International Journal of Botany Studies
www.botanyjournals.com
ISSN: 2455-541X
Received: 10-09-2025, Accepted: 09-10-2025, Published: 25-10-2025
Volume 10, Issue 10, 2025, Page No. 65-68

Current understanding of the role of Arbuscular Mycorrhizal fungi in agriculture and forestry

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Abstract
Arbuscular mycorrhizal fungi (AMF) are ancient, widespread symbionts that form associations with nearly 80% of terrestrial plant species, including most crops and trees. Advances in molecular biology, genomics and ecology have expanded our understanding of how AMF enhance plant growth, nutrient uptake and tolerance to stress. These fungi also improve soil structure, enhance carbon sequestration and interact synergistically with beneficial microbes. This makes them vital components of sustainable agriculture and forest ecosystems. However, many challenges persist, like context-dependent responses and the lack of standardised inoculum production. This review synthesises recent findings on the physiological, molecular and ecological roles of AMF in agriculture and forestry and highlights emerging trends in research, commercialisation and ecological restoration.

Keywords: Arbuscular mycorrhizal fungi, sustainable agriculture, soil health, symbiosis, forest restoration

Introduction
Arbuscular mycorrhizal fungi (AMF) are among the most ancient plant-microbe associations. The evidence of their existence dates back to 400 million years (Humphreys *et al*., 2010) [13]. AMF belong to the phylum *Glomeromycota* and form mutualistic relationships with the roots of higher plants. AMF provides phosphorus, nitrogen, sulfur and micronutrients in exchange for photosynthetically derived carbon. This symbiosis enhances plant productivity, soil fertility and ecosystem resilience (Martin & van der Heijden, 2024) [19].

In recent times, there has been a growing concern over soil degradation and excessive dependence on synthetic fertilisers. AMF have gained attention as biological tools for sustainable agriculture and restoration of degraded ecosystems (Chen *et al*., 2018; Kalamulla *et al*., 2022) [8, 16]. AMF have coevolved with plants since early terrestrial colonization. This has equipped them with physiological and molecular mechanisms to alleviate both biotic and abiotic stress, maintain soil structure and foster beneficial ecological interactions within the rhizosphere (Kalamulla *et al*., 2022) [16]. Recent progress in genomics, transcriptomics and metabolomics has revealed new insights into AMF-mediated carbon-nutrient coupling, soil aggregation and greenhouse gas mitigation (Shukla *et al*., 2025) [28]. Their crucial contribution to forest regeneration and carbon cycling underscores their ecological importance (Arévalo *et al*., 2025) [1].

This review integrates current findings to present a comprehensive understanding of AMF functions and their potential in agriculture and forestry.

Mechanisms and Functional Roles of AMF

1. Symbiotic development and nutrient exchange
AMF-plant interactions begin with molecular signalling. Root-secreted strigolactones stimulate AMF hyphal branching, while fungal lipo-chitooligosaccharides (Myc-LCOs) induce plant symbiotic gene activation (Basu *et al*., 2017) [4]. Calcium spiking and the activation of genes such as DMI3, RAM1, and PT11 facilitate arbuscule formation. This creates specialized sites for bidirectional nutrient exchange.

Recent studies reveal that AMF modulate phosphate and ammonium transporter genes in plants, such as OsPT11 in rice, which mediates mycorrhizal nutrient uptake while downregulating direct root transporters like OsPT2 and OsPT6. This regulatory shift underscores the metabolic integration of AMF in plant nutrient acquisition (Wang *et al*., 2017; Issam *et al*., 2022) [33, 15].

Through this symbiosis, AMF deliver phosphate, nitrogen and micronutrients to plants. In return, it receives carbohydrates and lipids (Martin & van der Heijden, 2024) [19]. The extraradical mycelium can extend beyond the nutrient depletion zone (up to 25 cm). As such, it can efficiently transport nutrients from otherwise inaccessible soil regions (Ortas & Rafique, 2017) [22]. Such molecular and physiological adaptations establish AMF as vital biotrophs. They are capable of reshaping plant root architecture and improving water and nutrient-use efficiency.

2. Influence on soil health and structure
AMF contribute significantly to soil aggregation. They do so through glomalin-related soil proteins (GRSPs). GRSPs act as natural binding agents, enhancing soil structure, water retention and carbon storage (Kalamulla *et al*., 2022) [16]. These glycoproteins stabilize microaggregates and improve soil fertility through carbon sequestration (Shukla *et al*., 2025) [28].

Recent evidence emphasizes that AMF-glomalin interactions are essential for maintaining soil stability even under heavy-metal stress. This contributes to improved soil resilience (Li *et al*., 2022) [17]. Their ability to influence physical, chemical and biological soil parameters establishes AMF as major soil health indicators (Fall *et al*., 2022) [11].

The hyphal network also enhances soil porosity and supports bacterial communities. This promotes nutrient cycling and microbial diversity (Mwampashi *et al*., 2024) [20]. Moreover, reduced tillage and low-disturbance agricultural practices help preserve AMF hyphal continuity.

This helps in promoting long-term soil structure and fertility (Bone *et al*., 2008) [6].

3. Interaction with the rhizosphere microbiome

AMF interact dynamically with rhizosphere microorganisms such as phosphate-solubilising and nitrogen-fixing bacteria. These interactions improve nutrient bioavailability and induce systemic resistance in plants (Boyno *et al*., 2025) [7]. Some studies have found that consortia comprising AMF, *Bacillus* and nitrogen-fixing bacteria enhance nutrient uptake and plant defence (Nanjundappa *et al*., 2019) [21]. This holds promise for developing microbial consortia for sustainable agriculture and soil health restoration.

AMF in Sustainable Agriculture

1. Nutrient acquisition and crop productivity

Numerous studies demonstrate AMF's ability to enhance phosphorus and micronutrient uptake. This helps in improving overall plant growth (Bhantana *et al*., 2021) [5]. A global meta-analysis reported yield increases of 30–40% in low-input systems following AMF inoculation (Mwampashi *et al*., 2024) [20].

AMF also enhance nitrogen fixation and nutrient transfer in cereal-legume intercropping systems, as seen in wheat–faba bean models. Here, AMF increased N_2 fixation and phosphorus uptake (Ingraffia *et al*., 2019) [14]. Co-inoculation with phosphate-solubilising bacteria (PSB) or rhizobacteria further enhances the efficiency of phosphorus uptake and reduces the need for synthetic fertilisers (Raklami *et al*., 2019) [24].

Morphological changes such as the formation of lateral roots, increased root hairs and improved root branching are well-documented outcomes of AMF inoculation under water or nutrient stress conditions (Liu *et al*., 2016) [18]. These changes collectively increase nutrient-use efficiency and productivity, especially in low-input systems.

2. Stress tolerance under drought, salinity and heavy metals

AMF improve plant resilience under drought by enhancing root hydraulic conductivity, osmotic balance and antioxidant enzyme activity (Wahab *et al*., 2023) [32]. Under salinity, AMF upregulate aquaporin and photosystem repair genes (RppsbA, RppsbD). This enhances osmolyte accumulation. As a result, there is an improved ionic homeostasis (Evelin *et al*., 2019; Sagar *et al*., 2021) [10, 26]. They also regulate plant hormones such as jasmonic acid, strigolactones and abscisic acid. Thus, AMF also influence stomatal conductance and photosynthetic efficiency (Kalamulla *et al*., 2022) [16].

In heavy-metal-contaminated soils, AMF immobilize metals within fungal tissues and glomalin matrices. This helps to reduce bioavailability and toxicity. This phytostabilisation mechanism significantly mitigates metal-induced oxidative stress (Riaz *et al*., 2021) [25]. Co-inoculation of AMF with *Bacillus* spp. further enhances plant tolerance to saline and toxic soils (Yadav *et al*., 2017) [34].

3. Biocontrol and induced systemic resistance

AMF induce plant defence mechanisms. They achieve this through different ways, like mycorrhiza-induced resistance (MIR), activating secondary metabolite synthesis and defence gene expression. Several studies have reported increased phenolic compound accumulation and reduced pathogen load in AMF-inoculated plants (Boyno *et al*., 2025; Umer *et al*., 2025) [7, 31]. This systemic resistance is regulated through jasmonic acid and salicylic acid pathways. These pathways enhance peroxidase, catalase and superoxide dismutase activity. *Rhizophagus intraradices* in rice upregulates *OsNPR1* and *OsAP2* genes. As a result, it provides enhanced resistance against pathogens even in pathogen-free environments (Pandey & Garg, 2017) [23].

Such properties make AMF valuable bioprotective agents for integrated pest and disease management in sustainable agriculture.

4. Carbon sequestration and greenhouse gas mitigation

AMF are vital contributors to soil carbon sequestration. Glomalin-related soil proteins and hyphal necromass contribute to stable soil carbon pools. This effectively reduces CO_2 and N_2O emissions (Shukla *et al*., 2025) [28]. Their involvement in nitrogen cycling further stabilises soil C:N ratios and supports long-term carbon balance (Martin & van der Heijden, 2024) [19].

5. Advances in inoculant technology and commercialisation

Advancements in AMF inoculum production include root-organ culture systems, liquid fermentation and bioreactor-based methods (Ghorui *et al*., 2025) [12]. Multi-strain formulations containing *Rhizophagus*, *Claroideoglomus* and *Funneliformis* species show improved adaptability across diverse soils.

Current research emphasizes developing site-specific bioinoculants that are tailored to local soils and crops (Diagne *et al*., 2020) [9]. Consortium inoculants combining AMF with rhizobia and PSB improve field performance and sustainability (Raklami *et al*., 2019) [24]. However, challenges remain in standardising AMF strain authentication, inoculum density and field-level efficacy.

AMF in Forestry and Restoration Ecology

AMF play a central role in forest regeneration, biodiversity maintenance and carbon cycling. Their inoculation enhances nutrient uptake and root development in forest species such as *Acacia*, *Shorea* and *Tectona* (Barea *et al*., 2011) [3]. Additionally, AMF contribute to seed germination and seedling establishment in degraded ecosystems. Mycorrhizal colonization improves soil aggregation, fertility and microbial diversity in tropical forests (Sulistiona, 2016; Tivane *et al*., 2022) [29, 30].

1. Forest soil fertility and regeneration

Although ectomycorrhizal fungi dominate temperate forests, AMF play a critical role in tropical and mixed systems (Chen *et al*., 2018; Arévalo *et al*., 2025) [8,1]. They enhance soil fertility, accelerate nutrient cycling and facilitate reforestation of degraded lands. Bibliometric analyses indicate a significant rise in research focusing on AMF in tropical restoration ecology.

2. Common mycorrhizal networks and ecosystem stability

Common mycorrhizal networks (CMNs) interconnect plant roots, facilitating nutrient and signal exchange (Martin & van der Heijden, 2024) [19]. These networks contribute to ecosystem stability, nutrient sharing and long-term forest resilience (Bahram *et al*., 2020; Selosse *et al*., 2023) [2, 27].

3. Integration into restoration practices

Integrating AMF into reforestation strategies through inoculation of nursery seedlings with native strains can significantly improve survival and biomass accumulation (Arévalo *et al*., 2025) [1]. Combining AMF with organic soil amendments enhances soil recovery and promotes early successional vegetation. Future restoration approaches may utilise multi-strain AMF consortia screened using omics-based methods for functional specificity (Martin & van der Heijden, 2024; Umer *et al*., 2025) [19, 31].

Conclusion

Arbuscular mycorrhizal fungi (AMF) are indispensable components of terrestrial ecosystems, offering multiple ecological and agricultural benefits. They enhance plant nutrition, soil structure, stress tolerance and biodiversity while contributing to carbon sequestration and sustainable ecosystem productivity.

As emphasized by recent studies, AMF form the backbone of sustainable agriculture through their roles in improving soil health, mitigating abiotic stresses and promoting nutrient-use efficiency (Kalamulla *et al*., 2022) [16]. Advances in genomics, molecular biology and biotechnology have transformed AMF from laboratory curiosities into practical agents for sustainable agriculture and ecological restoration.

Despite these advances, challenges remain. There are concerns related to field-level validation, inoculum standardisation and strain adaptability across soil types. Emerging directions include developing customised AMF consortia compatible with specific crops and environments. There is a necessity to utilise omics tools for strain selection and to integrate AMF inoculation into climate-resilient agriculture.

The integration of AMF with other beneficial microorganisms is a need of the hour. This needs to be coupled with long-term monitoring frameworks. This will pave the way for a more sustainable and resilient agricultural future and sustainable forestry.

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