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Arbuscular mycorrhizal fungi as drivers of sustainable crop production and soil health

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ABSTRACT

Modern farming relies heavily on chemical fertilizers to maintain high yields, yet this dependence is eroding soil quality, polluting waterways, and driving up input costs for farmers. A large part of the answer has been growing under our feet all along. Arbuscular mycorrhizal fungi (AMF) form partnerships with the roots of roughly four out of every five terrestrial plants, threading fine fungal filaments deep into the soil to fetch phosphorus, nitrogen, zinc, and water that plant roots alone cannot reach. In return, the plant shares carbohydrates produced by help of sunlight. This article examines how that ancient partnership works, why it matters for the future of farming, what recent research (2023–2025) has found about its use as a biofertilizers, and the practical hurdles that still stand between laboratory results and widespread field adoption. The fungi do other useful work of binding soil particles into stable aggregates, help crops tolerating drought and salty soils and also suppressing root rot disease. The article argues that AMF are an underused way to grow food without depleting the land.

Keywords: Arbuscular mycorrhizal fungi, Sustainable agriculture, Biofertilizers, Soil health, Nutrient uptake, Symbiosis, Stress tolerance

1. Introduction

Arbuscular mycorrhizal fungi (AMF) represent a widespread and ecologically important component of soil microbial communities, forming mutualistic symbiotic associations with the roots of most terrestrial plants. This plant-fungus association is considered to have originated more than 400 million years ago and has played an important role in the evolution and functioning of terrestrial ecosystems. During colonization, AMF penetrate the root cortex and form highly branched, tree like structures known as arbuscules within root cortical cells. These structures serve as major sites for bidirectional exchange, where the fungus supplies mineral nutrients acquired from the surrounding soil, while the host plant provides carbon compounds, primarily in the form of photosynthetically derived sugars, to support fungal growth and activity. The extensive extraradical hyphal network developed by AMF considerably expands the effective soil exploration capacity of the plant root system. Because fungal hyphae are considerably finer than roots and root hairs, they can penetrate soil micropores that are inaccessible to roots, thereby facilitating the acquisition of relatively immobile nutrients such as phosphorus, as well as nitrogen and micronutrients including zinc and copper. AMF hyphae can also contribute to plant water acquisition, particularly under conditions of limited soil moisture. Consequently, AMF colonization can improve plant nutrient acquisition, growth, and tolerance to environmental stresses, including drought. Interest in AMF has increased considerably in the context of sustainable agricultural intensification. Increasing fertilizer costs, concerns regarding nutrient losses and environmental degradation, and the growing frequency of drought and irregular rainfall have encouraged the development of biological approaches for improving nutrient-use efficiency and crop resilience. Recent reviews have highlighted AMF as a promising component of sustainable agricultural systems because of their potential to improve nutrient acquisition, enhance plant growth, and contribute to stress tolerance while reducing dependence on external inputs (Kumar *et al.*, 2025; Umer *et al.*, 2025) [1, 2]. However, AMF should be considered a complementary component of integrated crop and soil management rather than a universal substitute for mineral fertilizers or sound agronomic practices. Understanding their mechanisms, agronomic benefits, and practical limitations is therefore essential for their effective integration into modern agricultural systems.

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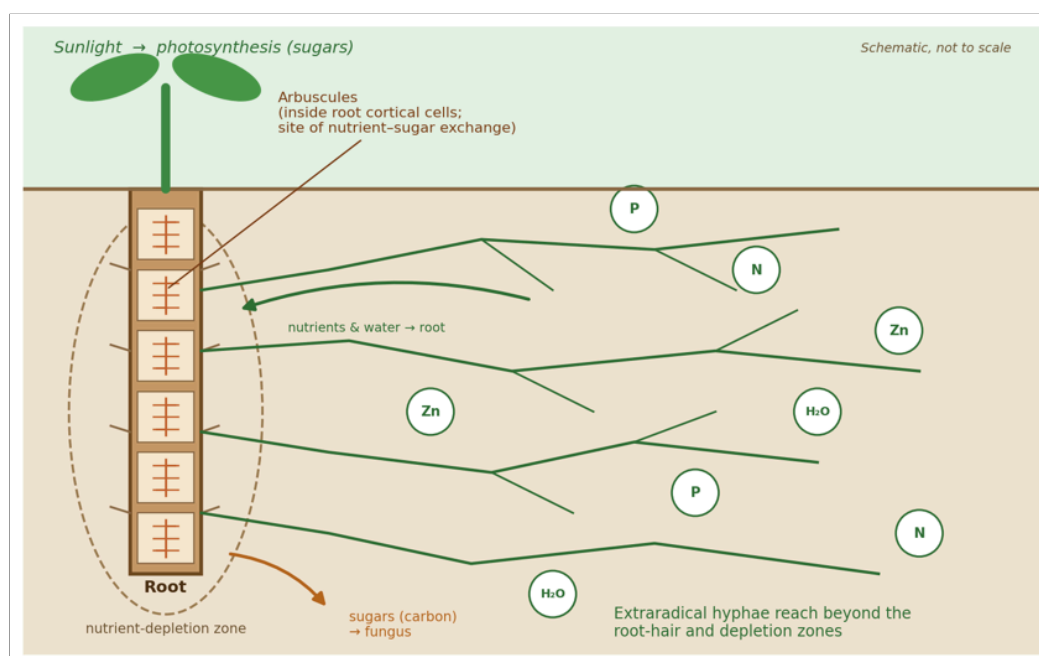


Figure 1. Schematic of the AMF partnership (not to scale). Arbuscules form inside root cortical cells, where nutrients and sugars are exchanged; extraradical hyphae extend beyond the root-hair and nutrient-depletion zones to collect water and nutrients, while the plant supplies the fungus with sugars from photosynthesis.

2. Understanding arbuscular mycorrhizal fungi in soil ecosystems

The association between arbuscular mycorrhizal fungi (AMF) and plants begins through a coordinated molecular signaling process in the soil, often before extensive root development has occurred. Germinating fungal spores perceive chemical signals released by host roots and, in response, produce signaling compounds that facilitate recognition and establishment of the symbiotic interaction. Following mutual recognition, the fungus develops specialized infection structures that penetrate the root tissues and extend into the cortical region, where highly branched arbuscules are formed within cortical cells. These arbuscules substantially increase the interface between fungal and plant tissues and facilitate the bidirectional exchange of resources, with nutrients acquired by the fungus being transferred to the plant in exchange for photosynthetically derived carbon compounds. Phosphorus acquisition is one of the most well-established benefits of AMF symbiosis. Phosphate is relatively immobile in soil and is therefore rapidly depleted from the rhizosphere surrounding actively growing roots, creating a localized phosphorus-depletion zone. The extensive extraradical hyphal network of AMF extends beyond this zone and explores soil volumes that are inaccessible to roots and root hairs. These hyphae acquire phosphate from the surrounding soil and transport it to the intraradical fungal structures, where it is subsequently transferred to the host plant. By substantially expanding the effective absorptive surface and soil exploration capacity of the root system, AMF can improve phosphorus acquisition and plant phosphorus nutrition, particularly under conditions of limited phosphorus availability (Solaiman *et al.*, 2024) [3]. The benefits of AMF symbiosis extend beyond improved nutrient acquisition and involve substantial physiological and biochemical modifications within the host plant. AMF colonization can modulate phytohormonal signaling and activate defence and stress-responsive pathways, thereby priming plants for more rapid and effective responses to subsequent environmental challenges. This phenomenon, commonly referred to as mycorrhiza-induced resistance (MIR), can enhance plant tolerance to abiotic stresses such as drought and salinity and may also improve resistance to certain soil- and foliar-associated pathogens. Although MIR shares functional similarities with induced systemic resistance mediated by some plant-growth-promoting rhizobacteria, the two responses involve distinct signaling mechanisms and microbial interactions (Umer

et al., 2025) [2]. Thus, AMF symbiosis represents a multifunctional biological process that integrates nutrient acquisition, plant physiological regulation, and stress defence responses, contributing to greater crop resilience and sustainable plant production.

2.1 Arbuscular mycorrhizal fungi: Building soil health and structure

Beyond their role in plant nutrition, arbuscular mycorrhizal fungi (AMF) contribute to soil structural development and functioning through their extensive hyphal networks and associated organic compounds. As AMF hyphae proliferate throughout the soil, they physically enmesh and stabilize soil particles, thereby promoting the formation and persistence of soil aggregates. AMF-associated compounds, including glomalin related soil proteins (GRSP), have also been implicated in aggregate stabilization; however, the precise biochemical identity and specific contribution of glomalin and GRSP to soil aggregation remain under discussion. In combination with fungal hyphae and other organic matter inputs, these compounds can enhance the stability of soil aggregates and improve soil structural properties. Improved aggregation can increase soil porosity, facilitate water infiltration and retention, enhance aeration and root penetration, and reduce the susceptibility of soil to erosion. Thus, sustained AMF activity may contribute to gradual improvements in soil physical quality and long-term soil health, complementing rather than replacing conventional nutrient-management practices.

2.2 Role of AMF in improving crop stress tolerance

Increasing climate variability and the greater frequency of drought events have intensified efforts to improve crop resilience through both breeding and agronomic interventions. In this context, arbuscular mycorrhizal fungi (AMF) are increasingly being considered as a complementary biological approach for enhancing plant tolerance to water deficit. A recent review of AMF–sorghum interactions identified AMF as a promising biofertilizers for dryland agriculture and highlighted the extensive extraradical hyphal network as a potential mechanism for improving plant water acquisition by accessing soil moisture beyond the effective rooting zone (Temesgen, 2024) [4]. AMF colonization may also contribute to improved plant water relations through enhanced nutrient acquisition, maintenance of physiological activity, and modulation of stress-responsive mechanisms. Similar beneficial effects have been reported in crops such as wheat, maize, and legumes, including improved recovery following periods of water

deficit and enhanced tolerance to salinity stress. However, the magnitude and consistency of these responses vary considerably depending on the host crop, AMF species or strain, soil conditions, and the intensity and duration of the imposed stress (Kumar *et al.*, 2025) [1]. Therefore, AMF should be regarded as a context dependent component of integrated strategies for improving crop resilience under increasingly variable climatic conditions.

2.3 Role of AMF in enhancing plant defence

Soil-borne pathogens, including *Fusarium*, *Rhizoctonia*, and *Phytophthora*, are responsible for substantial agricultural losses because they can persist in soil and infect susceptible crops across successive growing seasons. Arbuscular mycorrhizal fungi (AMF) can contribute to the suppression of soil-borne diseases through several complementary mechanisms. Root colonization by AMF may reduce pathogen establishment by occupying potential infection sites and modifying the availability of root-derived carbon compounds and exudates. In addition, AMF can stimulate host-plant defence responses,

including the activation of biochemical and molecular pathways associated with induced resistance. Improved nutrient acquisition and overall plant physiological status resulting from AMF symbiosis may further enhance the capacity of plants to tolerate or withstand pathogen infection. Recent evidence indicates that AMF can promote plant growth while contributing to disease suppression across diverse crop pathogen systems. Their effects may also extend to interactions with other beneficial microorganisms, with AMF potentially functioning synergistically with biocontrol organisms such as *Trichoderma*, *Pseudomonas*, and *Bacillus*. Such microbial interactions may strengthen plant defence, improve rhizosphere functioning, and enhance overall crop health (Umer *et al.*, 2025) [2]. Consequently, AMF represent a promising component of integrated biological disease-management strategies, although their effectiveness depends on the host plant, AMF identity, soil environment, pathogen complex, and prevailing crop-management conditions.

The main benefits and their caveats are summarized in Table 1 and Figure 2.

Table 1. Main agronomic benefits of AMF, proposed mechanisms and main caveats.

Benefit	Proposed mechanism	Main caveat
Nutrient uptake	Extraradical hyphae reach beyond the root depletion zone and deliver P, N, Zn, Cu and water	Response is small where soil phosphorus is already high
Soil structure	Hyphae and glomalin-related soil protein help bind particles into aggregates	The role of glomalin is still debated; effects build slowly
Drought and salinity tolerance	Better access to soil water; hormonal and physiological priming	Varies with crop, fungal strain and stress severity
Disease suppression	Competition for space and exudates; mycorrhiza-induced resistance; healthier plants	Depends on the pathogen and the host
Lower fertilizer need	Improved nutrient acquisition by colonized roots	Needs compatible management, such as reduced tillage and moderate phosphorus

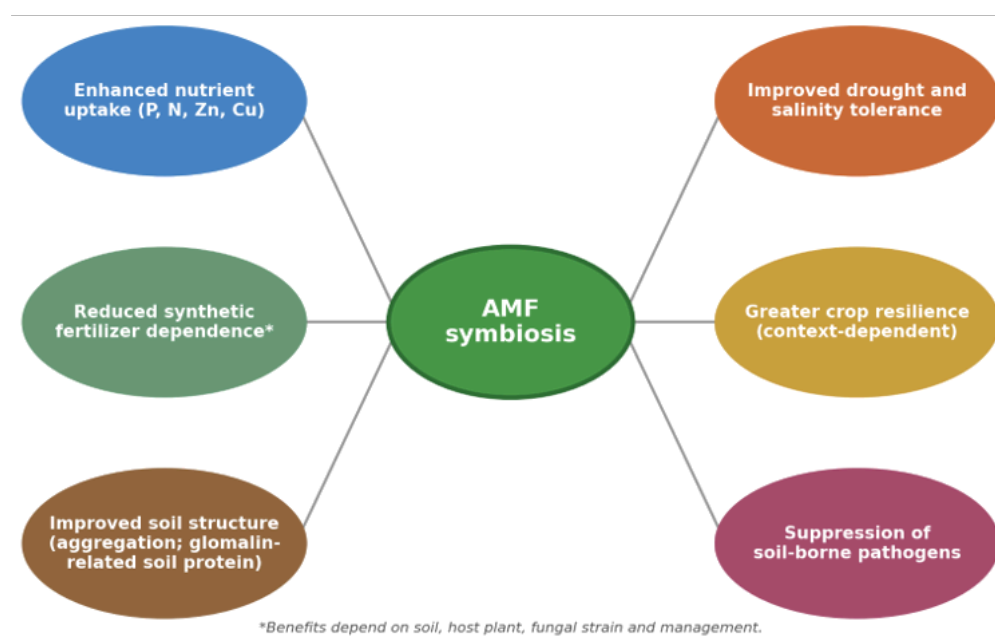


Figure 2. Arbuscular mycorrhizal fungi support sustainable farming through several interconnected pathways, from nutrient uptake to disease suppression. Benefits depend on soil, host plant, fungal strain and management.

2.4 Combining AMF with other biofertilizers

Increasing attention is being directed towards the combined application of arbuscular mycorrhizal fungi (AMF) and other beneficial microorganisms as an alternative to their individual use. Such microbial consortia may provide complementary functions and improve plant-microbe interactions within the rhizosphere. For example, Chen *et al.* (2023) [5] reported that the combined application of AMF and plant growth-promoting rhizobacteria (PGPR) enhanced soil fertility

and rice productivity compared with the application of either microbial group alone. The improved performance of the combined treatment suggests that AMF and PGPR may contribute through complementary mechanisms, including enhanced nutrient acquisition, improved root development, and modulation of the rhizosphere environment. These findings support the growing interest in microbial consortia as biofertilizers strategies, particularly because individual microbial inoculants may not simultaneously address the diverse nutritional, physiological, and environmental constraints encountered by

crops. Consequently, the integration of functionally complementary microorganisms represents a promising approach for developing more effective and resilient biological inputs for sustainable crop production.

3. Limitations to AMF adoption

Despite the potential benefits of arbuscular mycorrhizal fungi (AMF), their adoption as routine agricultural inputs remain constrained by several biological, technological, and agronomic limitations. AMF are obligate biotrophs and therefore cannot generally be propagated on conventional artificial media in the manner of many bacterial inoculants. Their multiplication requires association with living host roots, commonly through soil-based pot cultures or in vitro root-organ culture systems. This dependence on living hosts can make the production of large quantities of standardized, viable, and consistently effective inoculum relatively complex and costly. Furthermore, the efficacy of commercial AMF inoculants can vary considerably among products and production systems, while their performance may differ across soil types, climatic conditions, host crops, and management practices. The presence of indigenous AMF communities in agricultural soils can further influence the establishment and effectiveness of introduced strains through competition or interactions within the native microbial community. AMF benefits may also be limited under conditions of high soil phosphorus availability, where the plant's dependence on mycorrhizal phosphorus acquisition may be reduced. In addition, intensive tillage, excessive phosphorus fertilization, and certain fungicide applications can disrupt fungal hyphal networks or reduce AMF colonization, thereby limiting the establishment and functional contribution of inoculated fungi. Consequently, successful AMF application requires consideration of both inoculum quality and the broader soil and crop-management environment. Recent research suggests that many of these constraints can be addressed through improvements in inoculum production and formulation, appropriate selection of AMF strains or communities for specific soil and cropping conditions, and management practices that conserve indigenous mycorrhizal populations (Kumar *et al.*, 2025) [1]. Integrating AMF inoculation with practices such as reduced tillage, balanced phosphorus management, and the use of cover crops may further support the persistence and activity of fungal networks between cropping seasons. Thus, rather than functioning as a stand-alone input, AMF may be most effectively incorporated as a component of integrated soil and crop management systems designed to maintain beneficial soil microbial communities and improve resource-use efficiency.

4. Implications for farmers and policy support

For smallholder farming systems, arbuscular mycorrhizal fungi (AMF) may provide an opportunity to improve crop productivity and nutrient-use efficiency without a proportional increase in expenditure on mineral fertilizers. This potential is particularly relevant in regions where the high cost or limited availability of external agricultural inputs constrains crop production. In larger-scale commercial farming systems, the value of AMF may be associated more strongly with their potential contribution to crop resilience under drought, nutrient limitation, and other environmental stresses, although the magnitude and consistency of field responses remain dependent on crop, soil, climate, AMF community, and management conditions. The wider adoption of AMF-based technologies will require improvements in the availability, affordability, quality, and regional suitability of inoculants, together with effective extension and farmer-support programmes. Such programmes should emphasize not only the applica-

tion of commercial AMF products but also the conservation and management of indigenous mycorrhizal communities already present in agricultural soils. Practices such as reduced soil disturbance, balanced nutrient management, diversified cropping systems, and maintenance of living plant cover can help sustain native AMF populations and their associated functions. Therefore, a combination of locally adapted inoculant technologies and management practices that promote indigenous AMF communities may provide a more practical pathway for integrating mycorrhizal symbiosis into sustainable agricultural production systems.

5. Conclusion

Arbuscular mycorrhizal fungi (AMF) are best regarded as complementary plant-microbe symbionts that enhance nutrient acquisition and stress tolerance, rather than as substitutes for mineral fertilizers or sound agronomic management. Through their symbiotic association with plant roots, AMF can enhance nutrient and water acquisition, contribute to soil aggregation and structural stability, and improve plant tolerance to drought, salinity, and biotic stresses. Their integration with complementary beneficial microorganisms, including plant growth-promoting rhizobacteria, may further strengthen these functions and broaden their potential contribution to crop productivity and soil health. However, the effectiveness of AMF is strongly influenced by soil properties, host crop, fungal community, climatic conditions, and management practices. Therefore, wider adoption will depend on the development of reliable and affordable inoculants, identification of locally adapted AMF strains or communities, and management strategies that conserve indigenous mycorrhizal populations. Practices such as reduced tillage, balanced nutrient management, cover cropping, and microbial consortia can provide a supportive environment for AMF establishment and activity. Overall, greater understanding and effective management of plant-AMF interactions can help transform this ancient natural symbiosis into a practical component of climate-resilient, resource-efficient, and environmentally sustainable agriculture.

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