



REVIEW ARTICLE

Medicinal Plant-Arbuscular Mycorrhizal Networks in the Semi-Arid Landscapes of Marathwada: Challenges, Opportunities and Future Research

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ABSTRACT

The semi-arid region of Marathwada, Maharashtra, represents a biologically important yet environmentally fragile ecosystem characterized by low rainfall, recurrent droughts, degraded soils, and increasing anthropogenic disturbances. Despite these constraints, the region harbors a rich diversity of medicinal plant species that support traditional healthcare systems, local livelihoods, and biodiversity conservation. However, habitat degradation, unsustainable harvesting, land-use changes, and climate variability continue to threaten these valuable plant resources. Arbuscular mycorrhizal fungi (AMF) establish mutualistic associations with the roots of nearly 80% of terrestrial plant species, significantly improving nutrient acquisition, water-use efficiency, stress tolerance, and resistance to soil-borne pathogens. In medicinal plants, AMF not only enhance plant growth and biomass production but also influence the synthesis of pharmaceutically important secondary metabolites, thereby improving medicinal quality. This review synthesizes current knowledge on the diversity of medicinal plants and AMF in the semi-arid landscapes of Marathwada. It discusses ecological interactions between medicinal plants and AMF, their role in soil health, climate resilience, conservation, and sustainable cultivation, and identifies existing research gaps. Finally, the review highlights future research priorities aimed at integrating AMF-based technologies into biodiversity conservation, medicinal plant cultivation, and ecosystem restoration programs in the region.

Keywords: Arbuscular mycorrhizal fungi; Medicinal plants; Marathwada; Semi-arid ecosystem; Biodiversity; Sustainable agriculture; Climate resilience

INTRODUCTION

Medicinal plants have been an integral component of human healthcare since ancient civilizations and continue to serve as a primary source of therapeutic agents worldwide. These plants synthesize diverse bioactive phytochemicals, including alkaloids, flavonoids, phenolics, terpenoids, tannins, glycosides, saponins, and essential oils, which exhibit antioxidant, antimicrobial, anti-inflammatory, antidiabetic, anticancer, hepatoprotective, immunomodulatory, and neuroprotective properties (Mishra *et al.*, 2024; Otia *et al.*, 2024; Sarwade *et al.*, 2025). The growing interest in plant-derived pharmaceuticals, nutraceuticals, and herbal formulations has renewed global attention toward medicinal plant conservation and sustainable utilization (Sarwade *et al.*, 2024a; Sarwade *et al.*, 2024b).

Recent advances in plant ecology have demonstrated that the medicinal value of plants is not solely determined by genetic factors but is also strongly influenced by belowground interactions with beneficial microorganisms. These fungi establish one of the oldest mutualistic associations in terrestrial ecosystems, significantly enhancing nutrient uptake, water acquisition, stress tolerance, soil aggregation, and secondary metabolite biosynthesis (Bhale *et al.*, 2011; Sarwade *et al.*, 2012a; Sarwade *et al.*, 2024c). Consequently, AMF are increasingly recognized as essential components of sustainable medicinal plant production and ecosystem restoration.

Importance of Medicinal Plants

Medicinal plants constitute one of the most valuable biological resources on Earth, with approximately 50,000–70,000 plant species reported to possess medicinal properties. According to the World Health Organization (WHO), nearly 80% of the population in developing countries depends primarily on traditional herbal medicine for primary healthcare, while the global herbal medicine market continues to expand because of increasing demand for natural therapeutics (WHO, 2019).

India is recognized as one of the world's twelve megadiversity countries and harbors nearly 7,000–8,000 medicinal plant species used in Ayurveda, Siddha, Unani, Homeopathy, and numerous indigenous healthcare systems. Classical Ayurvedic texts describe hundreds of plant species whose pharmacological activities are increasingly supported by modern phytochemical and biomedical investigations.

Recent studies have demonstrated remarkable therapeutic potential in numerous medicinal plants such as *Moringa oleifera*, *Curcuma longa*, *Ocimum sanctum*, *Allium sativum*, *Hibiscus rosa-sinensis*, and *Cascabela thevetia*, owing to their rich phytochemical composition and broad-spectrum biological

activities (Mishra *et al.*, 2024; Otia *et al.*, 2024; Sarwade *et al.*, 2024b; Sarwade *et al.*, 2025). Likewise, phytochemical investigations of wild medicinal plants from the Himalayan region have revealed high antioxidant potential associated with phenolics and flavonoids (Sarwade *et al.*, 2024c).

The medicinal plant sector contributes significantly to India's economy through cultivation, processing, pharmaceutical manufacturing, cosmetics, nutraceuticals, and export of herbal products. However, excessive exploitation of natural populations, habitat degradation, invasive species, land-use changes, and climate change have accelerated the decline of many economically important medicinal species, necessitating sustainable cultivation supported by beneficial soil microorganisms.

Importance of Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (AMF) belonging to the phylum Glomeromycota are among the oldest terrestrial symbionts, having evolved nearly 400–450 million years ago. They colonize approximately 80–90% of terrestrial plant species and establish highly efficient mutualistic associations with plant roots (Smith & Read, 2008).

The AMF colonization process begins with the germination of fungal spores in the rhizosphere. Root-derived signaling molecules stimulate hyphal growth toward the host roots, followed by penetration into cortical tissues where specialized structures known as arbuscules are formed. These arbuscules function as nutrient exchange interfaces, while vesicles serve as storage organs. Beyond the root system, AMF develop extensive extraradical hyphal networks that greatly increase the absorptive surface area available for nutrient and water uptake.

Numerous investigations conducted in Marathwada have reported AMF associations with medicinal plants, angiosperms, pteridophytes, weeds, and economically important crops (Sarwade *et al.*, 2010; Bhale *et al.*, 2011; Sarwade *et al.*, 2011a; Sarwade *et al.*, 2012a; Sarwade *et al.*, 2012b). Studies on *Cassia tora*, *Xanthium strumarium*, and various medicinal plants have consistently demonstrated significant AMF colonization under natural field conditions (Sawant *et al.*, 2011; Sarwade *et al.*, 2012c).

Beyond nutrient acquisition, AMF enhance phosphorus uptake, improve drought tolerance, regulate phytohormones, strengthen plant immunity, increase soil aggregation through glomalin production, and stimulate secondary metabolite biosynthesis, thereby improving both plant productivity and medicinal quality (Sarwade *et al.*, 2024d; Sarwade *et al.*, 2024e).

Why Marathwada?

Marathwada, located in the central part of Maharashtra, comprises eight districts and is characterized by a semi-arid

tropical climate with low and erratic rainfall, recurrent droughts, high evapotranspiration, and nutrient-poor soils. These environmental constraints create a unique ecological setting where beneficial soil microorganisms play a critical role in sustaining plant diversity and ecosystem functioning. Despite harsh climatic conditions, Marathwada supports rich medicinal plant diversity distributed across forests, scrublands, grasslands, agricultural fields, and protected areas such as the Yedshi–Ramling Wildlife Sanctuary. Earlier investigations from the region have documented AMF associations in medicinal plants, angiosperms, pteridophytes, Euphorbiaceae, weeds, and agricultural crops, indicating remarkable fungal diversity adapted to semi-arid ecosystems (Sarwade *et al.*, 2010; Sarwade *et al.*, 2012a; Sarwade *et al.*, 2013; Gaikwad *et al.*, 2016; Sarwade *et al.*, 2021).

However, habitat fragmentation, intensive agriculture, overgrazing, mining, urbanization, and climate change continue to threaten both medicinal plant diversity and indigenous AMF communities. Although several localized studies have been conducted in Marathwada, a comprehensive synthesis integrating medicinal plant diversity with AMF ecological networks remains unavailable.

SCOPE OF THE REVIEW

This review integrates multidisciplinary information on medicinal plant diversity, arbuscular mycorrhizal biology, rhizosphere ecology, biodiversity conservation, and sustainable utilization within the semi-arid landscapes of Marathwada. It critically evaluates current knowledge regarding plant–AMF interactions, ecological functions, phytochemical enhancement, environmental stress tolerance, and conservation strategies while identifying major research gaps in the region.

Furthermore, the review highlights future research priorities involving molecular identification of indigenous AMF, microbiome analysis, ecological network modeling, GIS-based biodiversity mapping, climate resilience studies, and development of region-specific mycorrhizal biofertilizers. By integrating regional studies from Marathwada with global advances in mycorrhizal ecology, this review provides a scientific framework for conserving medicinal plant diversity and promoting sustainable medicinal plant production under changing environmental conditions.

Semi-Arid Landscapes of Marathwada

The Marathwada region of Maharashtra comprises eight districts—Chhatrapati Sambhajanagar (Aurangabad), Jalna, Beed, Dharashiv (Osmanabad), Latur, Nanded, Parbhani, and Hingoli. The region experiences a tropical semi-arid climate characterized by annual rainfall ranging

from approximately 500 to 800 mm, with considerable temporal and spatial variability (IMD, 2023). Frequent droughts and prolonged dry periods have significant ecological and socioeconomic consequences.

The predominant soils include Vertisols (black cotton soils), red loamy soils, and calcareous soils, many of which exhibit low organic carbon, phosphorus deficiency, poor microbial biomass, and declining fertility because of continuous cultivation and unsustainable land-use practices (FAO, 2022). These edaphic conditions considerably influence vegetation distribution and soil microbial diversity.

Natural vegetation consists mainly of tropical dry deciduous forests, thorn forests, scrublands, grasslands, and agroforestry systems. Dominant medicinal and tree species include *Azadirachta indica*, *Butea monosperma*, *Acacia nilotica*, *Aegle marmelos*, *Albizia lebbek*, *Terminalia* spp., and numerous drought-adapted herbs and shrubs (Champion & Seth, 1968).

Protected ecosystems such as the Yedshi–Ramling Wildlife Sanctuary serve as important biodiversity reservoirs, conserving medicinal plant diversity and native AMF communities. These fungal communities contribute significantly to nutrient cycling, soil aggregation, drought tolerance, carbon sequestration, and ecosystem resilience (Smith & Read, 2008; Begum *et al.*, 2019). However, increasing anthropogenic disturbances including deforestation, mining, agricultural intensification, groundwater depletion, invasive species, and climate change are accelerating biodiversity loss across Marathwada (IPCC, 2023). Sustainable conservation strategies integrating medicinal plant conservation with AMF-based ecological restoration are therefore urgently required.

DIVERSITY OF MEDICINAL PLANTS IN MARATHWADA

Regional Ecology

Marathwada, located in the rain-shadow region of Maharashtra, represents an ecologically unique semi-arid landscape characterized by prolonged droughts, erratic rainfall, high temperatures, and nutrient-deficient soils. Despite these harsh environmental conditions, the region harbors a rich diversity of medicinal plant species that have adapted to water-limited ecosystems through various physiological and biochemical mechanisms (Singh *et al.*, 2021; WHO, 2023). Medicinal plants have been used for centuries in traditional healthcare systems, including Ayurveda, Siddha, Unani, and folk medicine. These species contribute significantly to primary healthcare, pharmaceutical industries, nutraceutical production, and rural livelihoods. According to the World Health

Organization (2023), nearly 80% of the global population relies partly on plant-based traditional medicines for primary healthcare.

However, medicinal plant diversity in Marathwada is increasingly threatened by habitat fragmentation, overexploitation, agricultural expansion, invasive species, groundwater depletion, and climate change, emphasizing the urgent need for sustainable conservation strategies (MEA, 2005; IPCC, 2023).

Diversity and Distribution

The medicinal flora of Marathwada comprises numerous angiosperm families including Fabaceae, Lamiaceae, Rutaceae, Euphorbiaceae, Solanaceae, Apocynaceae, Combretaceae, Malvaceae, Asparagaceae, Menispermaceae, and Asteraceae (NMPB, 2022). Common medicinal plant species include *Withania somnifera*, *Tinospora cordifolia*, *Ocimum tenuiflorum*, *Azadirachta indica*, *Aegle marmelos*, *Terminalia arjuna*, *Phyllanthus emblica*, *Asparagus racemosus*, *Butea monosperma*, and *Aloe vera*. These species produce diverse phytochemicals such as alkaloids, flavonoids, terpenoids, tannins, phenolics, glycosides, saponins, and essential oils responsible for their therapeutic properties (WHO, 2023).

Ecological Importance

Medicinal plants contribute substantially to ecosystem functioning by maintaining biodiversity, improving soil stability, supporting pollinator communities, enhancing carbon sequestration, and providing habitats for beneficial microorganisms. Many medicinal plants also establish symbiotic relationships with arbuscular mycorrhizal fungi (AMF), which improve nutrient uptake, drought tolerance, and plant productivity (Smith & Read, 2008; Begum *et al.*, 2019).

Threats to Medicinal Plant Diversity

The medicinal plant diversity of the Marathwada region is increasingly threatened by a combination of natural and anthropogenic factors that adversely affect ecosystem stability and biological resources. Rapid habitat destruction resulting from agricultural expansion, infrastructure development, urbanization, and industrial activities has led to significant fragmentation and loss of natural vegetation. Deforestation and indiscriminate extraction of medicinal plants from wild habitats further reduce population size and genetic diversity, threatening the long-term survival of several economically and therapeutically important species. Unsustainable harvesting practices, particularly the removal of roots, bark, and whole plants before seed production, disrupt natural regeneration and increase the risk of local extinction. In addition, intensive agricultural practices involving excessive use of chemical fertilizers, pesticides, and

monocropping systems degrade soil quality, diminish beneficial microbial populations, and alter ecological interactions essential for plant growth (FAO, 2022; Begum *et al.*, 2019).

Environmental degradation is further intensified by mining activities, groundwater overexploitation, soil erosion, salinization, and declining soil organic matter, all of which reduce habitat suitability for medicinal plants and their associated arbuscular mycorrhizal fungi (AMF). The invasion of alien plant species competes with native medicinal flora for nutrients, water, and space, resulting in shifts in plant community composition and ecosystem functioning. Moreover, climate change has emerged as one of the most serious threats to semi-arid ecosystems by increasing the frequency of droughts, heat waves, irregular rainfall patterns, and extreme weather events, thereby affecting plant distribution, reproductive success, and phytochemical composition. These environmental changes also influence the diversity, abundance, and functioning of beneficial soil microorganisms, particularly AMF, which play a critical role in nutrient cycling, soil aggregation, drought tolerance, and sustainable medicinal plant production. Therefore, integrated conservation strategies combining habitat protection, sustainable harvesting, restoration of native vegetation, and conservation of belowground microbial diversity are essential to safeguard the medicinal plant wealth of Marathwada under changing climatic conditions (IPCC, 2023; Brundrett & Tedersoo, 2018; Rillig *et al.*, 2015; Tedersoo *et al.*, 2020; WHO, 2023).

BIOLOGY AND DIVERSITY OF ARBUSCULAR MYCORRHIZAL FUNGI (AMF)

Biology of AMF

Arbuscular mycorrhizal fungi (AMF) are obligate symbiotic fungi belonging to the phylum Glomeromycota. Fossil evidence indicates that AMF evolved more than 450 million years ago and played a crucial role in the colonization of terrestrial ecosystems by early land plants (Smith & Read, 2008; Brundrett & Tedersoo, 2018).

Approximately 80% of terrestrial vascular plants establish mutualistic associations with AMF, making them one of the most widespread plant-microbe symbioses in nature (Genre *et al.*, 2020). During colonization, fungal hyphae penetrate root cortical tissues where they develop arbuscules, vesicles, and intraradical hyphae that facilitate nutrient exchange between plant and fungus.

Taxonomic Diversity

Recent advances in molecular phylogenetics have significantly improved the classification of arbuscular mycorrhizal fungi (AMF), placing them within the phylum Glomeromycota, which comprises several families, including Glomeraceae, Acaulosporaceae, Gigasporaceae,

Diversisporaceae, Claroideoglomeraceae, Archaeosporaceae, Paraglomeraceae, and Ambisporaceae (Redecker *et al.*, 2013). Among these, the Glomeraceae is the most dominant and widely distributed family in agricultural and natural ecosystems because of its broad host range, rapid root colonization, and high ecological adaptability. Commonly reported genera such as *Rhizophagus*, *Glomus*, *Funneliformis*, *Claroideoglomus*, *Acaulospora*, *Gigaspora*, *Diversispora*, and *Scutellospora* play important roles in nutrient acquisition, soil aggregation, and plant stress tolerance, thereby contributing significantly to ecosystem functioning and sustainable crop production (Brundrett & Tedersoo, 2018; Tedersoo *et al.*, 2020; Genre *et al.*, 2020).

Life Cycle

The life cycle of arbuscular mycorrhizal fungi (AMF) begins with the germination of soil-borne spores under favorable environmental conditions. Root-derived signaling molecules, particularly strigolactones, stimulate hyphal branching and direct fungal growth toward host roots. Following host recognition, the fungal hyphae penetrate the root epidermis and colonize the cortical tissues, where highly branched arbuscules develop as the primary sites for nutrient exchange, while vesicles function mainly as storage organs. Simultaneously, extensive extraradical hyphae spread into the surrounding soil, enhancing the uptake of water and mineral nutrients before producing new spores that complete the life cycle (Figure 1). Unlike saprophytic fungi, AMF are obligate biotrophs and depend entirely on living host roots to complete their development and reproduction (Smith & Read, 2008).

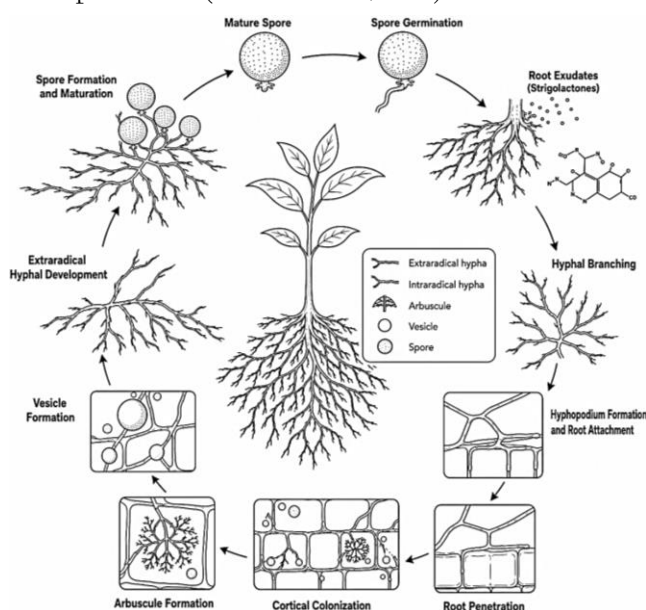


Figure 1 : Life cycle of Arbuscular Mycorrhizal Fungi (AMF)

Root Colonization

Root colonization by arbuscular mycorrhizal fungi (AMF) is a highly regulated process involving complex molecular

signaling between fungal propagules and host plant roots. After successful recognition and penetration, the fungus establishes an extensive symbiotic interface within the root cortex, forming arbuscules, which serve as the principal sites of bidirectional nutrient exchange, and vesicles, which function as storage structures for lipids and other reserves.

In addition, intraradical and extraradical hyphal networks develop to facilitate the efficient uptake and transport of phosphorus, nitrogen, micronutrients, and water from the surrounding soil to the host plant. These hyphal networks also contribute to improved soil aggregation and stability through the production of glomalin-related soil proteins (GRSP), thereby enhancing soil fertility, carbon sequestration, and overall ecosystem resilience (Rillig *et al.*, 2015; Smith & Read, 2008; Genre *et al.*, 2020; Choi *et al.*, 2022).

Functional Diversity

Arbuscular mycorrhizal fungi (AMF) exhibit remarkable functional diversity and play a pivotal role in maintaining plant productivity, soil health, and ecosystem stability. Through their extensive hyphal networks, AMF enhance the uptake of essential nutrients, particularly phosphorus, nitrogen, zinc, and copper, while improving water-use efficiency and increasing plant tolerance to drought, salinity, and heavy metal stress. They also promote soil aggregation through the production of glomalin-related soil proteins (GRSP), contribute to carbon sequestration, suppress soil-borne pathogens, and support biodiversity by strengthening belowground ecological interactions.

In medicinal plants, AMF further enhance the biosynthesis and accumulation of valuable secondary metabolites, including alkaloids, flavonoids, terpenoids, phenolic compounds, essential oils, and saponins, by improving mineral nutrition, regulating phytohormone balance, and modulating key metabolic pathways. These multifunctional benefits highlight the ecological and biotechnological importance of AMF in sustainable agriculture, conservation, and medicinal plant cultivation (Kapoor *et al.*, 2007; Smith & Smith, 2011; Chandrasekaran, 2022; Zhao *et al.*, 2022; Begum *et al.*, 2019).

MEDICINAL PLANT-ARBUSCULAR MYCORRHIZAL FUNGAL (AMF) INTERACTIONS

Symbiotic Relationship

Arbuscular mycorrhizal fungi (AMF) establish one of the most widespread and evolutionarily conserved mutualistic associations with terrestrial plants. During colonization, fungal hyphae penetrate the root cortex and form specialized structures known as arbuscules, which serve as the principal sites for nutrient exchange between the fungus and host plant. In return for mineral nutrients and water supplied by the fungus, the host plant allocates

photosynthetically derived carbohydrates and lipids to the fungal partner (Smith & Read, 2008; Luginbuehl *et al.*, 2017).

The establishment of AMF symbiosis begins with molecular signaling between plant roots and fungal spores. Root-secreted strigolactones stimulate fungal spore germination and hyphal branching, whereas AMF release Myc factors that activate the common symbiosis signaling pathway (CSSP), leading to successful root colonization (Genre *et al.*, 2020; Choi *et al.*, 2022).

In medicinal plants, this symbiotic association enhances plant vigor, nutrient uptake, stress tolerance, and biosynthesis of bioactive compounds. Species such as *Withania somnifera*, *Ocimum tenuiflorum*, *Tinospora cordifolia*, *Aloe vera*, *Asparagus racemosus*, and *Phyllanthus emblica* have shown significant improvements in growth and medicinal quality following AMF inoculation (Kapoor *et al.*, 2007; Chandrasekaran, 2022).

Mechanisms of Nutrient Uptake

Arbuscular mycorrhizal fungi (AMF) substantially enhance plant nutrient acquisition by extending the effective root surface area through an extensive extraradical hyphal network. These fine hyphae explore soil micropores beyond the root depletion zone, facilitating the uptake of relatively immobile nutrients, particularly phosphorus, as well as nitrogen, potassium, zinc, copper, iron, magnesium, and calcium. In addition to improving phosphorus acquisition, AMF enhance nitrogen uptake in both ammonium and nitrate forms through synergistic interactions with rhizosphere microorganisms, thereby increasing nutrient-use efficiency, plant growth, and overall productivity (Smith & Read, 2008; Smith & Smith, 2011; Hodge & Storer, 2015; Genre *et al.*, 2020).

Improvement of Water Relations and Drought Tolerance

Water deficit is a major constraint to medicinal plant cultivation in semi-arid regions such as Marathwada, where AMF play a crucial role in improving plant drought resilience. AMF enhance water uptake through extensive hyphal networks, increase root hydraulic conductivity, improve osmotic adjustment, regulate stomatal conductance, and promote the accumulation of osmoprotectants and antioxidant enzymes. Consequently, mycorrhizal plants exhibit higher relative water content, greater photosynthetic efficiency, enhanced chlorophyll stability, reduced oxidative stress, and improved biomass production under drought conditions compared with non-mycorrhizal plants (Augé, 2001; Begum *et al.*, 2019; Chandrasekaran, 2022).

Influence on Secondary Metabolite Production

Arbuscular mycorrhizal fungi (AMF) significantly stimulate the biosynthesis of pharmacologically important

secondary metabolites in medicinal plants by improving mineral nutrition, enhancing photosynthetic performance, regulating phytohormone signaling, activating defense responses, and modulating genes involved in secondary metabolism. Consequently, AMF increase the accumulation of alkaloids, flavonoids, phenolic compounds, terpenoids, glycosides, essential oils, tannins, and saponins, thereby improving both the medicinal quality and commercial value of plant products. Enhanced production of bioactive compounds has been reported in several medicinal species, including *Withania somnifera* (withanolides), *Ocimum tenuiflorum* (essential oils), *Artemisia annua* (artemisinin), *Aloe vera* (polysaccharides), and *Catharanthus roseus* (vincristine and vinblastine), highlighting the potential of AMF as sustainable biofertilizers for improving crop productivity and phytochemical yield (Kapoor *et al.*, 2007; Zhao *et al.*, 2022; Luginbuehl *et al.*, 2017).

ROLE OF AMF IN SOIL HEALTH

Soil Aggregation

Arbuscular mycorrhizal fungi (AMF) play a vital role in maintaining soil structure and fertility by promoting the formation of stable soil aggregates. Their extensive hyphal networks physically bind soil particles, while the secretion of glomalin-related soil proteins (GRSP) acts as a natural adhesive that enhances aggregate stability. Improved soil aggregation increases water infiltration, aeration, root penetration, and resistance to erosion, while also facilitating long-term carbon storage and improving overall soil quality. These functions make AMF indispensable for sustaining productive and resilient agroecosystems, particularly in semi-arid regions (Rillig *et al.*, 2015; Smith & Read, 2008).

Nutrient Cycling

AMF are integral components of the soil microbial community and contribute significantly to nutrient cycling through synergistic interactions with bacteria, actinomycetes, and other beneficial microorganisms. These interactions enhance the decomposition of organic matter, phosphorus mineralization, nitrogen transformation, and soil enzyme activities, thereby improving nutrient availability, microbial diversity, and overall soil fertility. By maintaining efficient nutrient cycling, AMF support sustainable ecosystem productivity and reduce dependence on chemical fertilizers (Hodge & Storer, 2015; van der Heijden *et al.*, 2015; Begum *et al.*, 2019).

Carbon Sequestration

Arbuscular mycorrhizal fungi contribute substantially to belowground carbon sequestration by transferring plant-derived carbon into fungal biomass, hyphal networks, and glomalin-related soil proteins, which stabilize soil organic

carbon over extended periods. This process enhances soil carbon storage, improves ecosystem resilience, and supports climate change mitigation by reducing atmospheric carbon dioxide levels. Consequently, AMF are increasingly recognized as key biological drivers of sustainable soil management and long-term carbon cycling in terrestrial ecosystems (Treseder & Allen, 2000; Rillig *et al.*, 2015).

AMF and Climate Change Adaptation

Climate change has intensified the frequency of droughts, heat waves, erratic rainfall, and soil degradation, posing significant challenges to medicinal plant cultivation in semi-arid regions such as Marathwada. Arbuscular mycorrhizal fungi (AMF) play a crucial role in enhancing plant resilience by improving water and nutrient uptake, increasing water-use efficiency, strengthening antioxidant defense systems, and reducing oxidative damage caused by environmental stresses. AMF also enhance tolerance to heat, drought, and salinity by regulating physiological and biochemical processes, maintaining photosynthetic activity, and improving soil structure through extensive hyphal networks and glomalin production. These multifunctional benefits not only improve plant survival and productivity under adverse climatic conditions but also enhance ecosystem stability and sustainable agricultural practices. Consequently, AMF are increasingly recognized as effective **nature-based solutions** for climate-resilient agriculture and ecosystem restoration in the face of global climate change (IPCC, 2023; Begum *et al.*, 2019; Augé, 2001; FAO, 2022).

ARBUSCULAR MYCORRHIZAL FUNGI IN SUSTAINABLE AGRICULTURE AND MEDICINAL PLANT CULTIVATION

Sustainable Production of Medicinal Plants

Sustainable cultivation of medicinal plants has become a global priority because increasing industrial demand, indiscriminate harvesting, and environmental degradation have significantly reduced natural populations. Conventional agricultural practices relying heavily on synthetic fertilizers and pesticides adversely affect soil fertility, microbial diversity, and medicinal plant quality. Consequently, environmentally friendly cultivation approaches that improve productivity while conserving natural resources are urgently required (FAO, 2022; WHO, 2023).

Arbuscular mycorrhizal fungi (AMF) represent one of the most promising biological alternatives for sustainable medicinal plant cultivation. By establishing mutualistic symbiosis with plant roots, AMF enhance nutrient acquisition, improve water-use efficiency, stimulate photosynthesis, increase stress tolerance, and reduce

dependence on chemical fertilizers. Numerous studies have demonstrated improved biomass, root development, flowering, and phytochemical accumulation in medicinal plants inoculated with AMF (Smith & Read, 2008; Begum *et al.*, 2019).

Common medicinal plants showing positive responses to AMF inoculation include *Withania somnifera*, *Ocimum tenuiflorum*, *Aloe vera*, *Tinospora cordifolia*, *Asparagus racemosus*, *Catharanthus roseus*, and *Phyllanthus emblica*, where increases in plant growth, nutrient uptake, and secondary metabolite production have been consistently reported (Kapoor *et al.*, 2007; Zhao *et al.*, 2022).

Integrated Nutrient Management

Integrated Nutrient Management (INM) is a sustainable approach that combines biofertilizers, organic amendments, and judicious use of chemical fertilizers to enhance soil fertility and crop productivity while minimizing environmental impacts. Arbuscular mycorrhizal fungi (AMF) are key components of INM because they improve phosphorus availability, enhance nitrogen-use efficiency, facilitate the uptake of essential micronutrients, and reduce the dependence on synthetic fertilizers. When integrated with organic inputs such as compost, farmyard manure, vermicompost, plant growth-promoting rhizobacteria (PGPR), and other beneficial microorganisms, AMF exhibit synergistic effects that enhance nutrient cycling, improve soil health, and increase the growth, yield, and quality of medicinal plants. These integrated practices promote long-term soil sustainability and support environmentally friendly agricultural production systems (Adesemoye *et al.*, 2009; Berruti *et al.*, 2016; Hodge & Storer, 2015).

AMF as Biofertilizers

Arbuscular mycorrhizal fungi (AMF) are among the most effective microbial biofertilizers owing to their ability to establish long-term mutualistic associations with plant roots and enhance nutrient acquisition through natural biological processes. AMF inoculation improves nutrient-use efficiency, reduces fertilizer requirements and production costs, enhances tolerance to abiotic stresses, and promotes soil quality, biodiversity, and ecosystem stability. These multifunctional benefits make AMF an essential component of organic farming, sustainable medicinal plant cultivation, and climate-smart agriculture, contributing to higher crop productivity while reducing the environmental footprint of intensive farming practices (Berruti *et al.*, 2016; FAO, 2022).

BIODIVERSITY CONSERVATION AND ECOLOGICAL RESTORATION

Conservation of Medicinal Plants

The long-term conservation of medicinal plants requires an integrated approach that protects both aboveground plant diversity and the belowground microbial communities that support ecosystem functioning. Since most medicinal plants form beneficial associations with arbuscular mycorrhizal fungi (AMF), conservation strategies should prioritize the preservation of native mycorrhizal diversity alongside plant genetic resources. Effective measures include *in situ* and *ex situ* conservation, seed banking, germplasm preservation, habitat restoration, sustainable harvesting practices, and active community participation. Integrating AMF conservation into these strategies enhances plant establishment, maintains genetic diversity, and ensures the sustainable utilization of medicinal plant resources for future generations (NMPB, 2022; Brundrett & Tedersoo, 2018; WHO, 2023).

Ecological Restoration

Arbuscular mycorrhizal fungi (AMF) play a fundamental role in the ecological restoration of degraded landscapes by facilitating plant establishment, improving root development, enhancing nutrient cycling, and increasing soil aggregation and water retention. Through extensive hyphal networks and interactions with diverse soil microorganisms, AMF improve carbon sequestration, restore soil fertility, and promote microbial diversity, thereby accelerating vegetation recovery and enhancing ecosystem resilience. In semi-arid regions such as Marathwada, inoculation with indigenous AMF has emerged as an effective restoration strategy for rehabilitating degraded soils and supporting sustainable ecosystem recovery under changing climatic conditions (Rillig *et al.*, 2015; FAO, 2022).

RESEARCH GAPS

Although considerable progress has been made in understanding the ecological and agricultural significance of arbuscular mycorrhizal fungi (AMF), several critical knowledge gaps remain regarding their associations with medicinal plants in the semi-arid landscapes of Marathwada. Comprehensive regional surveys of AMF diversity are scarce, and molecular characterization using high-throughput sequencing technologies is still limited. In addition, insufficient information is available on host specificity, plant-microbe interaction networks, and the effects of climate change on AMF diversity, community dynamics, and ecosystem functioning. Long-term ecological monitoring, GIS-based mapping of medicinal plant and AMF diversity, and the integration of genomics, transcriptomics, metabolomics, and microbiome-based approaches remain largely unexplored. Furthermore, the development and commercialization of indigenous AMF inoculants suitable for region-specific medicinal plants are inadequate, limiting their practical application in

sustainable agriculture. Addressing these research gaps through multidisciplinary approaches integrating molecular biology, ecology, bioinformatics, geospatial analysis, and conservation science will provide valuable insights into plant-microbe interactions and facilitate the sustainable management, conservation, and utilization of medicinal plant biodiversity under changing environmental conditions (Brundrett & Tedersoo, 2018; Genre *et al.*, 2020; Tedersoo *et al.*, 2020; IPCC, 2023; Chandrasekaran, 2022).

FUTURE PERSPECTIVES

Future research on medicinal plant-arbuscular mycorrhizal fungi (AMF) interactions should focus on integrating advanced molecular, ecological, and digital technologies to improve sustainable medicinal plant production and ecosystem management. High-throughput approaches such as DNA metabarcoding, whole-genome sequencing, metagenomics, transcriptomics, functional genomics and metabolomics will provide deeper insights into AMF diversity, functional traits, and plant-microbe interactions. In addition, the application of artificial intelligence (AI), remote sensing, and Geographic Information Systems (GIS) will facilitate biodiversity mapping, predictive modeling, and monitoring of ecosystem changes under climate change scenarios. Future efforts should also prioritize the development of indigenous AMF-based biofertilizers, climate-resilient cultivation practices, carbon sequestration studies, and ecosystem restoration using native AMF communities. Translating these scientific advances into practical agricultural technologies will require strong interdisciplinary collaboration among microbiologists, botanists, ecologists, soil scientists, pharmacologists, bioinformaticians, and conservation biologists. Such integrated approaches will enhance the conservation of medicinal plant biodiversity, improve phytochemical productivity, and promote sustainable agriculture in semi-arid regions such as Marathwada (van der Heijden *et al.*, 2015; Tedersoo *et al.*, 2020; FAO, 2022; IPCC, 2023).

CONCLUSION

Medicinal plants and arbuscular mycorrhizal fungi constitute an ecologically significant biological partnership that supports ecosystem functioning, biodiversity conservation, and sustainable agriculture in the semi-arid landscapes of Marathwada. AMF enhance plant growth, nutrient acquisition, drought tolerance, soil fertility, and biosynthesis of valuable secondary metabolites while simultaneously improving ecosystem resilience under climate change.

Considering increasing environmental degradation and biodiversity loss, conservation of both medicinal plants and indigenous AMF communities should become an integral component of regional biodiversity management programs.

Future research integrating molecular biology, ecology, biotechnology, and sustainable agriculture will facilitate development of innovative AMF-based technologies for medicinal plant cultivation and ecological restoration.

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