



Mycorrhizal Association with Medicinal Plants. A review

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DOI : <https://doi.org/10.5281/zenodo.17615293>

ARTICLE DETAILS

Research Paper

Accepted: 22-10-2025

Published: 10-11-2025

Keywords:

*Mycorrhizal Association,
Medicinal Plants,
Arbuscular Mycorrhizae,
Nutrient Uptake and
secondary Metabolites*

ABSTRACT

Mycorrhizal associations play a crucial role in enhancing the growth, productivity, and medicinal quality of plants by improving nutrient uptake, stress tolerance, and secondary metabolite synthesis. Arbuscular mycorrhizal fungi (AMF) and other types, including ectomycorrhizae, orchid mycorrhizae, and ericoid mycorrhizae, create symbiotic associations with almost 90% of terrestrial plants, including some with medicinal value. By increasing the availability of phosphorus, nitrogen, zinc, and other micronutrients and strengthening tolerance to abiotic stresses including drought, salt, and heavy metal toxicity, these relationships have a significant impact on plant physiology. Arbuscular mycorrhizal fungi (AMF) are recognized for diminishing vulnerability to soilborne pathogens and promoting the synthesis of bioactive compounds such as alkaloids, flavonoids, terpenoids, curcuminoids and glycosides. Which influence the therapeutic efficacy of medicinal plants Evidence from recent studies highlights the role of AMF in enhancing pharmacologically important metabolites in species such as *Withania somnifera*, *Ocimum basilicum*, *Curcuma longa*, *Artemisia annua*, and *Aloe vera*. This review explain agronomic and pharmaceutical significance of mycorrhizal fungi contribute to soil fertility, sustainable cultivation practices, and the conservation of endangered medicinal species. It also underscores the ecological and biotechnological potential of mycorrhizal fungi in



medicinal plant systems and identifies the need for further research on species-specific interactions, ecological distribution, and the optimization of mycorrhizal inoculants for large-scale applications.

Introduction

Medicinal plants have long been used to treat a variety of ailments diseases, including diarrhea , fever, colds and malaria (Titan ji et al.2008).They are also used to develop new drugs to treat serious diseases like cancer (Newman and Cragg,2007).Their therapeutic value is frequently attributed to the presence and abundance of active compounds from secondary metabolism, such as alkaloids, flavonoids, terpenoids, and phenolics (Hussein and El-Anssary,2018). These days, more than 25% of prescribed medicines in developed countries come from wild plants, while up to 80% of people in developing countries only use herbal medicines for primary care (Ekor,2014). The mycorrhizal fungi live in the soil and work with plants to make connections with their roots. They are symbiotic microorganisms (Smith and Read, 2008). Many medicinal plants grow in places that don't have a lot of nutrients, so these links are essential for them. According to Kapoor et al (2002) mycorrhizae help plants grow, take in nutrients better, become more resistant to stress, and make more secondary metabolites. The healing properties of these plants come mostly from secondary metabolites. As they grow naturally and when they are under stress, like when they have to compete with other species in the same area, their concentration goes up. The microorganisms that live with plants and help them have mostly been thought to be good for them and not dangerous. When used in an environmentally friendly way, growth-stimulating rhizosphere microbes have been shown to improve the quality, bioactive substances, and growth parameters of medicinal plants. The plant is better able to handle environmental stresses and pathogens when it has symbiotic microbes. The end product of secondary metabolism is one of the most valuable chemicals nature makes. Many different biological effects and high economic value can be attributed to secondary metabolites that are made better by microorganisms. (Allah Ditta,Poozesh ,Vahid 2020). Some arbuscular mycorrhizal fungi (AMF) help host plants are making easier for absorb nutrients, protecting from pathogens, making more resistant to environmental stressors, and making soil more stable by clumping together soil particles and keeping more water in the soil through mycelial networks (Jiang et al., 2023). AMF helps protect plants from plant diseases and salt stress, keeps plants healthy and the soil fertile over time, and could be used as biofertilizers (Wahab et al., 2023). The occurrence of arbuscular mycorrhizal fungi (AMF) is influenced by climate, soil type, and various host plants (Jiang et al., 2021). Deepika et al.



(2021) investigated impact of plant host and soil variables on composition of arbuscular mycorrhizal fungi (AMF) communities in plant roots across two geographically isolated mangrove estuaries exhibited similar plant species compositions. The colonization and community composition of arbuscular mycorrhizal fungi (AMF) change a lot depending on soil. This is probably changes in plant physiology and environmental conditions. This highlights the dynamic interaction between soil characteristics, host identity, and temporal variations in the development of AMF communities (Bi et al., 2021; Cera et al., 2021; Zuo et al., 2023; Ghosh et al., 2024). Medicinal plants have a lot of active chemicals used to treat and cure a lot of different diseases. AMF associations in plants change secondary metabolites and active ingredients. which affects quality of herbal medicines (Ran et al., 2022). There are many biotic and abiotic factors affect AMF populations Such information should be regarded as an essential prerequisite for success of plant reestablishment and cultivation initiatives. AMF as a biofertilizer for medicinal plant species is important microbes are spread out and colonizes soil. The biodiversity of these microbes changes from ecosystem to ecosystem and is affected by soil's physical and chemical properties (Ahmad, Nusrat, et al., 2024).

Medicinal plants and mycorrhizal association

Different types of Mycorrhizal Relationships in Medicinal Plants. Mycorrhizae are relationships between fungi in the soil and plant roots that help both. They are very important for the health of plants, the cycling of nutrients, and the balance of the ecosystem. These kinds of relationships are found in almost 90% of land plants including many are used for medicine (Smith and Read, 2008). These connections are very important in medicinal plants They help plants nutrient up take deal with stress and make more bioactive secondary metabolites (Kapoor et al., 2002). Medicinal plants have four main types of mycorrhizal relationships. These are arbuscular mycorrhizae (AMF), ecto-mycorrhizae, orchid mycorrhizae and ericoid mycorrhizae.

1. Arbuscular mycorrhizae Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) are the most common type of mycorrhizal association in medicinal plants. They are formed by fungi belonging to phylum glomeromycotan. Which colonize cortical cells of roots. The plant root AMF form highly branched structures called arbuscules. It serves as sites of nutrient exchange vesicles and act as storage organs (Smith and Read, 2008). Medicinal plants grow in nutrient-



poor environments and AMF associations significantly enhance phosphorus, nitrogen, zinc, and copper uptake (Giri & Mukerji, 2004). AMF induce systemic resistance, salinity tolerance, improve drought, and enhance biosynthesis of secondary metabolites (Ruiz-Lozano, 2003). AMF inoculation with *Glomus mosseae* of *Withania somnifera* led to increased biomass and enhanced withanolide accumulation, compounds known for their adaptogenic and immunomodulatory properties (Kapoor et al., 2004). AMF association in *Curcuma longa* (Turmeric) boosted curcumin concentration, enhancing its medicinal quality (Pandey et al., 2010). The critical role of AMF in improving both yield and pharmacological value of medicinal plants. Their ubiquity and functional importance of AMF are being increasingly explored as biofertilizers in sustainable medicinal plant cultivation (Wahab et al., 2023).

2. Ectomycorrhizae

Ectomycorrhizal relationships are common in woody medicinal plants *Pinus*, *Quercus*, and *Eucalyptus* genera. Ectomycorrhizal fungi don't get into the root cells like AMF. They wrap around the root tips and make a Hartig net. which is a network of cells that lets the plant and fungus share nutrients (Smith and Read, 2008). In forest ecosystems many medicinal plants grow together, ectomycorrhizal fungi play a very important role. *Eucalyptus globulus* is used a lot in traditional medicine for its essential oils, benefits from ectomycorrhizal associations. It take in more nitrogen, phosphorus and handle drought (Chen et al., 2016). The ectomycorrhizal relationships between pine species like pycnogenol from *Pinus pinaster*. The bark is used in herbal medicine, soil more stable and improve tree health (Rinaldi et al., 2008).

3. Orchid mycorrhizae

Mycorrhizae in orchids are very specific type of symbiosis that is needed for orchids to germinate and grow quickly. Orchid seeds are very small and don't have enough nutrients stored to start sprouting on their own. They need to be colonized by fungi that get along with them, mostly from the *Rhizoctonia* complex. These fungi provide the carbon and nutrients that seedlings need to grow (Dearnaley, 2007). The orchid mycorrhizae help *Dendrobium nobile* seeds sprout and grow. This is an important part of traditional Chinese medicine. These relationships with fungi boost production of alkaloid and it is a key part of its medicinal value (Yukawa and Kagawa, 2020). The orchid mycorrhizae help *Vanilla planifolia* used in medicine and food flavors, grow and reproduce in its natural environments. This orchid



mycorrhizae play an important role in medicinal plants . They help these species survive in ecosystems and affect the production of useful secondary metabolites.

4. Ericoid mycorrhizae

Ericoid mycorrhizae are mostly found in plants in the Ericaceae family. This family includes *Vaccinium* (blueberry and cranberry) and *Erica*. which are both medicinally important species. These plants usually do well in acidic, nutrient-poor soils and nitrogen is mostly bound up in organic matter. Fungi called ericoid mostly from genera *Oidiodendron* and *Rhizoscyphus* and make coils inside root epidermal cells (Smith and Read, 2008). These fungi are very good at breaking down complex organic matter which gives nitrogen and phosphorus to host plants (Perotto et al., 2012). Ericoid mycorrhizae help medicinal plants like blueberries (*Vaccinium* spp.) take in more nutrients and make more flavonoids and anthocyanins .which are chemicals are known to fight inflammation and free radicals (Dalmastrri et al., 2020).

Benefits of mycorrhizal associations for medicinal plants

Mycorrhizal fungi shows mutualistic associations with roots of medicinal plants, providing critical ecological and physiological advantages. These symbiotic relationships help plants grow, produce more and become more resilient by making easier to get nutrients, making them more resistant to environmental stress, encouraging the production of secondary metabolites. These benefits are especially important for medicinal plants, healing properties depend a lot of bioactive compounds are made.

1.Improved nutrient uptake

The most important mycorrhizal associations helps plants take in nutrients better. Arbuscular mycorrhizal fungi (AMF) spread their hyphal networks rhizosphere. which makes root system's surface area for absorption bigger. The host plants get nutrients like phosphorus. It is very important for moving energy, growing roots and secondary metabolism (Smith and Read, 2008). AMF help plants take in more nitrogen, zinc and copper. which are all important for making proteins, enzymes, and antioxidants. Medicinal plants are often grown in soils a lot of nutrients. So it's important to improve nutrient



absorption to keep growing well and to make sure pharmacologically active metabolites. AMF-colonized *Withania somnifera* exhibited enhanced phosphorus absorption, leading to increased production of withanolides, a crucial bioactive compound (Kapoor et al., 2004).

2. Enhanced secondary metabolites

Alkaloids, flavonoids, terpenoids, phenolics, and essential oils are examples of secondary metabolites that make plants useful for medicine. Mycorrhizal fungi have been demonstrated to affect the biosynthesis of these metabolites by regulating nutrient availability, hormonal signaling and stress responses (Kapoor et al., 2002). Inoculating with AMF increased the amount of glycyrrhizin in *Glycyrrhiza glabra* (licorice), menthol in *Mentha arvensis* (mint), and curcumin in *Curcuma longa* (turmeric), making these plants more effective for treating illnesses (Hao et al., 2011; Pandey et al., 2010). The mechanism involves making phosphorus and nitrogen more available, which speeds up the phenylpropanoid pathway that makes flavonoids and phenolic compounds. So, mycorrhizal relationships are good for plant nutrition and are also directly related to the quality of medicinal crops for making medicines.

3. Stress tolerance

Medicinal plants frequently face abiotic stresses such as drought, salinity and heavy metal contamination especially cultivated in marginal soils. Mycorrhizal fungi provide stress tolerance by improving water uptake, controlling osmotic balance, and lowering oxidative damage (Ruiz-Lozano, 2003). AMF-colonized *Aloe vera* exhibited enhanced drought tolerance attributed to improved root hydration and water-use efficiency (Singh et al., 2013). AMF have been documented to mitigate salt-induced oxidative stress in *Sesbania grandiflora* and another medicinal plant by regulating antioxidant enzyme activities (Giri & Mukerji, 2004). AMF trap heavy metals in their fungal structures, which makes the host plant less toxic to metals. This adaptation is especially helpful for growing medicinal plants in soils that are polluted, as it protects both the plants and the harvested plant material.



4. Pathogen resistance

The improving nutrition and stress tolerance mycorrhizal associations make plants better able to fight off soilborne pathogens like *Fusarium*, *Rhizoctonia*, and *Phytophthora*. This protection comes from a number of different things such as competition for root colonization sites, making plants stronger and starting systemic resistance (Gianinazzi et al., 2010). AMF trigger the activation of defense -related pathways such as phenylpropanoid and jasmonic acid pathways. This leads to more phytoalexins, phenolics and lignin being made. These substances make cell walls stronger and stop pathogens from getting in. In *Ocimum basilicum* (basil), AMF inoculation diminished vulnerability to root pathogens while concurrently increasing essential oil content (Copetta et al., 2006). These two benefits show how important AMF is for both the environment and medicine in medicinal plants.

List of mycorrhizal associations in medicinal plants

Medicinal plant	Mycorrhizal fungi	Mycorrhizal fungi	Reference
<i>Withania somnifera</i> (Ashwagandha)	<i>Glomus mosseae</i>	Increased biomass, higher withanolide content	Kapoor et al., 2004
<i>Glycyrrhiza glabra</i> (Liquorice)	Arbuscular mycorrhizal fungi	Enhanced root growth and glycyrrhizin accumulation	Kapoor et al., 2002
<i>Artemisia annua</i> (Sweet wormwood)	Arbuscular mycorrhizal fungi	Increased artemisinin production	Hao et al., 2011
<i>Ocimum basilicum</i> (Basil)	Arbuscular mycorrhizal fungi	Higher essential oil yield	Copetta et al., 2006
<i>Aloe vera</i>	Arbuscular mycorrhizal fungi	Improved nutrient uptake and drought tolerance	Singh et al., 2013
<i>Mentha arvensis</i> (Mint)	Arbuscular mycorrhizal fungi	Higher menthol concentration	Sangwan et al., 2011
<i>Tinospora cordifolia</i> (Guduchi)	Arbuscular mycorrhizal fungi	Increased alkaloid content	Verma et al., 2008
<i>Curcuma longa</i> (Turmeric)	Arbuscular mycorrhizal fungi	Enhanced curcumin content	Pandey et al., 2010



Mechanism of mycorrhizal association with medicinal plants

Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), not only improve the growth and nutrient uptake of medicinal plants but also strongly influence the synthesis and accumulation of secondary metabolites and it is foundation of their therapeutic value. These compounds alkaloids, flavonoids, terpenoids, phenolics, glycosides and essential oils play crucial roles in plant defense, stress tolerance, and pharmaceutical applications. The influence of AMF on secondary metabolism is mediated through a combination of nutrient effects, defense pathway activation, hormonal regulation, and photosynthetic enhancement.

1. Nutrient-mediated effects

Nutrient availability is a primary determinant of secondary metabolite biosynthesis. AMF improve the uptake of essential elements particularly phosphorus (P) and nitrogen (N). Which are critical precursors for many metabolic pathways. Phosphorus is directly linked to ATP production, nucleic acid synthesis and membrane phospholipids. High phosphorus availability enhances shikimate and phenylpropanoid pathways leading to increased phenolics and flavonoids (Smith and Read, 2008). Nitrogen is a key component of amino acids, alkaloids and proteins. Improved nitrogen uptake under AMF symbiosis supports biosynthesis of nitrogen-containing metabolites such as alkaloids (Kapoor et al., 2002). AMF association with *Glycyrrhiza glabra* (licorice) significantly enhanced glycyrrhizin production due to better phosphorus nutrition. The *Curcuma longa* (turmeric), curcumin content increased with AMF colonization (Pandey et al., 2010). Thus, nutrient-mediated effects represent a fundamental mechanism by which mycorrhizae enhance medicinal quality.

2. Defense activation

The activation of plant defense pathways and AMF colonization induces mild stress like signals. which stimulate the plant's innate immune system and metabolic defense mechanisms. The most critical pathways is the phenylpropanoid pathway. which is responsible for synthesis of flavonoids, phenolics, tannins, and lignin (Gianinazzi et al., 2010). The accumulation of phenolic compounds strengthens cell walls against pathogens and also increases concentration of bioactive molecules with antioxidant and antimicrobial properties. AMF colonization elevated artemisinin levels a sesquiterpene lactone with



potent anti-malarial properties (Hao et al., 2011). *Ocimum basilicum* (basil) AMF increased levels of essential oils, phenolics, improving both medicinal quality and pathogen resistance (Copetta et al., 2006). This mechanism illustrates AMF act as elicitors, priming plants produce higher amounts of valuable secondary metabolites.

3. Harmonal regulation

Mycorrhizal associations influence plant hormonal balance and regulate secondary metabolism. The key hormones include auxins, jasmonic acid (JA), salicylic acid (SA), and abscisic acid (ABA). Auxins (indole-3-acetic acid, IAA) promote root development and biomass accumulation, indirectly enhancing metabolite production. Jasmonic acid (JA) is a well-known signaling molecule for secondary metabolism, especially for terpenoids, alkaloids, and flavonoids. AMF colonization up-regulates JA signaling and metabolite biosynthesis (Bucking and Kafle, 2015). Salicylic acid (SA) is activated in response to biotic stresses. AMF influence SA levels and enhance phenolic accumulation. The increased JA levels in AMF-colonized plants have been linked to higher production of menthol in *Mentha arvensis* (mint) and withanolides in *Withania somnifera* (ashwagandha). These findings highlight the role of hormonal regulation in linking AMF colonization for secondary metabolite enhancement.

4. Improved photosynthesis and carbon assimilation

Secondary metabolites are carbon-rich molecules; their synthesis depends heavily on photosynthetic efficiency and assimilate supply. AMF improve photosynthesis, enhancing chlorophyll content, stomatal conductance, and water-use efficiency (Ruiz-Lozano, 2003). Increased photosynthesis provides a larger pool of carbohydrates and metabolic pathways leading to terpenoids, flavonoids, and alkaloids. AMF colonization improved photosynthetic rates, carbohydrate accumulation, and supported higher levels of polysaccharides and anthraquinones (Singh et al., 2013).

Applications of mycorrhizal associations in medicinal plants

Mycorrhizal fungi, especially arbuscular mycorrhizal fungi (AMF), play a crucial role in the growth, health, and medicinal quality of plants. Their ability to enhance nutrient uptake, stress tolerance, and



secondary metabolite biosynthesis. It is valuable in natural ecosystems but also in modern agriculture, pharmaceutical production, and conservation biology. Sustainable cultivation and natural medicines grows applications and future potential of mycorrhizal associations in medicinal plants are being increasingly recognized.

1. Biofertilizer use in cultivation

The most practical application of AMF is their use as biofertilizers in medicinal plant cultivation. Chemical fertilizers effective in improving yield, reduce soil quality, harm beneficial microorganisms and pose environmental risks. AMF reduce dependency on chemical fertilizers by enhancing uptake of phosphorus, nitrogen, zinc, and copper by ensuring balanced plant nutrition (Smith & Read, 2008). Inoculation of AMF in *Withania somnifera* resulted in greater biomass, higher withanolide content and need for phosphate fertilizers (Kapoor et al., 2004). *Aloe vera* grown with AMF demonstrated improved drought tolerance and nutrient use efficiency (Singh et al., 2013). These findings highlight AMF can support sustainable and eco-friendly cultivation of medicinal plants, ensuring high yields without environmental degradation.

2. Pharmaceutical relevance

The pharmaceutical industry relies on high-quality production of bioactive compounds from medicinal plants. The inoculation with AMF has been shown to significantly enhance production of pharmacologically important secondary metabolites such as alkaloids, flavonoids, essential oils, terpenoids and phenolics. AMF association increased artemisinin content in *Artemisia annua* plant widely used for anti-malarial drugs (Hao et al., 2011). Similarly curcumin concentration in *Curcuma longa* was elevated in AMF-colonized plants (Pandey et al., 2010). AMF inoculants can be strategically employed to boost pharmaceutical yield and quality of medicinal plants making biotechnological tool for large-scale production of plant-based medicines.



3. Conservation biology

Many medicinal plants face threats of overharvesting, conservation, habitat destruction and climate change. Mycorrhizal fungi play a vital role in strategies restoration by aiding establishment and growth of endangered or slow-growing species in degraded habitats. AMF have been used to improve seedling establishment and survival of rare medicinal species during reintroduction efforts (Muthukumar et al., 2017). The enhancing of root colonization, improving nutrient availability, and increasing stress tolerance, AMF promote long-term sustainability of threatened medicinal plant populations. This ecological application underscores their importance in biodiversity conservation and ecological restoration programs.

4. Biotechnological potential

The biotechnology have opened new opportunities for integrating mycorrhizal fungi with plant tissue culture, genetic engineering, and metabolite enhancement strategies. The tissue culture systems AMF inoculation can improve plantlet survival rates during transplantation, enhance root development, stress resilience combining AMF with elicitors and metabolic engineering. The production of specific secondary metabolites. AMF-mediated modulation of the phenylpropanoid and terpenoid pathways can be harnessed to increase yields of valuable compounds like curcuminoids, withanolides, and glycosides (Ran et al., 2022).

Conclusion

Mycorrhizal associations with medicinal plants enhancing nutrient uptake, stress tolerance, pathogen resistance and production of pharmacologically active compounds. They are eco-friendly, sustainable approach to improving cultivation and conservation of medicinally important species. The four types of mycorrhizal associations arbuscular mycorrhizal fungi, ecto-mycorrhizae, orchid mycorrhizae and ericoid mycorrhizae play important roles in supporting medicinal plants. AMF are most widespread, boosting nutrient uptake and secondary metabolite production. Ecto-mycorrhizae support woody medicinal plants, particularly in forest ecosystems. Orchid mycorrhizae are essential for orchid seed germination and survival. The ericoid mycorrhizae enable ericaceae plants to thrive in nutrient-poor soils and enhance their bioactive compounds. It focuses on species-specific interactions, ecological dynamics



and biotechnological applications of mycorrhizal fungi to maximize their potential in herbal medicine production. The benefits of mycorrhizal associations for medicinal plants are multifaceted. The improving nutrient uptake, enhancing secondary metabolite synthesis, conferring tolerance to abiotic stresses and providing protection against pathogens, mycorrhizal fungi contribute to both ecological resilience and pharmacological quality of medicinal plants. These advantages make mycorrhizal associations a cornerstone of sustainable cultivation strategies, reducing dependence on chemical fertilizers and pesticides ensuring high yields of bioactive compounds. The applications of mycorrhizal associations in medicinal plants extend sustainable agriculture to pharmaceutical production, conservation and biotechnology. Such strategies will ensure not only sustainable cultivation of medicinal plants but also the consistent supply of high-quality herbal medicines for growing global demand.

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