming what is known as the Hartigieg network a network through which nutrient exchange occurs without penetrating individual cell membranes. ECM associations are a key characteristic of woody plants trees and shrubmore so than of herbaceous or conventionally cultivated crops., these fungi are particularly efficient at translocating nutrients, including nitrogen (especially from organic sources), to their host plants. This ability makes ECM fungi extremely important in forest ecosystems and nutrient-poor soils.
- Other specialized or less common types of mycorrhizal fungi: In addition to AMF and ECM, there are other types of associated mycorrhizal fungi such as ericoidy mycorrhizae common in acidic soils and erythritophilic plants , orchid mycorrhizae, and other specialized forms that may be important in specific ecological or taxonomic contexts. However, for many studies—especially those focusing on medicinal, herbaceous, or agricultural plants AMF remains the most relevant and widely used type of mycorrhizal fungi. Biological and Functional Features of Mycorrhizal Fungi

This association with mycorrhizal fungi provides numerous biological and physiological advantages to the host plant, especially when nutrient availability is limited, environmental conditions are stressful, or soil structure is not ideal for incorporating according to [10]:

1- Improved Water and Nutrient Uptake: The mycorrhizal filamentous network explores a much larger area of the soil than roots alone, enabling more efficient uptake of water and phosphorus, which are often limited in the soil due to its low mobility, as well as micronutrients and other essential minerals.

2- Improved Abiotic Stress Tolerance: Mycorrhizal fungi-colonized plants, especially AMF-colonized plants, usually show higher resistance to abiotic stresses such as drought, salinity, and heavy metal toxicity owing to the improvement in the water ratio, nutrient balance, and modulation of physiological stress responses on account of osmotic modification, antioxidant activity, and hormonal signaling.

3- Soil Structural Improvement: The mycorrhizal hyphae, especially those of AMF, contribute to soil compaction and its stabilization through the production of various substances, like glycoproteins. One well-known example is glomalin, which physically binds together the soil particles. This improves the porosity, aeration, and water-holding capacity of the soil for its better health. This will not only be beneficial for the host plant but also for the long-term fertility and resilience of the ecosystem.

4- Improved Resistance to Pathogens: Mycorrhizal symbiosis may protect the plants against soil-borne pathogens, including fungi, nematodes, and bacteria, through several mechanisms that include competition for infection sites, stimulation of plant defense systems, including systemic resistance, improvement of nutritional status, and modification of root structure.

5- Promoting Plant Growth and Biomass Productivity: Mycorrhizal symbiosis promotes nutrient and water uptake of plants, maintaining better stress tolerance. Consequently, an improved soil-root environment often has highly positive effects on the growth of plants and biomass production. Often, yields are increased, a very key factor in the case of medicinal plants and crops.

Due to the widespread occurrence and multiple positive roles on plants and soils, mycorrhizal symbiosis performs a critical role in the functioning and stability of terrestrial ecosystems. The exploitation of mycorrhizal symbiosis in agriculture, horticulture, forestry, and the restoration of ecosystems will have a contribution toward sustainable production, reducing reliance on chemical fertilizers, improving soil quality, and enhancing plant resilience to stressful conditions.

The main mechanisms by which these fungi, particularly root-associated fungi, enhance plant growth, physiological functions, and the production of secondary metabolites are described below, the main mechanisms supported by empirical studies demonstrating these effects, especially in plants that produce medicinal or bioactive compounds [11]. Mechanical pathways according to [12] include:

1. Expanded absorption network: When a plant's roots are colonized by AMF, the fungal hyphae extend deep into the surrounding soil to explore soil volumes beyond the capacity of the root system alone. This network allows for more efficient uptake of water and mineral nutrients, especially phosphorus (P), micronutrients, and sometimes nitrogen (N).
2. Improved Water and Nutrient Uptake – Stress Resilience: This enhanced uptake capacity becomes critical under environmental stresses such as drought, poor soil, and nutrient deficiencies. Plants colonized with AMF often have improved water relations, better nutrient status, and greater tolerance to abiotic stresses such as water scarcity, salinity, and heavy metals, which supports both growth and metabolism.
3. Increased Growth, Biomass Accumulation, and Photosynthetic Capacity: Improved nutrient and water supply enables plants to develop greater biomass both aboveground and in the roots. Increased leaf biomass is often associated with increased photosynthetic capacity, leading to increased production of photosynthetic products sugars and carbon structures that can serve as precursors for secondary metabolites.
4. Activation or Modulation of Secondary Metabolite Metabolic Pathways: In addition to nutritional effects, AMF symbiosis can also induce metabolic and physiological changes in plants, including alterations in hormone balance such as jasmonic acid, gibberellins, and cytokinins, and stimulation of signaling pathways for example, through nitric oxide, reactive oxygen species, and stress signals which increases the activity of biosynthetic enzymes such as PAL and CHS, and increases the density or size of secretory structures glandular capillaries . This may lead to increased biosynthesis of secondary compounds phenols, flavonoids, terpenoids, alkaloids, and others.

5. Synergistic Effects: Growth + Metabolic Stimulation → Higher Yield and Quality: The combination of improved growth increased biomass and metabolic stimulation means that the plant not only produces more raw materials, but these raw materials may also contain higher concentrations of active compounds, thus improving both quantity and quality.

Several recent studies support these mechanistic benefits of AMFs, applying them to medicinal plants or plants that produce beneficial secondary metabolites. A few illustrative examples are provided below according to [13] :

1- A recent study on Salvia miltiorrhiza found that inoculation with a variety of AMFs (rather than a single species) significantly enhanced root productivity and secondary metabolite accumulation compared to non-mycorrhizal control groups. The effect was stronger when using richer and more compatible AMF groups.

2- A comprehensive review summarizing numerous studies concluded that symbiotic relationships with AMFs can improve both biomass and bioactive compound content in a wide range of medicinal plants although the magnitude of this improvement depends heavily on the plant genotype, the AMF strain, growing conditions, and harvest time. For example, in St. John's wort *Hypericum perforatum* inoculated with AMF such as Rhizophagus or mixed AMF species, the concentrations of valuable anthraquinone compounds (such as hypericin and pseudhypericin) were significantly increased compared to non-mycorrhizal plants.

In licorice species medicinal roots, AMF genus Glomus colonization resulted in significantly higher levels of glycyrrhizic acid, leucorrhein, and flavonoids compared to plants grown without AMF even under stressful soil conditions such as salinity and nutrient deficiency [14]. AMF inoculation improved the survival, growth, and development of micro-propagated medicinal seedlings transplanted from the laboratory to the greenhouse and soil, enhancing establishment success a crucial step in intensive propagation of medicinal species.

2. Materials and Methods

Taken together, this evidence suggests that the use of AMF (alone or in combination) in the cultivation of medicinal and aromatic plants offers a promising and environmentally friendly strategy for according to [15] :

- Increasing total biomass (yield),
- Enhancing the concentration and accumulation of important active compounds secondary metabolites,
- Improving adaptability to harsh environmental conditions drought, poor soil, nutrient deficiencies, and salinity,
- Reducing the need for chemical fertilizers or intensive soil fertilization,
- Supporting sustainable agriculture/herbal medicine production even in less-than-ideal or degraded soils.

This supports the idea that incorporating AMF co-culture into cultivation protocols especially for medicinal plants is an effective way to produce high-quality, high-yielding herbal material crucial in areas suffering from soil degradation or environmental stress.

The symbiotic relationship between root-associated fungi especially rhizome fungi – AMF and medicinal plants not only promotes growth and nutrient/water uptake but also significantly influences the plant's secondary metabolism that is, the biochemical pathways responsible for the production of flavonoids, terpenoids, alkaloids, phenols, and other pharmacologically relevant compounds [16], this modification can lead to increased concentration, yield, or altered properties of bioactive compounds, thereby enhancing the medicinal and commercial value of the plants.

The effect of AMF on secondary metabolism appears to arise through both nutritional and non-nutritive (signaling/regulatory) mechanisms, and these mechanisms often interact to produce the final effect according to [17]:

- Nutritional/Growth Effects: Enhancing water and nutrient uptake, AMF increases overall plant vigor, leaf , root biomass, and photosynthetic capacity. This increases the availability of carbon structures, energy, and metabolic resources that can be converted to the biosynthesis of secondary metabolites rather than simply primary growth.
- Activation of Biosynthetic Pathways: AMF colonization can trigger cascades of signaling through changes in plant hormones, reactive oxygen species/nitrogen species, and defense signals that regulate key enzymes of secondary metabolism. For example, increased activity of phenylalanine ammonia lyase (PAL) and chalcon synthase (CHS) key enzymes of the phenylpropanoid/flavonoid pathways has been reported in AMF-colonized plants.
- Modulation of plant defense and stress responses: Since many secondary metabolites act as defenses against pathogens, abiotic stress drought, salinity, heavy metals, or oxidative stress, the presence of AMF may mimic mild "stress or signaling conditions" that stimulate increased production of these compounds.
- Morphological/structural changes that facilitate metabolite accumulation: AMF may induce changes such as increased density or size of secretory structures glandular hairs, or improved root/bud structure, which may provide greater "storage capacity" or potential for the biosynthesis of metabolites such as terpenoids or essential oils.

Due to these interrelated mechanisms, the effect of AMF fungi on secondary metabolites tends to be heterogeneous it varies with plant species/genotype, AMF strain, environmental conditions soil, light, nutrient status, cultivation method, and even harvest time.

Over the past decade, experimental research has accumulated consistent evidence that colonization with AMF fungi enhances the concentrations or yield of bioactive compounds in many medicinal or aromatic plants. Some typical results such as of *Salvia miltiorrhiza*, inoculation with a variety of AMF fungi multiple species significantly improved root biomass and the accumulation of medicinal secondary metabolites more effectively than inoculation with a single fungus. This suggests that the richness and compatibility of the AMF fungal community influence the yield and quality of medicinal compounds [18]. Research conducted on several species even non-traditional medicinal herbs such as *Solanum nigrum*, *Digitaria sanguinalis*, and Ipomoea purpurea has shown that AMF colonization leads to increased total concentrations of phenols, flavonoids, and terpenoids in the roots, seeds, or reproductive organs compared to non-mycotic root controls. This suggests that the effects of AMF on secondary metabolites are not limited to high-value medicinal species but may reflect general plant physiological responses [19].

The inoculation of medicinal and aromatic plants (MAPs) has been consistently associated with higher content of terpenoids, phenols, flavonoids, and sometimes alkaloids. The review confirmed that symbiotic relationships between AMF and MAPs are a promising and environmentally friendly approach to improving the quantity and quality of herbal raw materials. Also, under stress conditions drought, salinity, heavy metals, the presence of AMF helped to mitigate the negative effects on plant growth and even stimulated the production of stress-related secondary metabolites such as phenols and antioxidants, which may enhance the therapeutic or protective potential of medicinal plants [20].

Despite numerous positive reports, the enhancement of secondary metabolites induced by AMF is neither universal nor guaranteed. Several factors influence the results, including according to [21] :

- Plant species/genotype: Different plants respond differently; some may show large increases in certain compounds, while others show limited or no change.
- AMF strain or community composition: The type of AMF used or a combination thereof affects the magnitude and direction of metabolite changes. Mixed inoculants often outperform single-strain inoculants.
- Environmental and agricultural conditions: Soil fertility, water availability, light intensity, nutrient status, and stress factors all influence how the plant's interaction with AMF affects secondary metabolism.
- Temporal factors: The timing of colonization, plant growth stage, and harvest time can significantly alter metabolite characteristics.

Therefore, to reliably utilize AMF fungi in medicinal plant cultivation, the fungus, the growing environment, and harvesting protocols must be carefully designed.

3. Results

The use of AMF fungi especially diverse AMF fungal communities offers a sustainable and “green” biotechnology for improving the productivity and quality of medicinal plants, reducing reliance on chemical fertilizers or intensive agricultural inputs , this strategy is particularly valuable in marginal soils, degraded lands, or those under environmental stress drought, poor soil, salinity, where conventional agriculture struggles, for industries that rely on herbal raw materials pharmaceuticals, cosmetics, and nutrient-drugs, AMF-mediated cultivation can improve the consistency, potency, and potentially standardization of active compounds. However, implementation should be preceded by preliminary trials for each plant species to determine the best AMF strain/combination, optimal soil and growing conditions, and harvest time for maximizing metabolite yield [22].

With the increasing prevalence of soil pollution caused by heavy metals, industrial pollutants, and declining soil quality and fertility the need for sustainable farming strategies that combine plant production especially medicinal/aromatic plants with soil restoration is growing. Symbiosis with mycorrhizal fungi, particularly fungi, provides a promising framework for such dual-purpose approaches. AMF fungi can mitigate heavy metal toxicity by fixing the metals in the soil or fungal structures, thus reducing their uptake by the host plant. For example, in metal-contaminated sites, AMF fungi have increased the production of soil-binding glycoproteins such as glomalin, which stabilize the soil structure and bind heavy metals, reducing their bioavailability [23].

In many cases, the metals accumulate in fungal hyphae or root-associated fungal structures (such as vesicles and appendages) rather than in plant buds, preventing the translocation of toxic metals to the aerial parts used medicinally or consumed include :

- Improved plant growth and nutrient uptake under stress, even in contaminated or degraded soils, the mycelial network of fungal hyphae enhances water and nutrient uptake especially phosphorus and micronutrients, thus improving plant nutrition under stress.

- Improved nutrition and water status help plants maintain their growth, biomass accumulation, and physiological performance photosynthesis and root growth, despite environmental stress or soil toxicity.
- Improved soil structure, sestoration, and long-term health, Mycorrhizal fungi contribute to improved soil structure by producing glomalin and other soil-binding materials, enhancing soil compaction, porosity, and stability. This helps rehabilitate degraded or compacted soils, improving their fertility and suitability for long-term plant growth.

This soil improvement not only supports the host plant but also the broader soil microbial communities, promoting biodiversity and ecological resilience in contaminated soils. In contaminated soils, plants inoculated with AMF may be more effective in phytoremediation (plant extraction or fixation) because AMF can modify the bioavailability of metals, affect the types of metals, and reduce metal translocation to buds, while maintaining plant health.

Larger analyses confirm that AMF sometimes in combination with other soil organisms such as earthworms significantly improves the efficiency of phytoremediation in heavy metal-contaminated soils by fixing metals in the root zone or fungal tissues, improving plant growth, and reducing metal translocation to edible/medicinal parts [**24**].The effectiveness of AMF-based remediation depends on several factors: the type and concentration of contaminants heavy metals, organic toxins, soil properties (pH, texture, organic matter), the type or community of AMF used, and the host plant species. Under severe contamination, AMF alone may not be sufficient.

In some cases, high levels of heavy metals reduce the rate of AMF colonization, which may limit its beneficial effects, for medicinal or aromatic plants intended for human use, it is essential to monitor the accumulation of heavy metals in plant tissues roots and surface parts. If heavy metals accumulate significantly, the product may be unsafe despite its good growth or yield.

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In a greenhouse experiment on Lavandula angustifolia (lavender) grown in soil contaminated with lead (Pb) and nickel (Ni), inoculation with AMF Funneliformis mosseae mitigated the negative effects of heavy metal stress: plants exhibited better growth improved nutrient status, and increased essential oil production under low to moderate contamination compared to non-mycorrhizal controls. In a review focusing on cadmium (Cd)-contaminated soil, AMF inoculation demonstrated a reduction in cadmium uptake and toxicity, improved nutrient uptake especially phosphorus, enhanced antioxidant activity, and support for overall plant health under cadmium stress. Larger analyses confirm that AMF sometimes in combination with other soil organisms such as earthworms significantly improves the efficiency of phytoremediation in heavy metal-contaminated soils by fixing metals in the root zone or fungal tissues, improving plant growth, and reducing metal translocation to edible/medicinal parts. The effectiveness of AMF-based remediation depends on several factors: the type and concentration of contaminants (heavy metals, organic toxins), soil properties (pH, texture, organic matter), the type (or community) of AMF used, and the host plant species. Under severe contamination, AMF alone may not be sufficient. In some cases, high levels of heavy metals reduce the rate of AMF colonization, which may limit its beneficial effects, for medicinal or aromatic plants intended for human use, it is essential to monitor the accumulation of heavy metals in plant tissues roots and surface parts. If heavy metals accumulate significantly, the product may be unsafe despite its good growth or yield.

4. Conclusion

As reviewed in this study, the symbiosis between medicinal or aromatic plants and mycorrhizal fungi particularly mycorrhizal fungi derived from fungi (AMFs) offers a promising synergy with far-reaching benefits. Under favorable conditions (suitable fungal species, a compatible plant host, and reasonably managed soil), this partnership can enhance plant growth, improve nutrient and water uptake, stimulate secondary metabolism, and even contribute to soil reclamation when plants are grown in contaminated or degraded soil. At the same time, the effectiveness and reliability of mycorrhizal-assisted cultivation or reclamation strategies are not guaranteed: results vary considerably depending on numerous factors fungal strain, plant species, soil properties fertility, pollutant levels, and pH, and environmental conditions. Furthermore, colonization and beneficial effects may be reduced or fail entirely if soil contamination is severe or if other stressors override this symbiosis. Therefore, while mycorrhizal fungi (AMF)-based strategies hold great potential, they require careful and context-specific application. They should not be considered “universal cures,” but rather tools that, when used judiciously, can contribute to the sustainable cultivation of medicinal plants, improve the production of bioactive compounds, and partially restore soil health. Accordingly, the development of this approach depends on ongoing scientific work and clinical trials. Key areas for future research and application include identifying and utilizing the most compatible mycorrhizal plant soil formulations that is, screening different species or communities of mycorrhizal fungi (AMFs) with specific medicinal plant species under local soil/climatic conditions to find the best matches and conducting long-term, controlled field trials, particularly in contaminated or degraded soils, to assess not only plant productivity and compound content, but also soil quality, microbial community dynamics, and environmental safety heavy metal accumulation and ecological balance. Establishing standardized protocols for inoculation, cultivation, and harvesting to ensure reproducible and comparable results across studies and applications and implementing integrated and comprehensive land-use and soil management strategies that combine mycorrhizal fungal inoculation (AMF) with organic fertilization, micro-irrigation, crop rotation or intercropping, and reduced reliance on chemical fertilizers/pesticides, with the goal of achieving sustainable agriculture, environmental protection, and the production of high-quality medicinal plants, assessing the health and safety of medicinal plants grown in marginal/contaminated soils for human use, including heavy metal uptake analysis and secondary metabolite profiles to ensure safe and effective products. the partnership between medicinal plants and mycorrhizal fungi represents promising prospects at the intersection of pharmacology, agriculture, and environmental science. Through rigorous research and carefully designed applications, this could enable the production of high-quality medicinal plants even under challenging environmental conditions, while contributing to soil remediation and environmental sustainability.

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