



REVIEW ARTICLE

Impact of Mycorrhizae on Soil Health and Fertility in Maharashtra's Agricultural Lands: A Critical Analysis

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Manuscript Details

Manuscript Submitted : 20/02/2025

Manuscript Revised : 23/02/2025

Manuscript Accepted : 15/03/2025

Manuscript Published : 15/04/2025

Available On

<https://plantaescientia.com/ojs>

Cite This Article As

Sarwade Prakash Pralhad, Gaisamudre (Sarwade) Kavita Narayan, Bhise Damaji Shankar, Chandanshive Shahaji Shivaji & Gaikwad Rajesh Shrirangrao (2025). Impact of Mycorrhizae on Soil Health and Fertility in Maharashtra's Agricultural Lands: A Critical Analysis *Pla. Sci.* 2025; Vol. 08 Iss. 2:20-33

DOI-

<https://doi.org/10.32439/ps.v8i2.20-33>

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ABSTRACT

Soil degradation and declining fertility pose major threats to agricultural sustainability in Maharashtra, which is one of India's most agriculturally diverse states. Conventional input-intensive farming practices have led to issues such as nutrient depletion, erosion, salinity, and reduced soil organic matter content. Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), offer a promising biological solution by enhancing nutrient uptake, improving soil structure, and fostering microbial diversity. This review critically examines the role of mycorrhizae in improving soil health and fertility across the different agro-climatic regions of Maharashtra. This highlights the mechanisms through which AMF enhance phosphorus availability, reduce dependence on chemical fertilizers, and increase crop productivity and quality. Case studies of crops such as tomatoes, onions, and legumes have demonstrated the practical benefits of AMF inoculation in both rainfed and irrigated systems. The study also explored synergies between mycorrhizae and sustainable practices, such as organic farming, biochar use, composting, and crop rotation. This review concludes by emphasizing the need for region-specific field trials, biotechnology-driven improvements in AMF efficiency, and long-term soil health monitoring. Integrating mycorrhizal applications into climate-resilient agricultural models could play a pivotal role in achieving soil restoration, reducing input costs, and improving the livelihood of smallholder farmers across the state.

Keywords: Mycorrhizae, Arbuscular Mycorrhizal Fungi (AMF), Soil Health, Soil Fertility, Maharashtra Agriculture, Sustainable Farming, Nutrient Uptake, Biofertilizers

INTRODUCTION

Maharashtra is one of India's most agriculturally significant states with a vast and varied agroecological landscape. Major crops include cereals (e.g., jowar, bajra, rice), pulses (e.g., tur, moong), oilseeds (e.g., soybean, groundnut), fruits (e.g., grapes, mangoes, bananas), and high-value vegetables like onions and tomatoes (Ramgirkar & Talhar, 2024). However, the agricultural sector faces multiple challenges related to soil health and fertility, which directly affect crop productivity and farmers' livelihoods.

Recurring problems include the following.

- **Soil erosion and compaction**, especially in hilly and semiarid regions.
- **Nutrient depletion and imbalances** are often due to intensive monocropping and over-reliance on chemical fertilizers.
- **Salinity and pH fluctuations** in irrigated zones.
- **Declining organic matter** and microbial activity in both rainfed and irrigated systems.

These issues are exacerbated by Maharashtra's exposure to climate variability, with frequent droughts in regions such as Marathwada and Vidarbha making soil restoration an urgent priority (Narayanamoorthy, 2004).

Definition and Classification of Mycorrhizae

Mycorrhizae are mutualistic associations between certain types of fungi and roots of most terrestrial plants. In this symbiosis, the fungus assists in nutrient and water uptake, whereas the host plant supplies the fungus with carbohydrates (B, 2024). Mycorrhizal fungi can be broadly classified as follows.

- **Arbuscular Mycorrhizal Fungi (AMF)** are the most widespread, forming intracellular associations with herbaceous crops and many trees. These are especially important in tropical and subtropical agricultural systems such as those in Maharashtra (Abdullahi et al., 2023).
- **Ectomycorrhizae** are mainly associated with forest trees (e.g., pine and oak), which are not common in typical agricultural fields (Aggarwal et al., 2011).
- **Ericoid and Orchid Mycorrhizae** are specialized types that are limited to certain plant families.

AMF, which belong primarily to the phylum *Glomeromycota*, are particularly relevant for Maharashtra's dominant crops such as cotton, legumes, vegetables, and fruit trees

(Kowalczyk & Błazkowski, 2013). Many researchers in India, such as Bhale et al., (2010), Sarwade et al., 2011;2012), Sawant et al., (2011) and Sandhya et al., (2013;2016) have documented AMF in various plant species of medicinal plants (Sarwade et al., 2024) include species such as *Cinnamomum zeylanicum* (Kumar et al., 2024), *Moringa oleifera* (Otia et al., 2024), and *Allium sativum* L. (Mishra et al., 2024). Recent studies by Sandhya et al., (2013; 2016) and Prakash et al., (2021) have expanded knowledge on AMF distribution and diversity in different plants across the country.

Importance of Studying Mycorrhizae in the Regional Agricultural Context

In Maharashtra, where soil degradation is an ongoing threat to food security, mycorrhizal fungi offer a natural and cost-effective method for enhancing soil fertility and crop productivity (Njeru et al., 2020). These fungi improve:

- **Phosphorus and micronutrient uptake** which are often limiting in regional soils.
- **Soil structure and water retention** are essential for rainfed agriculture.
- **Microbial diversity** supports nutrient cycling and disease resistance.

Understanding and harnessing AMF can help reduce fertilizer dependency, promote sustainable farming, and improve resilience against drought and other climate stressors, which are especially critical for smallholder farmers.

Objectives and Scope of the Review

This review critically analyzes the role of mycorrhizal fungi, particularly AMF, in improving soil health and fertility in Maharashtra agricultural systems (Mgolozeli et al., 2020). The main objectives are to:

- Examine current soil health challenges across key agroclimatic regions.
- Assess how mycorrhizae affect soil physical, chemical, and biological properties.
- Explore evidence of mycorrhizal effects on crop performance and nutrient use efficiency.
- Highlight synergies with sustainable practices such as organic farming and biochar application.
- Identify research gaps and future directions for integrating AMF into regional soil fertility management strategies.

REVIEW OF LITERATURE

Types of Mycorrhizal Fungi (with Emphasis on Arbuscular Mycorrhizal Fungi-AMF)

Mycorrhizal fungi (AMF) are a diverse group of soil microorganisms that form mutualistic associations with the roots of most terrestrial plants. These relationships are pivotal for plant health and ecosystem functioning (Aggarwal et al., 2011). The main types include:

1. **Arbuscular Mycorrhizal Fungi (AMF)** are the most prevalent form of mycorrhizae, forming associations with over 80% of the vascular plants, including most crops and herbaceous species (B, 2024). These fungi belong to the phylum *Glomeromycota* and are characterized as follows:
 - i. The formation of **arbuscules**, highly branched hyphal structures within root cortical cells, facilitates efficient nutrient exchange (Kowalczyk & Błaszowski, 2013).
 - ii. Development of **vesicles** that serve as storage organs.
 - iii. **Intracellular colonization** of the root cortex (penetrating the cell wall but not the plasma membrane) (Ajemagebisa, 2024).
 - iv. A generalist approach to host selection, forming associations with a wide range of plant species.

AMF do not form visible fruiting bodies and are obligate biotrophs, meaning they rely entirely on the host plant for carbon (Vishwakarma et al., 2022).

Ectomycorrhizal Fungi (EMF)

Found predominantly in temperate and boreal forests, EMF associate with trees such as pines, birches, oaks, and eucalypts (Phillips et al., 2013). Unlike AMF, they:

1. A mantle or sheath is formed around the root tips.
2. Develop a Hartig net that extends between but not into root cortical cells (Wallander, 2006).
3. Typically, they belong to the phyla *Basidiomycota* and *Ascomycota* and often produce conspicuous fruiting bodies (e.g., mushrooms). EMF plays a key role in forest nutrient cycles, particularly in the decomposition of nitrogen and organic matter (Wang et al., 2025).

Ericoid Mycorrhizae

These fungi form associations with plants of the *Ericaceae* family, such as heathers and blueberries, which often grow in acidic and nutrient-poor environments (Lee, 2002).

- i. They produce intracellular coils within the root hair cells (Stoyke & Currah, 1991).
- ii. Capable of degrading complex organic materials and facilitating nutrient acquisition in challenging soils (Tupapac Otero et al., 2013).

Orchid Mycorrhizae

It is essential for the germination and early development of orchids, the tiny seeds of which lack sufficient nutrient reserves (Suryantini et al., 2015).

- i. Fungi from genera such as *Rhizoctonia* colonize orchid embryos and provide carbon and nutrients.
- ii. This association often transitions to mutualism as the orchid matures.

Mechanism of Plant-Fungus Symbiosis

The mycorrhizal relationship is a finely tuned mutualistic interaction that results in the reciprocal exchange of resources and signaling molecules (Azcón-Aguilar & Bago, 1994).

- **Benefits to the Fungus:** The fungus obtains carbon compounds (primarily glucose and sucrose) synthesized by the host plant through photosynthesis. This carbon transfer accounts for up to 20% of the photosynthetic output of the host (Usuki & Narisawa, 2007).
- **Benefits to the Plant:** The host plant gains improved access to essential soil nutrients (e.g., phosphorus, nitrogen, and micronutrients) and water. Mycorrhizal networks also increase the effective absorptive surface area of roots and improve soil structure (Usuki & Narisawa, 2007).

Colonization Process:

1. **Spore germination:** Triggered by proximity to root exudates (Gobert & Plassard, 2008).
2. **Hyphal growth:** directed toward the plant root in response to chemical signals.
3. **Appressorium formation:** A specialized structure that initiates root penetration (Wipf et al., 2019).
4. **Intracellular development:** In AMF, hyphae penetrate the root cortex and form arbuscules for nutrient exchange.

Signal Exchange:

- Plants release strigolactones that stimulate fungal metabolism and hyphal branching (Cope et al., 2019).
- Fungi respond by producing Myc factors and lipochitooligosaccharides that activate the common symbiosis signaling pathway (CSSP) in plant cells (Sun et al., 2015).
- This complex molecular dialogue is crucial for the establishment and maintenance of symbiosis (Wu et al., 2023).

Role in Nutrient Cycling

Mycorrhizal fungi are fundamental for nutrient acquisition, particularly in ecosystems with low nutrient availability or poor soil structure (Sathiyadash et al., 2017).

Phosphorus (P) Cycling

- AMF are particularly important for P uptake because of the immobility of phosphate ions in soil.
- Their extensive extraradical hyphae explored beyond the depletion zone surrounding the roots, accessing inorganic P.
- They can also secrete phosphatases, which liberate phosphate from organic compounds (Haynes & Swift, 1985).

Nitrogen (N) cycling

- While AMF predominantly absorb inorganic nitrogen (e.g., ammonium and nitrate), EMF can decompose organic matter and access complex organic N compounds (Wang et al., 2025).
- EMF contributes significantly to N mineralization and immobilization, affecting the overall N availability in forest ecosystems.

Micronutrient Uptake

- Mycorrhizae enhance the acquisition of micronutrients, such as zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe) (Rengel, 2015).
- This is achieved through mechanisms such as acidification of the rhizosphere, chelation, and redox reactions, mediated by fungal enzymes (Haynes & Swift, 1985).

Influence on Plant Stress Resistance and Pathogen Protection

Mycorrhizal fungi contribute to plant resilience to both abiotic and biotic stressors.

Abiotic Stress Resistance

- **Drought:** Hyphal networks increase soil water extraction, whereas physiological changes in root structure improve water use efficiency (Ortas et al., 2020).
- **Salinity:** Mycorrhizal associations reduce sodium uptake, enhance potassium retention, and maintain ionic balance (Casarrubias-Castillo et al., 2019).
- **Heavy Metals:** Fungi can bind to toxic metals within their cell walls or vesicles, thereby reducing plant exposure.
- **Temperature Extremes:** Mycorrhizal colonization can induce the expression of heat shock proteins and cold-responsive genes (Casarrubias-Castillo et al., 2019).

Biotic stress and pathogen defence

- **Physical Barrier:** Mycorrhizal structures can act as barriers to pathogen entry (Rashad et al., 2021).
- **Competition:** Mycorrhizal fungi outcompete pathogenic microbes in root colonization sites and nutrients.
- **Induced Systemic Resistance (ISR):** Colonization triggers plant defence signaling pathways, including those mediated by jasmonic acid and salicylic acid.
- **Antimicrobial Compounds:** Some mycorrhizal fungi secrete secondary metabolites that inhibit pathogenic growth (Pu et al., 2022).

*Soil Health and Fertility in Maharashtra**Current Status of Soil Health*

Maharashtra, with its varied agro-climatic zones, faces multiple soil health challenges that directly affect agricultural productivity (Kale et al., 2023). Continuous cultivation, improper irrigation, and overdependence on chemical fertilizers have led to significant soil degradation (Rego et al., 2007).

Key issues include:

- **Soil erosion**, especially in hilly and semi-arid zones, results in the loss of topsoil and organic matter, affecting water retention and root penetration.
- **Salinity and alkalinity**, particularly in irrigated areas of western Maharashtra, have worsened because of poor drainage and overuse of saline water, impairing plant growth and microbial life (Power & Prasad, 1998).
- **Nutrient depletion**, mainly of nitrogen (N), phosphorus (P), potassium (K), and micronutrients, such as zinc and boron, is widespread because of crop intensification without replenishment. Studies have shown that over 60% of soils in Maharashtra are deficient in phosphorus, and more than 40% lack adequate nitrogen (Rego et al., 2007).

Fertility Trends Across Regions

Soil fertility in Maharashtra varies significantly across the major regions (Raghavendra, 1974).

- **Marathwada** suffers from frequent droughts and low organic matter content due to reduced biomass return, leading to poor nutrient cycling and fertility loss (Shroff et al., 2018).
- **Vidarbha**, with a predominance of black cotton soil (regur), has a relatively better structure, but shows increasing phosphorus fixation and micronutrient deficiencies, affecting long-term fertility (Athare et al., 2023).
- **Konkan**, with lateritic soils and high rainfall, faces nutrient leaching and acidity issues, which compromise nutrient availability despite the high biomass input (Patil et al., 1990).
- **Western Maharashtra** is more intensively farmed, but excessive irrigation and input use have led to soil compaction, salinity, and nutrient imbalances (Gudewar et al., 2023).

Limitations of Conventional Fertilizers and Chemical Inputs

The widespread use of chemical fertilizers has helped achieve short-term yield gains but has also contributed to long-term soil degradation (Matos et al., 2022).

- **Imbalanced fertilization** (primarily heavy nitrogen) disrupts the nutrient ratio and microbial activity in the soil.

- **Reduced soil organic carbon** due to minimal organic amendments has weakened soil structure and biological health (Chaudhary et al., 2024).
- **Suppression of beneficial microbes**, including mycorrhizal fungi, occurs due to pesticide and fungicide overuse, which undermines natural nutrient cycling and plant-microbe symbioses (Sarwade et al., 2024).
- **Economic inefficiency** is also a growing concern, as input costs increase, while diminishing returns from degraded soils reduce profitability for farmers (Sharma et al., 2022).

Impact of Mycorrhizae on Soil Health

Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), play pivotal roles in enhancing soil health by directly influencing their physical, chemical, and biological properties (Rillig, 2004). Their widespread presence in the rhizosphere contributes to the resilience and sustainability of agricultural ecosystems, particularly in regions such as Maharashtra where soil degradation is a growing concern (Javeed et al., 2023).

Improvement in Soil Structure (Aggregation and Porosity)

One of the most visible contributions of mycorrhizae is the improvement of soil physical structure. The fungal hyphae form a vast network that binds soil particles together, promoting the formation of stable soil aggregates (Prayudyaningsih et al., 2021). These aggregates:

- Enhance **soil porosity**, facilitating better water infiltration and retention.
- Improve **aeration**, enabling healthy root respiration.
- Reduce **soil compaction**, allowing easier root penetration and seedling emergence.

In semi-arid zones of Maharashtra such as Marathwada and Vidarbha, where soils often suffer from poor water retention and compaction, the aggregation promoted by AMF is especially valuable for maintaining productivity under moisture stress.

Role of Glomalin and Other Mycorrhizal Exudates

A key biochemical contribution of AMF to soil health is the production of glomalin, a glycoprotein secreted by hyphae. Glomalin exerts several important effects (Channavar et al., 2024).

- Acts as a **binding agent** for soil particles, enhancing aggregate stability.
- Increases **carbon sequestration** in the soil, contributing to long-term soil fertility and climate change mitigation.
- Protects soil particles from erosion by improving cohesion and water-stable aggregates

In addition to glomalin, AMF releases organic acids and enzymes that influence nutrient solubility and microbial activity. These exudates improve soil chemistry by mobilizing bound nutrients and interacting with beneficial soil microbes (Uhlmann et al., 2004).

Enhancement of Microbial Diversity and Soil Organic Matter

The presence of AMF fosters a diverse and functionally robust soil microbiome (Biswas & Kole, 2017). This occurs through:

- **Improved root exudation patterns**, which provide energy-rich compounds that feed beneficial bacteria and fungi.
- **Symbiotic interactions** that support nitrogen-fixing bacteria, phosphate-solubilizing microbes, and decomposers.
- **Increased microbial biomass and activity**, which drive organic matter decomposition and nutrient mineralization.

Over time, these processes contribute to the accumulation of soil organic matter (SOM), which is essential for maintaining soil fertility, buffering pH, and increasing the cation exchange capacity (Miltner et al., 2011).

In degraded Maharashtra soils, where SOM is often below optimal levels, AMF inoculation can gradually restore biological activity and organic content, especially when integrated with compost or cover cropping strategies.

Impact on Soil Fertility and Crop Productivity

Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), enhance soil fertility by improving nutrient availability and uptake, which ultimately influences crop productivity (Ajemagebisa, 2024). In Maharashtra's diverse agro-ecological zones, ranging from the semi-arid regions of Marathwada to the high-rainfall Konkan coast, mycorrhizal associations offer practical solutions for soil fertility constraints and diminishing crop yields.

Enhanced Nutrient Uptake (Especially Phosphorus)

Phosphorus (P) is a critical yet immobile macronutrient in soil, often rendered unavailable due to fixation in inorganic forms (Gao & Zhang, 2024). AMF significantly enhances phosphorus uptake through the following mechanisms:

- **Extensive hyphal networks** that explore soil volumes beyond the root depletion zone.
- **Phosphatase enzymes** that mobilize inorganic and organic phosphorus compounds.
- **Improved root surface area** via colonization, facilitating better absorption of nitrogen (N), potassium (K), zinc (Zn), and other micronutrients.

This nutrient enhancement is particularly valuable in Maharashtra phosphorus-deficient soils, where over 60% of the tested samples showed suboptimal P levels (Lu et al., 2023).

Reduction in Fertilizer Dependency

Mycorrhizal inoculation reduces the need for synthetic fertilizers, which are often overused because of poor nutrient efficiency (Hossain & Siddique, 2020). Benefits include:

- **Lower input costs** for smallholder farmers by reducing fertilizer application by 25–50% without compromising yield.
- **Mitigation of nutrient runoff** and leaching, thereby protecting water quality and reducing environmental degradation.
- **Greater nutrient use efficiency (NUE)**, as the fungi store and release nutrients in synchrony with plant demand (Salim & Raza, 2019).

This is especially crucial in regions such as Vidarbha and western Maharashtra, where intensive agriculture and overirrigation have led to nutrient imbalances and soil fatigue.

Case Studies and Data from Maharashtra

Numerous trials and field studies conducted across Maharashtra have confirmed the efficacy of AMF in boosting crop performance (Qian et al., 2024).

- **Tomatoes (*Solanum lycopersicum*)** in Pune and Nashik showed yield increases of up to 18–25% with AMF inoculation, attributed to better phosphorus and zinc uptake (Mbodje et al., 2025).

- Onions (*Allium cepa*) grown in Latur and Solapur exhibited improved bulb size and shelf life, with a 15–20% reduction in phosphorus fertilizer requirement (Zhang et al., 2023).
- Legumes (e.g., pigeon pea and chickpea) in Marathwada benefited from dual symbiosis with AMF and *Rhizobium*, resulting in increased biomass and nodulation efficiency, especially in low-input systems (Wen et al., 2024).

These results highlight the role of mycorrhizae in bridging the yield gaps across different soil and climatic zones in the state.

Influence on Yield and Crop Quality

Beyond yield quantity, mycorrhizal symbiosis improves the nutritional quality and stress tolerance of crops (Kazakov et al., 2024).

- Higher protein content in legumes and cereals due to better nitrogen assimilation. (Hayman, 1986).
- Enhanced antioxidant and vitamin levels in fruits and vegetables, contributing to better marketability and health benefits.
- Greater resistance to drought and soil-borne pathogens, leading to more stable and resilient crop performance under variable climatic conditions (Parra-Londono et al., 2023).

In a state such as Maharashtra, where smallholder farmers frequently face erratic rainfall and rising input costs, the adoption of mycorrhizae can improve both agronomic and economic outcomes.

Integration with Sustainable Practices

The incorporation of mycorrhizal fungi into sustainable agricultural practices holds great promise for restoring degraded soils and building long-term ecological resilience, especially in regions such as Maharashtra (Adnan et al., 2022), which are experiencing soil fertility loss and climate variability (Sarwade et al., 2024). The synergistic use of mycorrhizae with organic farming, biochar, compost, and diversified cropping practices offers a holistic approach for sustainable land management (Kale et al., 2023).

Mycorrhizae and Organic Farming

Mycorrhizal fungi are naturally compatible with organic farming systems that emphasize biological inputs and soil health (Sofi et al., 2017).

- Minimal chemical disturbance in organic systems allows mycorrhizal networks to thrive and form effective symbiotic relationships.
- Organic matter sources like farmyard manure (FYM), green manures, and vermicompost support the soil microbial biomass, creating a conducive environment for mycorrhizal colonization.
- In Maharashtra, many smallholder farmers have begun integrating AMF inoculants in organic vegetable production (e.g., tomatoes, okra, and eggplant), reporting enhanced root health and yield consistency under low-input conditions (Reddy et al., 2024).

Organic systems also benefit from the ability of mycorrhizae to suppress pathogens, thereby reducing the need for organic pesticides and naturally enhancing crop resilience.

Synergies with Biochar, Compost, and Crop Rotation

Several sustainable soil amendments and practices have enhanced AMF effectiveness.

- Biochar, a carbon-rich byproduct of biomass pyrolysis, acts as a microhabitat for mycorrhizal fungi, improving colonization rates and hyphal survival. When applied with AMF, biochar enhances soil structure, water retention, and nutrient exchange (Safaei Asadabadi et al., 2021).
- Compost provides slow-release nutrients and a balanced microbial environment that supports both fungal and bacterial symbionts (Mowrer et al., 2022).
- Crop rotation, especially involving mycorrhiza-dependent crops like legumes, prevents fungal dormancy and promotes continued colonization across growing seasons. Legumes also enrich the soil with nitrogen, which synergizes with the phosphorus-mobilizing capacity of AMF (Ramazanoglu et al., 2025).

In Maharashtra, trials combining AMF with compost and biochar in rainfed regions (e.g., Vidarbha) have demonstrated improved plant biomass, nutrient use efficiency, and soil moisture retention, which are key indicators of soil system resilience.

Impact on Long-Term Soil Sustainability and Carbon Sequestration

Mycorrhizae contribute significantly to long-term soil sustainability through the following mechanisms (Hossain, 2021):

- **Carbon sequestration:** The production of glomalin-related soil proteins (GRSP) by AMF contributes to stable soil organic carbon pools. Glomalin binds to soil particles and protects carbon from microbial decomposition (Kumari et al., 2025).
- **Reduction in external inputs:** As AMF reduce fertilizer and pesticide needs, they decrease the ecological footprint of farming and reduce the soil chemical load (Yang et al., 2024).
- **Soil resilience:** Mycorrhizal systems buffer the soil against erosion, nutrient loss, and extreme weather events by improving aggregation, microbial diversity, and nutrient cycling (Dahiya et al., 2022).

The cumulative effect of AMF integration with sustainable practices ensures a regenerative soil system that not only supports productivity today but also safeguards it for future generation.

LIMITATIONS AND CHALLENGES

Despite the well-documented ecological and agronomic benefits of mycorrhizal fungi, several practical and systemic limitations have restricted their widespread application in modern agriculture (Salgado et al., 2017). These challenges include biological variability, technological constraints, and socioeconomic barriers.

Variability in Effectiveness Across Crops and Soil Types

- **Host specificity and responsiveness:** Although arbuscular mycorrhizal fungi (AMF) are generalists, not all plant species respond equally to mycorrhizal colonization. Some crops (e.g., legumes and maize) often show strong positive responses, whereas others (e.g., Brassicaceae, such as canola or mustard) are non-mycorrhizal and derive no direct benefit (Bartolome-Esteban & Schenck, 1994).
- **Soil conditions:** The mycorrhizal function is heavily influenced by soil texture, pH, nutrient availability, moisture, and microbial communities (Becerra et al., 2014). For instance:
 - High phosphorus soils can suppress mycorrhizal colonization, reducing the incentive for plant-fungal cooperation.

- Compacted or saline soils can impair fungal hyphal growth and spore germination (Soti et al., 2021).

- **Ecological variability:** Climate, seasonal variation, and local biodiversity also affect the abundance and activity of the native mycorrhizal communities (Bouamri et al., 2014).

Commercial Availability and Viability of Inoculants

- **Limited strain diversity:** Commercial AMF inoculants often include only a few species (e.g., *Rhizophagus irregularis*), which may not perform well across diverse environments or match native fungi (Varga et al., 2014).
- **Viability and shelf life:** AMF spores are biologically complex and are sensitive to storage conditions. Maintaining the viability of commercial products is challenging (Singh & Chahar, 2021).
- **Inoculation efficiency:** The success of field inoculation varied. In some cases, the introduced fungi fail to establish or are outcompeted by native microbes (Dietrich et al., 2020). Additionally, the results may not translate from controlled experiments to open field conditions.
- **Cost:** High production and application costs can limit adoption, particularly in low-income agricultural settings (Agnolucci et al., 2019).

Impact of Conventional Farming Practices

- **Tillage:** Frequent or deep soil disturbances disrupt hyphal networks and reduce fungal biomass, undermining long-term colonization (Wilkes et al., 2020).
- **Chemical inputs**
 - Fungicides may directly suppress mycorrhizal growth and spore viability.
 - High nitrogen or phosphorus fertilizers can reduce plant dependence on fungal symbiosis and diminish colonization rates (Meyer et al., 2021).
- **Monoculture systems:** These limit microbial diversity and reduce the ecological niches required to support robust mycorrhizal communities (Eisenhauer et al., 2017).

Need for Farmer Education and Policy Support

- **Knowledge gaps:** Many farmers lack awareness of the benefits of mycorrhizal fungi or misunderstand their applications. This limits the integration of mycorrhizal management in farming systems (Monika et al., 2019).
- **Extension services:** There is a need for better agricultural extension programs to educate growers on soil biology, inoculant application methods, and the role of fungi in sustainable farming (Adesemoye et al., 2017).
- **Policy and incentives**
 - Agricultural policies often emphasize chemical fertilizers and pesticides over biological amendments.
 - Few subsidies or regulatory incentives exist to support the use of microbial inoculants or practices that enhance mycorrhizal function (e.g., no-till or cover cropping) (Benami et al., 2020).
- **Research and regulation:** More field-based research is needed to evaluate the long-term impacts and optimize inoculant formulations. Additionally, regulatory frameworks for microbial products vary widely and may hinder innovation and market entry.

Future Prospects and Research Needs

While mycorrhizal fungi have demonstrated substantial promise in improving soil health and crop productivity, there is still untapped potential, particularly in geographically and climatically diverse states such as Maharashtra. Future research and policy focus should address regional variability, technological innovation, and the alignment of AMF applications with broader sustainability and climate goals.

Recommendations for Region-Specific Field Trials

Despite encouraging results from isolated studies, systematic and large-scale field trials tailored to Maharashtra's agroclimatic zones are limited. Future efforts should focus on the following aspects.

- **Identifying crop-specific and soil-specific AMF strains** effective in different regions, such as the drought-prone Marathwada and Vidarbha or the high-rainfall Konkan.
- **AMF efficacy was tested under real farm conditions** using representative crops (e.g., cotton, sugarcane, pulses, and onions) to generate practical and scalable data.

- **Developing local inoculant production units** and integrating AMF into state agricultural extension programmes.

Such trials will help to establish regionally optimized AMF formulations and usage protocols that maximize benefits and farmer adoption.

Role of Biotechnology in Enhancing AMF Efficiency

Biotechnological advancements have offered several avenues for enhancing the functionality and field performance of AMF.

- **Molecular identification and selection** of highly effective AMF strains using genomic tools to match host plant and soil types.
- **Genetic enhancement** of AMF to improve phosphorus solubilization, drought tolerance, and symbiotic efficiency.
- **Use of synthetic biology and microbial consortia** combining AMF with other beneficial microbes, such as nitrogen-fixing and phosphate-solubilizing bacteria.
- **Formulation technology** for more stable, long-lasting AMF inoculants (e.g., encapsulated, slow-release bioformulations).

These innovations will help overcome current limitations such as low shelf life, inconsistent colonization, and narrow host ranges.

Long-Term Soil Health Monitoring Strategies

Robust soil health monitoring frameworks are essential to evaluate the sustained benefits of AMF-based interventions.

- **Establishment of AMF colonization benchmarks** for different crops and agro-ecological zones.
- **Key soil health indicators** such as glomalin levels, microbial biomass, aggregate stability, and nutrient bioavailability were monitored over multiple cropping seasons.
- **GIS-based soil mapping and remote sensing tools** were incorporated to assess the regional impact of AMF over time.
- **Involve participatory research** with farmers for long-term observations and data feedback.

These strategies can inform adaptive soil management and help quantify the long-term ecological returns of AMF adoption.

Integration with Climate-Resilient Agriculture.

Mycorrhizae have great potential in climate-resilient agricultural systems, which will become increasingly important as Maharashtra experiences erratic rainfall, rising temperatures, and prolonged dry spells.

- Enhanced drought tolerance through improved root water uptake and soil moisture conservation.
- Increased nutrient use efficiency reduces greenhouse gas emissions associated with fertilizer production and application.
- Synergies between agroforestry and perennial cropping systems improve carbon sequestration and ecosystem stability.
- Contribution to adaptive strategies for marginal soils where conventional input-based systems are ineffective or unsustainable.

Integrating AMF with climate-smart agriculture frameworks, such as the National Mission for Sustainable Agriculture (NMSA), will make them a core component of future soil and climate policies in the state.

CONCLUSION

This review critically examines the impact of mycorrhizal fungi on soil health and fertility across diverse agricultural landscapes in Maharashtra. With widespread soil degradation, characterized by erosion, nutrient depletion, and declining organic matter, mycorrhizae have emerged as a biologically sound and ecologically sustainable solution for restoring and enhancing soil productivity. Key insights from the analysis include the following.

- Improved soil structure and aggregation facilitated by mycorrhizal hyphal networks and glomalin production, which enhanced porosity, reduced erosion, and improved water retention.
- Enhanced nutrient uptake, particularly phosphorus and micronutrients, reduced dependency on synthetic fertilizers and improved crop yields and resilience.
- Positive interactions with sustainable practices such as organic farming, biochar, compost, and crop rotation amplify the long-term ecological benefits of soil systems.
- Potential for region-specific implementation supported by field trials, biotechnology, and integration into climate-resilient agriculture frameworks.

Given these benefits, the adoption of mycorrhizal applications is not merely a supplementary practice, but a foundational step in rebuilding Maharashtra's degraded soils. For smallholder farmers, in particular, this approach offers a low-cost, high-impact method to achieve stable yields while preserving soil integrity.

Ultimately, there is an urgent need for a paradigm shift toward biologically integrated soil fertility management, one that places soil microbiota, particularly mycorrhizal fungi, at the center of sustainable agriculture. This shift requires coordinated efforts in research, policy, and farmer education to ensure that biological soil amendments become widespread and effective tools in Maharashtra's pursuit of resilient, equitable, and regenerative farming systems.

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