International Journal of Botany Studies
www.botanyjournals.com
ISSN: 2455-541X
Received: 08-02-2026, Accepted: 09-03-2026, Published: 24-03-2026
Volume 11, Issue 1, 2026, Page No. 344-351

The multifaceted role of arbuscular mycorrhiza in plant growth and soil health: Implications for Sustainable Agriculture

Urmila Ramtirth Verma[1], Dr. Sharda Anil vaidya[2]
[1] Research Scholar, Department of Botany, Smt. C.H.M. College (Autonomous), Ulhasnagar, Maharashtra, India
[2] Retired Associate Professor, Department of Botany, Smt. C.H.M. College (Autonomous), Ulhasnagar, Maharashtra, India

Abstract
Arbuscular mycorrhizal fungi (AMF) establish a natural symbiosis with plant roots, playing a pivotal role in enhancing plant growth, soil fertility, and overall ecosystem stability. This review examines the diverse roles of AMF in improving nutrient and water absorption, increasing plant resilience to environmental stresses, and strengthening defense mechanisms against pathogens. The extended hyphal network of AMF facilitates the mobilization and uptake of essential nutrients such as phosphorus, nitrogen, zinc, and iron, which are often limited in the soil. In addition to boosting nutrient acquisition, AMF enhance abiotic and biotic stress tolerance, regulate hormonal balance, and activate systemic resistance pathways that protect plants from diseases. Beyond their influence on plants, AMF contribute significantly to soil health by improving aggregation, promoting carbon sequestration, and supporting beneficial microbial communities. These fungi thus serve as key agents for maintaining soil structure and reducing erosion. Integrating AMF into modern agricultural systems offers an environmentally sound approach to reducing dependence on chemical fertilizers, improving productivity, and ensuring long-term agricultural sustainability.

Keywords: Arbuscular mycorrhizal fungi (AMF), nutrient uptake, stress tolerance, disease resistance, soil health, sustainable agriculture.

Introduction

Mycorrhizae can be described as a mutually beneficial association between fungi and the roots of plants, where the fungus usually inhabits the root system of a host plant, enhancing its ability to absorb water and nutrients, while the plant supplies the fungus with carbohydrates generated through photosynthesis (Rastogi *et al*., 2024) [48]. This symbiotic relationship aids the plant in thriving within a soil ecosystem by providing various benefits (Begum *et al*., 2019) [9].

Research on mycorrhizae began earnestly in the late 1800s, but it wasn't until the 1900s that its importance for plant growth and soil health became fully acknowledged. Initial research focused mainly on the identification and classification of mycorrhizal fungi. As scientists investigated further, they discovered the extensive role mycorrhizae play in promoting nutrient exchange between soil and plants. This finding represented a major shift in understanding plant nutrition and soil biology. The 20th and 21st centuries have seen a significant increase in mycorrhizal research, especially concerning sustainable agriculture and forestry, which has led to innovative farming methods that incorporate mycorrhizal fungi for improved crop yields and better soil conservation (Rastogi *et al*., 2024) [48].

The frequent use of chemical fertilizers, pesticides, and herbicides creates challenges for both human health and soil quality (Yang *et al*., 2004) [66]. Biofertilizers are composed of a blend of natural substances, including microbes that promote the growth, development, and overall health of plants. Arbuscular mycorrhizal fungi (AMF) function as growth regulators in most terrestrial environments, and researchers have been encouraged to utilize AMF as a biofertilizer (Khalique *et al*., 2022).

Symbiotic relationships between arbuscular mycorrhizal fungi and plant roots are prevalent in nature and can offer various advantages to the host plant. These advantages encompass enhanced nutrition, greater resistance to soil-borne pests and diseases, improved stress tolerance, and better soil structure. Numerous agricultural crops form mycorrhizal associations, if equivocal evidence that crops benefit from their arbuscular mycorrhizal (AM) partnerships similarly (Paul *et al*., 2006) [43].

AM fungi play a crucial role in sustainable agricultural systems because they thrive in conditions where nutrient availability is low and when nutrients are bound to organic matter and soil particles (Soibam *et al*., 2021) [4]. Nevertheless, there are significant gaps in our knowledge regarding the AM association, particularly concerning the role of AMF species diversity in achieving the full spectrum of benefits and the impact of various agronomic methods on the ecology and functionality of AMF (Paul *et al*., 2006) [43]. Effective management of arbuscular mycorrhizal fungi has the potential to enhance the profitability and sustainability of agricultural practices.

Types of Mycorrhizae

The term "mycorrhizae," which translates to "Fungus Root," refers to the symbiotic relationship that mycorrhizae establish with plant roots, benefiting both. Mycorrhizae are specific to their host plants and can only colonize certain plants, which means that some soils may lack the native mycorrhizae required to support these plants. Consequently, most plants can benefit from the introduction of mycorrhizae into the soil. Globally, over 150 species of mycorrhizal fungi can be found across various soil types and climates. There are multiple forms of mycorrhizal associations, but the most prevalent and important for agriculture are Arbuscular Mycorrhizae (AM) and Ectomycorrhizae (ECM) (Milton *et al*., 2021) [37].

1. Ectomycorrhizae (ECM)

ECM fungi create a protective layer around the root tips and invade the root cortex without actually entering the cells. They are predominantly linked with trees and shrubs. ECM fungi play a vital role in forest ecosystems and are utilized in reforestation and afforestation initiatives (Milton *et al*., 2021) [37].

2. Arbuscular Mycorrhizae (AM)

AM fungi penetrate the cortical cells of root systems in plants, forming structures known as arbuscules and vesicles. These arbuscules and vesicles facilitate the transfer of nutrients between the fungus and the plant. AM fungi are linked to most crop plants, such as cereals, legumes, and vegetables (Milton *et al*., 2021) [37].

Role of Arbuscular Mycorrhizae in Plant Growth

Arbuscular mycorrhizae (AM) are essential for plant development, as they establish a symbiotic connection that improves the availability and absorption of nutrients and water, boosts photosynthetic rates, enhances antioxidant activities, and raises resilience to environmental stress. Additionally, AM fungi positively influence both primary and secondary metabolites, which in turn enhances plant growth, yield, and productivity (Khan *et al*., 2022) [29].

1. Enhanced nutrient and water uptake

AMF enhanced the absorption of mineral nutrients and water by host plants. It was observed that the extra-root mycelia of AMF were extensively spread throughout the soil, intertwining to create a vast network of mycelium, which expanded the root system's range for absorbing water and nutrients, particularly phosphate and nitrate, simultaneously for various plants (Weng *et al*., 2022) [63].

Mycorrhizal fungi can absorb and transport nearly all 15 essential macro- and micronutrients necessary for plant growth. These fungi secrete powerful chemical compounds into the soil that help mobilize tightly bound nutrients like phosphorus, iron, and other mineral nutrients. The processes involved in dissolving and transporting nutrients are crucial for providing plants with nutrition, and this necessitates consideration of high fertility levels in non-mycorrhizal plants to ensure their health (Cabral *et al*., 2016) [12]. Mycorrhizal fungi develop an intricate network of hyphae that captures and absorbs nutrients, replenishing the soil's nutritional resources. In the absence of mycorrhiza, much of this fertility is depleted or lost from the soil ecosystem. Mycorrhizal relationships may directly affect the growth of host plants by enhancing nutrient acquisition through the fungal partner. The two main phases in nutrient absorption from the soil and the release of these nutrients via mycorrhizal association include: a) Mobilization and acquisition by fungal mycelia and b) Transportation of the absorbed nutrients across the fungal–root interface (Khrieba, 2019).

The colonization by AMF boosts the uptake of nutrients in plants. When AMF are introduced to the plant, they enhance the acquisition of macro and micronutrients, resulting in increased photosynthesis and a greater accumulation of photosynthates. In soils lacking nutrients, AMF facilitate nutrient uptake by plants by enhancing the root system's surface absorbing capacity (Khaliq *et al*., 2021) [28]. Studies have shown that AMF inoculation in tomato plants resulted in higher uptake of K, N, P, and calcium (Ca) and improved plant growth (Balliu *et al*., 2015) [7]. AMF establishes a mutualistic relationship with the roots of the plant, which aids in the absorption of various mineral nutrients such as Ca, N, P, and zinc (Zn) (Li *et al*., 2016). AMF synthesize siderophores (ferricrocin, glomuferrin) (Haselwandter, 2008; Winkelmann, 2017) [23, 65], which have the ability to chelate iron (Fe), especially under Fe-deficiency conditions. The chelated Fe becomes available for uptake by both plants and fungi (Etesami *et al*., 2021) [20].

1.1 Phosphorus (P)

Arbuscular mycorrhizal (AM) fungi are particularly proficient at enhancing phosphorus (P) uptake because their external hyphae can reach soil areas that are beyond the depletion zones surrounding roots, where they can mobilize P and transfer it to the host plant through arbuscules. Numerous studies have documented significant increases in plant P concentration and P-use efficiency after colonization by AM fungi in environments with low to moderate soil P availability. AM fungi enhance nutrient uptake by broadening the root absorption area and also exude compounds like glomalin, a glycoprotein released by AM fungal hyphae and spores. In the soil, glomalin facilitates the absorption of hard-to-dissolve nutrients like iron (Fe) and phosphorus (P) (Smith and Read, 2008; Begum *et al*., 2019; Kumar *et al*., 2024) [2, 9, 56]. Phosphorus can be readily taken up from soil particles, which leads to the formation of Pi-free areas around the roots. The extraradical hyphae of mycorrhizal roots stretch beyond these P-depleted regions, allowing the absorption of bioavailable Pi that is otherwise inaccessible to plants.

AM fungi are recognized as some of the most efficient soil microorganisms for P absorption, outperforming non-mycorrhizal (NM) roots. Smith and Read (2008) [56] demonstrated that in soils with low P availability, AM-infected roots absorb and store more P compared to the roots of non-mycorrhizal plants. The mycorrhizal relationship improves root biomass, increases root length, and enhances the uptake of P, Fe, and zinc (Zn) in wheat plants (Ingraffia *et al*. 2019) [24].

1.2 Nitrogen (N) and other macronutrients

In trees and specific crops, nitrogen (N) is the main factor that can limit growth. Enhanced nitrogen nutrition has also been recorded with arbuscular mycorrhizal fungi (AMF) associations in various studies (Courty *et al*., 2015; Koegel *et al*., 2017) [17, 30]. The absorption of nitrogen by AMF can occur in both organic forms (like amino acids) and inorganic forms (such as ammonium and nitrate ions) (Leigh *et al*., 2009) [32]. AMF can facilitate nitrogen uptake in plants directly through extraradical mycelial absorption and intraradical mycelial transport, or they can indirectly affect nitrogen acquisition by modifying root characteristics (specific root area, root branching intensity, root tissue density) and regulating the expression of nitrogen-related transport proteins. Numerous studies have indicated that AMF can also transfer nitrogen to neighboring plants (Battini *et al*., 2017; Turrini *et al*., 2018) [8, 59].

1.3 Micronutrients and beneficial elements (Zn, Cu, Fe, etc.)

Arbuscular mycorrhizal fungi (AMF) can significantly improve the absorption of micronutrients, particularly copper (Cu), zinc (Zn), and iron (Fe), which often have limited bioavailability due to their propensity to form insoluble complexes or their uneven distribution in the soil (Allen *et al*., 2009; Campos *et al*., 2018) [5, 14]. Additionally, AMF can facilitate the mobilization and solubilization of these micronutrients by releasing organic acids and enzymes, which convert these elements into forms that are more accessible to plants (Plassard *et al*., 2010) [44]. By regulating the levels of micronutrients in plant tissues, these fungi provide a buffering system that reduces the risk of deficiency or toxicity (Mahmud *et al*., 2022) [36]. As a result, AMF are essential for enhancing nutrient uptake in plants, converting less accessible micronutrients into bioavailable forms, and protecting against nutrient imbalances.

Rajapitamahuni *et al*. (2023) [46] discovered that the relationship between plants and AMF is vital for maintaining iron balance by modifying root structure and generating root exudates that enhance iron solubility. The symbiotic relationship with AMF increases the expression of high-affinity iron transporters in plant roots, aiding in the uptake of iron from the soil. Furthermore, AMF can boost the production of iron-chelating substances, such as phytosiderophores, within plant roots. These strategies lead to improved iron absorption and distribution throughout the plant, resulting in better growth and nutrient uptake. Interactions between bacteria and AMF in endophytic environments and the hyphosphere are also critical to the dynamics of iron.

2. Enhanced Disease Resistance

Mycorrhizal fungi improve plant resistance to diseases through various mechanisms. One key mechanism involves enhancing plant nutrition, especially phosphorus absorption, which bolsters the overall health of the plant and its capacity to fend off pathogens. Additionally, mycorrhizal associations trigger systemic resistance in plants, akin to the systemic acquired resistance (SAR) initiated by pathogen attacks (Patel and Thakur, 2023) [50].

Systemic resistance (SR) is activated in host plants when arbuscular mycorrhizal fungi (AMF) colonize them, leading to the activation of defense-related genes (DRGs) linked to salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) signaling pathways that are crucial for resisting pathogens (Stratton *et al*., 2022) [57]. AMF also modulate the expression of pathogenesis-related proteins and boost the activity of antioxidant enzymes, effectively minimizing oxidative stress during pathogen assaults. Furthermore, AMF modify root exudation patterns, which indirectly hinder pathogens by reshaping the rhizosphere microbiome (Schouteden *et al*., 2015; Afridi *et al*., 2024) [2, 54].

Another important mechanism is the physical barrier established by the mycorrhizal hyphae. This extensive network of hyphae can serve as a physical obstruction against pathogen invasion and colonization. Moreover, mycorrhizal fungi compete with pathogens for space and nutrients in the rhizosphere, thereby limiting pathogen establishment and growth. These fungi also alter the composition of the microbial community in the rhizosphere, fostering beneficial microorganisms capable of suppressing pathogens. Such changes in the microbial community can bolster the plant's disease resistance through mechanisms like microbial antagonism, competition, and the production of antimicrobial substances by advantageous microbes (Patel and Thakur, 2023) [50]. Research by Pu *et al*. (2022) demonstrated that mycorrhizal colonization improved the resistance of *Salvia miltiorrhiza Bunge* (known as Danshen in Chinese) against Fusarium wilt caused by *Fusarium oxysporum.*

3. Increases Stress tolerance

Mycorrhizal fungi play an essential role in enhancing plant resilience against both abiotic and biotic stresses. Arbuscular mycorrhizal fungi (AMF) enable host plants to thrive in challenging conditions by facilitating a complex series of interactions between the plant and the fungus, which leads to improved photosynthesis and other traits related to gas exchange (Birhane *et al*., 2012) [11], along with enhanced nutrient and water absorption. Multiple studies have documented increased resistance to various abiotic and biotic stresses, such as drought, salinity, herbivory, temperature, metal toxicity, and diseases as a result of this fungal relationship (Rodriguez *et al*., 2008; Ahanger *et al*., 2014; Salam *et al*., 2017) [3, 49, 52].

3.1 Abiotic Stress Tolerance

Arbuscular mycorrhizal fungi (AMF) establish a symbiotic relationship with most terrestrial plants, assisting them in handling environmental stresses such as drought, salinity, extreme temperatures, and heavy metal toxicity. Some of the mechanisms include:

- Enhanced uptake of water and nutrients, particularly phosphorus, even when soil moisture or nutrient levels are low (Wahab *et al*., 2022) [61].
- Regulation of plant hormones such as ABA (abscisic acid), IAA (indole-3-acetic acid), and cytokinins, which play critical roles in stress responses and root development (Begum *et al*., 2019) [9].
- Improvement of the antioxidant system through increased activity of enzymes like superoxide dismutase and peroxidases, mitigating oxidative damage from stress factors (Bahadur *et al*., 2019) [6].
- Adjustment of osmotic balance and photosynthetic processes, resulting in enhanced plant growth and yield during unfavorable conditions (Wahab *et al*., 2022) [61].
- Specific adaptations, such as increased drought resistance, arise from elevated ABA levels induced by AMF, which lead to better stomatal regulation and minimized water loss (Tang *et al*., 2022) [58].

3.2 Biotic Stress Tolerance

- AMF also significantly contribute to the ability of plants to endure biotic stresses like pathogen assaults and pest infestations by:
- Reinforcing plant cell walls and stimulating the production of defensive secondary metabolites (Farhaoui *et al*., 2025) [1].
- Competing with root pathogens for space and nutrients, which effectively lowers the incidence of diseases in plants (Farhaoui *et al*., 2025) [1].
- Modulating plant immune responses, resulting in systemic resistance and increased tolerance to various soil-borne diseases (Farhaoui *et al*., 2025) [1].

Role of AMF in Improving Soil Health

The primary global threats to soil functionality include soil erosion, the loss of soil organic carbon, excessive input usage, and nutrient imbalance (Montanarella *et al*., 2016) [39]. The worldwide decline in soil fertility has escalated due to unsustainable land management practices like overgrazing, bush burning, continuous crop cultivation, and specific tillage methods. Nevertheless, the application of Arbuscular Mycorrhizal Fungi (AMFs) has been recognized as a sustainable strategy to enhance soil health (Fall *et al*., 2022) [21].

AMFs not only influence plant growth and yield but have also been shown to enhance various soil properties, including soil aggregation and structure, nutrient availability, water retention, microbial activity, and the cycling of nitrogen, carbon, and phosphorus (Sadhana, 2014; Jamiołkowska *et al*., 2018; Parihar *et al*., 2020) [25, 42, 51].

1. Improved soil aggregation and physical structure

Arbuscular Mycorrhizae Fungi positively influence the structure of soil. The mycelia of AMF exist in large quantities within soils. These hyphae possess the ability to form stable soil aggregates. Mycorrhizal fungi serve as a long-lasting agent for binding soil through the generation of a glycoprotein (glomalin) by the extramatrical mycelia (Singh *et al*., 2020) [55]. This glomalin is hydrophobic, thermo-tolerant, and resistant to high soil temperatures. The hydrophobic nature of glomalin allows soil aggregates to resist water, with production peaking in aging mycelia. The glycoprotein is gradually biodegradable by soil bacteria and fungi. The primary role of glomalin is to stabilize soil aggregates (Mubekaphi, 2019) [40], functioning as an adhesive that connects smaller soil aggregates (less than 250 μm in diameter) to form more stable larger aggregates. These macro-aggregates facilitate improved water infiltration, minimize surface runoff, mitigate soil erosion, decrease the loss of nutrients and organic matter, enhance gas exchange, improve the retention of water and minerals, particularly potassium, and consequently boost crop yields (Parihar *et al*., 2020) [42]. Moreover, the mycelial network consistently rejuvenates itself, and the remnants of dead mycelia help maintain soil structure until they decompose (Gianinazzi *et al*., 2010). These dead mycelia also contribute to the reserves of organic matter and act as physical binders in soil aggregation. All these processes help lessen the risk of soil compaction and foster soil fertility (Norton *et al*., 2020) [41]. It can be stated that AMFs enhance soil structure through their chemical and biophysical processes, including enmeshment and alignment. An improved soil structure leads to better aeration, water infiltration, and root penetration, resulting in healthier plants and more sustainable farming practices.

2. Increased Soil carbon (C) cycle and sequestration

Arbuscular Mycorrhizae Fungi have a crucial function in the global carbon cycle. The hyphae of AMF facilitate the movement of carbon into the soil and serve as an important connection in the terrestrial carbon cycle. In fact, AMF effectively enhances carbon sequestration by relocating carbon away from areas of high respiratory activity near the roots and into soil aggregates (Zhu and Miller, 2003) [67]. Research has shown that mycorrhizal roots generate a demand for carbon. As atmospheric CO_2 levels rise, the transfer of carbon from plants to AMF also increases, encouraging the growth of AMF (Drigo *et al*., 2010) [19]. This need for carbon comes from the host plant's carbon fixed during photosynthesis (Parihar *et al*., 2020) [42]. Furthermore, extramatrical hyphae of AMF account for 20–80% of soil microbial biomass, which includes 15% of soil organic carbon (Leake *et al*., 2004) [31]. As previously mentioned, AMF is essential for the creation and preservation of soil aggregates by producing Glomalin. This glomalin aids in safeguarding organic matter from microbial breakdown, enhances the hydrophobic properties and stability of macro-aggregations, thereby regulating soil carbon loss and boosting soil carbon reserves (Wilson *et al*., 2009) [64].

3. Reduced Soil Erosion and Nutrient Leaching

AMF can lead to positive modifications in soil structure that enhance its physical, chemical, and biological characteristics. In addition to boosting plant growth and promoting root system development, AMF also safeguard the soil from wind and water erosion (Gutjahr and Paszkowski, 2013) [22]. AMF create a network of hyphae that interacts with plant roots, which significantly contributes to the reduction of soil erosion.

Nutrient leaching is unfavorable as it contaminates both surface and groundwater while decreasing soil fertility levels. AMF help retain nutrients in the soil by minimizing their loss through leaching, thus reducing the risk of groundwater contamination (Chen *et al*., 2018) [16]. AMF positively influence the soil's capacity to hold water and its nutrient availability. These advantages of AMF are especially noticeable in arid regions where low soil fertility and erosion pose significant challenges for agricultural productivity. Cultivating crops that form associations with AMF can help address these issues, leading to better crop yields by enhancing soil quality and reducing nutrient leaching (Cavagnaro *et al*., 2015) [15]. Nitrate nitrogen is frequently lost through leaching beyond the rhizosphere, but it is retained by AMF hyphae, making it accessible for plant use (Cameron *et al*., 2013) [13].

4. Enhanced microbial communities

Arbuscular mycorrhizal fungi affect the composition, variety, and activity of microbial populations in the soil through either competitive or collaborative mechanisms. All these activities of AMFs play a role in enhancing soil health. The widespread network of AMFs fosters a diverse and dynamic microbial community in the soil, which is essential for nutrient cycling (Fall *et al*., 2022) [21].

Microbial processes in the soil enhance its fertility through the collaborative efforts of microorganisms, as well as competition and parasitism. AMFs engage with various microorganisms in the soil to further boost fertility. Research has shown that AMF secretions impact the structure and functioning of microbial communities in the rhizosphere (Veresoglou and Rillig, 2012) [60].

Numerous soil microorganisms work in harmony with AMFs, aiding in plant growth and defense. These beneficial interactions cover areas such as nutrient uptake, biological control of root pathogens, increasing plant resilience to environmental stresses, and enhancing soil fertility. AMF communities shape the physical and chemical conditions within the rhizosphere and regulate different microbial interactions in the soil (Alimi *et al*., 2021) [4].

Mycorrhization has a direct impact on both the quantity and quality of root exudates, which in turn affects the microbial composition in the rhizosphere (Li *et al*., 2023) [35].

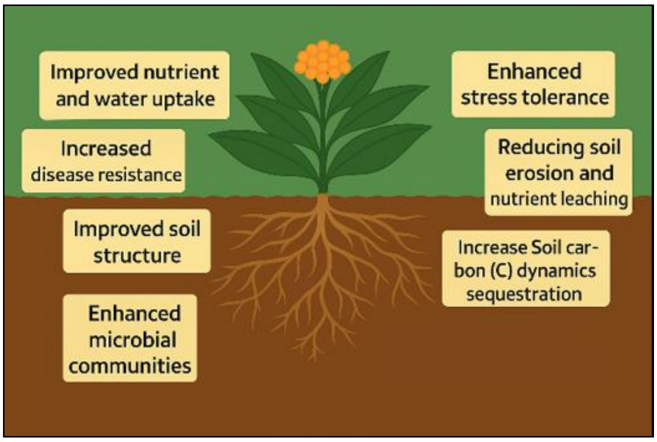

Fig 1: Role of Mycorrhizae in plant growth and soil health

Mycorrhizae in Sustainable Agriculture

Sustainable agriculture focuses on maintaining long-term productivity, promoting environmental welfare, and ensuring economic sustainability without jeopardizing the ability of future generations to satisfy their needs. In recent years, the incorporation of beneficial soil microorganisms has attracted attention as a green alternative to chemical fertilizers. Notably, the symbiotic relationship with arbuscular mycorrhizal fungi (AMF) is essential for nutrient absorption, soil structure, resilience to stress, carbon capture, and ecosystem stability, making it integral to sustainable farming practices that provide an environmentally friendly route to enhance productivity while safeguarding ecological integrity.

AMF significantly aids in converting nutrients into forms that are easily accessible to plants, which is especially beneficial when nutrients are scarce. The growth of AMF contributes to improved soil quality and stability, ultimately facilitating superior plant development (Diaz-Urbano *et al*., 2023) [18].

Utilizing the inherent qualities of soil can lessen the dependency on costly chemical inputs such as fertilizers and pesticides, which also harm the environment. A decrease in chemical application will not only reduce expenses but also lessen environmental harm. Minimizing water and fuel consumption can lead to reduced costs and increased agricultural efficiency. Preventing ecological contamination protects ecosystems, thereby supporting long-term sustainability in farming (Liu *et al*., 2023) [35]. As an effective bioinoculant in sustainable agriculture, AMF facilitates higher food production while conserving the ecological system and maintaining environmental sustainability (Kalamulla *et al*., 2022) [26]. The implementation and oversight of effective management systems ensure that soil remains favorable for crop cultivation while encouraging beneficial soil microbes.

By enhancing plant genetics and promoting positive soil interactions, farmers can boost crop yields, diminish reliance on external inputs, and reduce environmental impacts. Thus, recognizing the historical, environmental, and ecological importance of AMF can yield valuable insights for their potential use and advantageous roles in contemporary agricultural systems and ecosystem restoration. Leveraging these beneficial plant relationships can lead to sustainable land management practices and improve soil health for future generations. In summary, incorporating mycorrhizal associations into farming methods exemplifies a sustainable approach that boosts soil health, mitigates environmental effects, and enhances crop output. These practices are crucial for ensuring enduring agricultural sustainability and resilience (Samanta *et al*., 2025) [53].

Conclusion

Mycorrhizal fungi are essential for plant development as they improve the absorption of nutrients and water, enhance soil structure, and boost plants' resistance to diseases and environmental challenges. Incorporating them into farming practices presents several advantages, such as decreasing fertilizer usage, enhancing crop quality, improving soil health, and promoting environmental sustainability. As we look for sustainable approaches to global food production, the significance of mycorrhizae in agriculture will grow. By gaining insight into and utilizing mycorrhizal associations, farmers can enhance crop yield and sustainability, aiding in the establishment of a more resilient agricultural system. Future advancements, including improved inoculation methods and their integration into sustainable practices, underline the potential of mycorrhizae to transform agriculture. Real-world applications and case studies in India provide persuasive evidence of their effectiveness, reinforcing the importance of mycorrhizae in achieving sustainable and productive agricultural systems.

References

1. Farhaoui A, Taoussi M, Laasli SE, Legrifi I, El Mazouni N, Meddich A, *et al*. Arbuscular mycorrhizal fungi and their role in plant disease control: A state-of-the-art. The Microbe,2025:8:100438. https://doi.org/10.1016/j.microb.2025.100438
2. Afridi MS, Kumar A, Javed MA, Dubey A, De Medeiros FHV, Santoyo G. Harnessing root exudates for plant microbiome engineering and stress resistance in plants. Microbiol. Res.,2024:279:127564. https://doi.org/10.1016/j.micres.2023.127564
3. Ahanger MA, Tyagi SR, Wani MR, Ahmad P. Drought tolerance: role of organic osmolytes, growth regulators, and mineral nutrients. Physiological mechanisms and adaptation strategies in plants under changing environment,2014:1:25–55. https://doi.org/10.1007/978-1-4614-8591-9_2
4. Alimi A, Adeleke R, Moteetee A. Soil environmental factors shape the rhizosphere arbuscular mycorrhizal fungal communities in South African indigenous legumes (Fabaceae). Biodivers. J. Biol. Divers.,2021:22:2466–2476. https://doi.org/10.13057/biodiv/d220503
5. Allen JW, Shachar-Hill Y. Sulfur transfer through an arbuscular mycorrhiza. Plant Physiol.,2009:149:549–560.
6. Bahadur A, Batool A, Nasir F, Jiang S, Mingsen Q, Zhang Q, *et al*. Mechanistic Insights into Arbuscular Mycorrhizal Fungi-Mediated Drought Stress Tolerance in Plants. International Journal of Molecular Sciences,2019:20:4199. https://doi.org/10.3390/ijms20174199

7. Balliu A, Sallaku G, Rewald B. AMF inoculation enhances growth and improves the nutrient uptake rates of transplanted, salt-stressed tomato seedlings. Sustainability,2015:7:15967–15981.
8. Battini F, Grønlund M, Agnolucci M, Giovannetti M, Jakobsen I. Facilitation of phosphorus uptake in maize plants by mycorrhizosphere bacteria. Sci. Rep.,2017:7:4686.
9. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, *et al*. Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. Frontiers in plant science,2019:10:1068.
10. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, *et al*. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. Frontiers in Plant Science,2019:10:466052. https://doi.org/10.3389/fpls.2019.01068
11. Birhane E, Sterck F, Fetene M, Bongers F, Kuyper T. Arbuscular mycorrhizal fungi enhance photosynthesis, water use efficiency, and growth of frankincense seedlings under pulsed water availability conditions. Oecologia,2012:169:895–904. https://doi.org/10.1007/s00442-012-2258-3
12. Cabral C, Ravnskov S, Tringovska I, Wollenweber B. Arbuscular mycorrhizal fungi modify nutrient allocation and composition in wheat (*Triticum aestivum* L.) subjected to heat-stress. Plant and Soil,2016:408:385-399.
13. Cameron KC, Di HJ, Moir JL. Nitrogen losses from the soil/plant system: A review. Ann. Appl. Biol.,2013:162:145–173.
14. Campos C, Carvalho M, Brigido C, Goss MJ, Nobre T. Symbiosis Specificity of the Preceding Host Plant Can Dominate but Not Obliterate the Association Between Wheat and Its Arbuscular Mycorrhizal Fungal Partners. Front. Microbiol.,2018:9:2920.
15. Cavagnaro TR, Bender SF, Asghari HR, van der Heijden MGA. The role of arbuscular mycorrhizas in reducing soil nutrient loss. Trends Plant Sci.,2015:20:283–290.
16. Chen ECH, Morin E, Beaudet D, Noel J, Yildirir G, Ndikumana S, *et al*. High intraspecific genome diversity in the model arbuscular mycorrhizal symbiont *Rhizophagus irregularis*. New Phytol.,2018:220:1161–1171.
17. Courty PE, Smith P, Koegel S, Redecker D, Wipf D. Inorganic nitrogen uptake and transport in beneficial plant root-microbe interactions. Crit. Rev. Plant Sci.,2015:34:4–16.
18. Díaz-Urbano M, Goicoechea N, Velasco P, Poveda J. Development of agricultural bio-inoculants based on mycorrhizal fungi and endophytic filamentous fungi: co-inoculants for improve plant-physiological responses in sustainable agriculture. Biol Control.,2023:182:105223. https://doi.org/10.1016/j.biocontrol.2023.105223
19. Drigo B, Pijl AS, Duyts H, Kielak AM, Gamper HA, Houtekamer MJ, *et al*. Shifting carbon flow from roots into associated microbial communities in response to elevated atmospheric CO2. Proc. Natl. Acad. Sci. U.S.A.,2010:107:10938–10942. https://doi.org/10.1073/pnas.0912421107
20. Etesami H, Jeong BR, Glick BR. Contribution of Arbuscular Mycorrhizal Fungi, Phosphate–Solubilizing Bacteria, and Silicon to P Uptake by Plant. Frontiers in Plant Science,2021:12:1355. https://doi.org/10.3389/fpls.2021.699618
21. Fall AF, Nakabonge G, Ssekandi J, Founoune-Mboup H, Apori SO, Ndiaye A, *et al*. Roles of Arbuscular Mycorrhizal Fungi on Soil Fertility: Contribution in the Improvement of Physical, Chemical, and Biological Properties of the Soil. Frontiers in Fungal Biology,2022:3:723892. https://doi.org/10.3389/ffunb.2022.723892
22. Gutjahr C, Paszkowski U. Multiple control levels of root system remodeling in arbuscular mycorrhizal symbiosis. Front. Plant Sci.,2013:4:204.
23. Haselwandter K. Structure and function of siderophores produced by mycorrhizal fungi. Mineral. Mag.,2008:72:61–64.
24. Ingraffia R, Amato G, Frenda AS, Giambalvo D. Impacts of arbuscular mycorrhizal fungi on nutrient uptake, N2 fixation, N transfer, and growth in a wheat/faba bean intercropping system. PloS one,2019:14:e0213672.
25. Jamiołkowska A, Ksiezniak A, Gałazka A, Hetman B, Kopacki M, Skwaryło-Bednarz B. Impact of abiotic factors on development of the community of arbuscular mycorrhizal fungi in the soil: a review. Int. Agrophys.,2018:32:133. https://doi.org/10.1515/intag-2016-0090
26. Kalamulla R, Karunarathna SC, Tibpromma S, Galappaththi MCA, Suwannarach N, Stephenson SL, *et al*. Arbuscular Mycorrhizal Fungi in Sustainable Agriculture. Sustainability,2022:14:12250. https://doi.org/10.3390/su141912250
27. Kayama M, Yamanaka T. Growth characteristics of ectomycorrhizal seedlings of *Quercus glauca*, *Quercus salicina*, and *Castanopsis cuspidata* planted on acidic soil. Trees Struct. Funct.,2014:28:569–583.
28. Khaliq A, Perveen S, Alamer KH, Rafique Z, Alsudays IM, Althobaiti AT, *et al*. Arbuscular Mycorrhizal Fungi Symbiosis to Enhance Plant–Soil Interaction. Sustainability,2021:14:7840. https://doi.org/10.3390/su14137840
29. Khan Y, Shah S, Hui T. The Roles of Arbuscular Mycorrhizal Fungi in Influencing Plant Nutrients, Photosynthesis, and Metabolites of Cereal Crops—A Review. Agronomy,2022:12:2191. https://doi.org/10.3390/agronomy12092191
30. Koegel S, Mieulet D, Baday S, Chatagnier O, Lehmann MF, Wiemken A, *et al*. Phylogenetic, structural, and functional characterization of AMT3;1, an ammonium transporter induced by mycorrhization among model grasses. Mycorrhiza,2017:27:695–708.
31. Leake J, Johnson D, Donnelly D, Muckle G, Boddy L, Read D. Networks of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. Can. J. Bot.,2004:82:1016–1045. https://doi.org/10.1139/b04-060
32. Leigh J, Hodge A, Fitter AH. Arbuscular mycorrhizal fungi can transfer substantial amounts of nitrogen to their host plant from organic material. New Phytol.,2009:181:199–207.

33. Li W, Hu XY, Zhu CS, Guo SX, Li M. Control effect of root exudates from mycorrhizal watermelon seedlings on *Fusarium* wilt and the bacterial community in continuously cropped soil. Frontiers in Plant Science,2023:14.
34. Li X, Zeng R, Liao H. Improving crop nutrient efficiency through root architecture modifications. J. Integr. Plant Biol.,2016:58:193–202.
35. Liu Y, Lu J, Cui L, Tang Z, Ci D, Zou X, *et al*. The multifaceted roles of arbuscular mycorrhizal fungi in peanut responses to salt, drought, and cold stress. BMC Plant Biol.,2023:23:36. https://doi.org/10.1186/s12870-023-04053-w
36. Mahmud MS, Chong KP. Effects of Liming on Soil Properties and Its Roles in Increasing the Productivity and Profitability of the Oil Palm Industry in Malaysia. Agriculture,2022:12:322.
37. Milton M, Kumar S, Singh A, Kumar V, Bisarya D. Mycorrhizae and their importance in agriculture. 8,2021:201-206.
38. Mohammad Imad khrieba. Mycorrhizae's Role in Plant Nutrition and Protection from Pathogens. Curr Inves Agri Curr Res,2019:8:1045. https://doi.org/10.32474/CIACR.2019.08.000277
39. Montanarella L, Pennock DJ, McKenzie N, Badraoui M, Chude V, Baptista I, *et al*. World's soils are under threat. Soil,2016:2:79-82. https://doi.org/10.5194/soil-2-79-2016
40. Mubekaphi C. Soil organic carbon, glomalin related soil protein and related physical properties after 15 years of different management practices in a subtropical region of South Africa. Doctoral thesis, 2019.
41. Norton JM, Pellegrino E, Gamper HA, Ciccolini V, Ercoli L. Forage rotations conserve diversity of arbuscular mycorrhizal fungi and soil fertility. Front. Microbiol.,2020:10:2969. https://doi.org/10.3389/fmicb.2019.02969
42. Parihar M, Rakshit A, Meena VS, Gupta VK, Rana K, Choudhary M, *et al*. The potential of arbuscular mycorrhizal fungi in C cycling: a review. Arch. Microbiol.,2020:202:581-1596. https://doi.org/10.1007/s00203-020-01915-x
43. Paul G, Hodge A, Goodlass G, Bending G. Arbuscular mycorrhizal fungi and organic farming. Agriculture, Ecosystems & Environment,2006:113:17-35. https://doi.org/10.1016/j.agee.2005.09.009
44. Plassard C, Dell B. Phosphorus nutrition of mycorrhizal trees. Tree Physiol.,2010:30:1129-1139.
45. Pu C, Ge Y, Yang G, Zheng H, Guan W, Chao Z, *et al*. Arbuscular mycorrhizal fungi enhance disease resistance of *Salvia miltiorrhiza* to *Fusarium* wilt. Frontiers in Plant Science,2022:13:975558. https://doi.org/10.3389/fpls.2022.975558
46. Rajapitamahuni S, Kang BR, Lee TK. Exploring the Roles of Arbuscular Mycorrhizal Fungi in Plant-Iron Homeostasis. Agriculture,2023:13:1918. https://doi.org/10.3390/agriculture13101918
47. Rajendra Kumar RK, Meena Y, Tak P, Kumar Chachaiya P. Fungi Boost Up Plant Growth by ImprovingNutrient Uptake: A Review. Environment and Ecology,2024:42:1364—1368. https://doi.org/10.60151/envec/OVGG9937
48. Rastogi M, Verma S, Reeturaj J. Role of Mycorrhizae in Nutrient Uptake and Soil Health in Agriculture. Advances in soil fertility and nutrient management,2024:59-77.
49. Rodriguez RJ, Henson J, Van Volkenburgh E, Hoy M, Wright L, Beckwith F, *et al*. Stress tolerance in plants via habitat-adapted symbiosis. Int. Soc. Microb. Ecol.,2008:2:404-416. https://doi.org/10.1038/ismej.2007.106
50. Rohan Patel, Bhargavi Thakur. Impact of mycorrhizal fungi on plant disease resistance. International Journal of Horticulture and Food Science,2023:5:110-111.
51. Sadhana B. Arbuscular Mycorrhizal Fungi (AMF) as a biofertilizer-a review. Int. J. Curr. Microbiol. Appl. Sci,2014:3:384-400.
52. Salam EA, Alatar A, El-Sheikh MA. Inoculation with arbuscular mycorrhizal fungi alleviates harmful effects of drought stress on damask rose. Saudi J. Biol. Sci.,2017:25:1772-1780. https://doi.org/10.1016/j.sjbs.2017.10.015
53. Samanta I, Ghosh K, Saikia R, Savita, Maity PJ, Chowdhary G. Arbuscular mycorrhizal fungi - a natural tool to impart abiotic stress tolerance in plants. Plant Signaling & Behavior,2025:20. https://doi.org/10.1080/15592324.2025.2525843
54. Schouteden N, De Waele D, Panis B, Vos CM. Arbuscular mycorrhizal fungi for the biocontrol of plant-parasitic nematodes: a review of the mechanisms involved. Front. Microbiol.,2015:6:1280. https://doi.org/10.3389/fmicb.2015.01280
55. Singh AK, Zhu X, Chen C, Wu J, Yang B, Zakari S, *et al*. The role of glomalin in mitigation of multiple soil degradation problems. Crit. Rev. Environ. Sci. Technol.,2020:1-35. https://doi.org/10.1080/10643389.2020.1862561
56. Smith S, Read D. Mycorrhiza symbiosis. 3rd ed,2008.
57. Stratton CA, Ray S, Bradley BA, Kaye JP, Ali JG, Murrell EG. Nutrition vs association: plant defenses are altered by arbuscular mycorrhizal fungi association not by nutritional provisioning alone. BMC Plant Biol.,2022:22:400. https://doi.org/10.1186/s12870-022-03795-3
58. Tang H, Hassan MU, Feng L, Nawaz M, Shah AN, Qari SH, *et al*. The Critical Role of Arbuscular Mycorrhizal Fungi to Improve Drought Tolerance and Nitrogen Use Efficiency in Crops. Frontiers in Plant Science,2022:13:919166. https://doi.org/10.3389/fpls.2022.919166
59. Turrini A, Bedini A, Loor MB, Santini G, Sbrana C, Giovannetti M, *et al*. Local diversity of native arbuscular mycorrhizal symbionts differentially affects growth and nutrition of three crop plant species. Biol. Fertil. Soils,2018:54:203-217.
60. Veresoglou SD, Rillig MC. Suppression of fungal and nematode plant pathogens through arbuscular mycorrhizal fungi. Biol. Lett.,2012:8:214-217. https://doi.org/10.1098/rsbl.2011.0874
61. Wahab A, Muhammad M, Munir A, Abdi G, Zaman W, Ayaz A, *et al*. Role of Arbuscular Mycorrhizal Fungi in Regulating Growth, Enhancing Productivity, and Potentially Influencing Ecosystems under Abiotic and Biotic Stresses. Plants,2022:12:3102. https://doi.org/10.3390/plants12173102
62. Wang H, Wang Y, Cheng X, *et al*. Arbuscular mycorrhizal fungi colonization facilitates nitrogen uptake in cotton under nitrogen - reduction condition.

BMC Plant Biol,2025:25:1129. https://doi.org/10.1186/s12870-025-07204-3

63. Weng W, Yan J, Zhou M, Yao X, Gao A, Ma C, *et al*. Roles of Arbuscular mycorrhizal Fungi as a Biocontrol Agent in the Control of Plant Diseases. Microorganisms,2022:10:1266. https://doi.org/10.3390/microorganisms10071266
64. Wilson GW, Rice CW, Rillig MC, Springer A, Hartnett DC. Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: Results from long term field experiments. Ecol. Lett.,2009:12:452-461. https://doi.org/10.1111/j.1461-0248.2009.01303.x
65. Winkelmann G. A Search for Glomuferrin: A potential siderophore of arbuscular mycorrhizal fungi of the genus *Glomus*. BioMetals,2017:30:559-564.
66. Yang S, Li F, Malhi SS, Wang P, Suo D, Wang J. Long-term fertilization effects on crop yield and nitrate nitrogen accumulation in soil in northwestern China. Agron. J.,2004:96:1039-1049.
67. Zhu YG, Miller RM. Carbon cycling by arbuscular mycorrhizal fungi in soil-plant systems. Trends Plant Sci.,2003:8:407-409. https://doi.org/10.1016/S1360-1385(03)00184-5