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Insights and applications of Arbuscular mycorrhizal fungi

Shalvi Pandey*, Pooja Goswami* & Sukrit Chandra*

Department of Bioscience and Biotechnology, Banasthali University, Rajasthan 30402, India

*Email: goswami10march@gmail.com

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Abstract

In natural ecosystems, rhizospheric soils are teeming with diverse biological organisms that enhance plant growth, nutrient absorption, stress tolerance and disease prevention. Among these organisms, arbuscular mycorrhizal (AM) fungi are particularly significant due to their symbiotic relationships with plants. Their application extends beyond natural ecosystems into agricultural and horticultural practices, where they contribute to improved soil health and plant productivity. This review discusses the benefits of incorporating AM fungi into modern agricultural systems to improve nutrient uptake, soil structure and plant resilience. It emphasizes the need for strategies to restore and maximize AM fungi's efficacy, ensuring sustainability and productivity in agriculture, industry and natural ecosystems.

Keywords

Arbuscular mycorrhizal; plant growth; nutrient; stress; disease; sustainable agriculture; soil health; ecosystem services

Introduction

Arbuscular mycorrhizal (AM) fungi, a pivotal component of soil microbiomes, form symbiotic relationships with plant roots, profoundly influencing plant health, growth and ecosystem dynamics. Soil quality in agroecosystems refers to the soil's ability to support crop growth and development sustainably by recycling nutrients and maintaining biological communities and soil texture. Healthy soil ensures food security, ecosystem services and biological control of diseases and pests (1). However, soil degradation, caused by factors like heavy grazing, infrastructure development, deforestation and poor agricultural management, poses a significant challenge to sustainable agriculture (2).

The over-reliance on pesticides and agrochemicals for higher crop yields leads to health issues, environmental pollution and disturbances in biological communities. Various symbiotic and non-symbiotic bacteria and fungi are used worldwide as inoculants to boost crop productivity (3, 4). AM fungi, with their extra-radical hyphae (ERH), help form soil macroaggregates through glomalin, a glycoprotein on ERH cell walls, which stabilizes soil structure during drying and wetting cycles. Plant-microbe interactions can enhance plant productivity under stress and normal conditions, supporting sustainable agriculture (5, 6). Despite the importance of these interactions, the widespread use of chemical fertilizers and other anthropogenic activities has threatened the viability and effectiveness of AM fungi in many systems. This review aims to provide a comprehensive overview of the current knowledge regarding the uses of AM fungi across different domains. It explores their fundamental functions in various fields and the challenges faced in integrating these fungi into modern practices. By synthesizing insights from recent research and field studies, this review highlights the importance of AM fungi in promoting ecological balance and advancing sustainable practices, offering a foundation for future innovations and applications in this critical area of study.

2. AMF Application in Agricultural Systems

The integration of AMF into agricultural systems plays a crucial role in enhancing plant growth by facilitating better nutrient uptake and improving stress tolerance. AMF contribute to soil health by fostering beneficial microbial communities and enhancing soil structure, which in turn promotes overall soil stability. These fungi form symbiotic relationships with plant roots, leading to improved nutrient availability, increased resilience to environmental stressors and healthier, more productive crops.

2.1 Enhanced Plant Vitality and Productivity

Approximately 90% of plant species, including ferns, bryophytes and flowering plants, can form symbiotic relationships with arbuscular mycorrhizal fungi (7). Many crops benefit from AMF inoculation, as numerous studies have demonstrated improved plant health and yield (8). AMF inoculum enhances root branching and root hair development, leading to better water and nutrient uptake and increased plant biomass (7, 9). For instance, (10) found that AMF-inoculated soils developed greater masses and more extensive extra-radical hyphal mycelium compared to non-inoculated soils. (11) found in their study that the combined application of AMF, with plant growth-promoting rhizobacteria as biofertilizer significantly enhanced several plant yields in beans and wheat. In addition to enhancing nutrient uptake, AMF inoculum improves plant stress tolerance by modulating the balance of phytohormones such as auxins, gibberellins and cytokinins, which are crucial for regulating plant growth and development (12, 13). This modulation supports a more robust root system, contributing to better resilience against environmental stressors (14). However, the effectiveness of AMF in agriculture is influenced by various external factors, including field plowing, fertilizer application and cultivation methods (15, 16). To maximize the benefits of AMF inoculation, it is essential to tailor its application to specific conditions, ensuring optimal integration with existing agricultural practices.

2.2 Nutrient Uptake

AMF establish a symbiotic relationship with plant roots, characterized by the formation of arbuscules within plant cells. These arbuscules facilitate efficient nutrient exchange between the fungus and the plant. A prime example is the symbiotic phosphate transporter (PT), such as *Medicago truncatula* MtPT4 and rice OsPT11, which are exclusively expressed in arbuscule-containing cells (17). (18) found that the AM-related phosphate absorption pathway is a distinctive evolutionary trait conserved across terrestrial plants since the emergence of angiosperms. The primary benefit of AM symbiosis is the enhanced delivery of phosphate to the host plant (19, 20). Phosphate, along with other essential nutrients like nitrogen, sulfur, copper and zinc, is transferred from the fungus to the plant through the arbuscules, leading to higher nutrient concentrations in mycorrhizal plants (21, 22). Despite this, many AM-induced nutrient transporters' expression patterns, protein localization and functions remain largely unexplored.

Notably, AM-related pathways not only aid nutrient uptake but also improve overall plant physiology and development. Research by (23, 24) highlights that mycorrhizal plants exhibit increased photosynthetic potential. Furthermore, even in the absence of AM fungi, plants can enhance root and shoot growth by overexpressing the transporter PDR1, which is involved in AM signalling, as shown in studies on petunias (25). This suggests that AM and its signalling mechanisms may drive plant growth through nutrient-related pathways and possibly other, as-yet-unidentified mechanisms.

2.3 Soil Structure Improvement

AMF significantly contribute to soil structure, which is a major benefit provided by these fungi in both agricultural and natural environments (26). The hyphal network of AM fungi, combined with their favourable impact on root system development and plant growth (27, 28), shields the soil from wind and water erosion. A key factor in soil aggregate stabilization is glomalin, a glycoprotein produced by AM fungi. Glomalin is known for its extractability and immuno-reactive properties rather than being a specific gene product or chemically uniform molecule (29). The combined actions of AM fungi on soil properties lead to greater water retention, which is advantageous for plant growth. In arid regions with sandy, dry soils, the advantages of AM fungi are particularly crucial. These soils often exhibit low fertility and are highly susceptible to wind and rain erosion. Under such conditions, mycorrhizal plantings may be a viable means of reducing soil erosion and enhancing soil fertility (30).

AM fungi have distinct mechanisms of action when it comes to preventing nutrient leakage. First, improved soil structure enables more nutrient sequestration to the micro- and macro-aggregates in mycorrhizal soil. Second, AM fungi take up nutrients from the soil solution (31, 14). Third, mycorrhizal soils have better soil solution retention capacities (32), which benefits the plant's availability of both water and nutrients. An extensive overview of the advantages that AM fungi provide to tomato plants stressed by drought (33). Mineral nutrients such as phosphorus (P) and nitrogen (N) have been shown to drain less from mycorrhizal soils, although other minerals may also be involved. Collectively, AM fungi create closed nutrient cycles that facilitate the integration of soil nutrient fluxes and ultimately enhance soil fertility over the long run (34).

2.4 Increasing Plant Resilience

Mycorrhizal roots frequently show exceptionally strong intracellular and intercellular fungal colonization, which can exceed 90% of the entire length of the root (35). The extent to which mycorrhizae improve host plant resilience to external environmental pressures varies depending on the type of stress and the plant species. The application of AMF, particularly in areas prone to extreme drought or highly saline conditions, has been shown to increase the stress resistance of host plants (36). For instance, AMF application to grapevine roots increased the root system's water retention and osmotic tolerance, increasing the plant's water-holding capacity under drought conditions (37). In wheat plants, AMF-enhanced root branching led to higher levels of antioxidant enzymes and the accumulation of osmoprotectants, thus boosting the plant's ability to tolerate high salinity (38). In many agricultural contexts, mycorrhizae can buffer crops against the adverse effects of climate change. An example of this is the improved temperature resilience of AMF-inoculated Durum wheat (39). Notably, despite their resilience, mycorrhizal plants often show

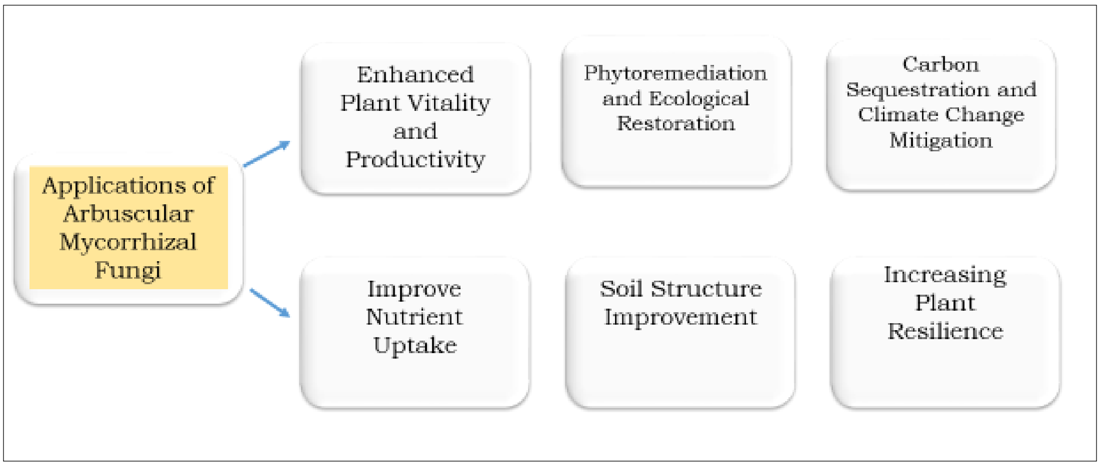

Fig. 1. Various applications of Arbuscular mycorrhiza fungi.

significantly slower growth than their non-mycorrhizal counterparts, highlighting the need for further research into optimizing their integration into modern agriculture (40).

2.5 Other Applications

AMF role in sustainable agriculture extends beyond enhancing crop growth and soil health. They are also critical in broader ecological and environmental applications, such as phytoremediation and carbon sequestration, which have significant implications for ecosystem restoration and climate change mitigation.

Phytoremediation and Ecological Restoration

AMF have been recognized for their potential in phytoremediation, a process that uses plants and associated microbes to remove, stabilize, or degrade contaminants in soil and water. AMF can enhance the phytoremediation capabilities of plants by improving their tolerance to heavy metals and other pollutants. The fungi achieve this by binding heavy metals in the soil, reducing their bioavailability and facilitating the plants' ability to sequester or detoxify these contaminants (41). Additionally, AMF contribute to the rehabilitation of degraded lands by promoting plant establishment, enhancing soil structure and increasing nutrient availability in poor or contaminated soils (42). This makes them invaluable tools in ecological restoration projects, particularly in areas affected by mining, industrial waste, or deforestation.

Carbon Sequestration and Climate Change Mitigation

The role of AMF in carbon sequestration has gained attention in recent years due to their potential to mitigate climate change. AMF contribute to soil carbon storage by promoting the formation of stable soil aggregates, which protect organic carbon from decomposition. Additionally, the extensive hyphal networks of AMF increase the amount of carbon stored in soil organic matter, thereby enhancing the soil's capacity to sequester carbon over the long term (43, 14, 44). This process is particularly important in agricultural systems, where intensive farming practices often deplete soil carbon stocks. Furthermore, AMF has been shown to influence the composition of root exudates, leading to changes in the microbial community and the stabilization of organic carbon in soils (45). Integrating AMF into agricultural and land management practices can enhance carbon sequestration, thereby reducing greenhouse gas emissions and contributing to climate change mitigation efforts. While the potential applications of AMF are vast, there are practical challenges that must be addressed to ensure their widespread adoption in agriculture and other domains. One of the primary challenges is the economic cost associated with AMF inoculum production and application, which can be a barrier for small-scale farmers (46). Additionally, the scalability of AMF-based practices remains a concern, particularly in large-scale agricultural systems where the uniform application of AMF inoculum may be difficult to achieve.

Moreover, the effectiveness of AMF in improving crop yield and soil health is influenced by various factors, including soil type, crop species and environmental conditions. As such, there is a need for more targeted research to develop AMF inoculum formulations that are tailored to specific agricultural contexts (47). Education and training programs for farmers are also essential to ensure the proper application of AMF inoculum and to promote the adoption of sustainable farming practices that incorporate AMF.

Conclusion

In conclusion, the multidimensional role of AMF in improving agricultural production, endorsing soil health and contributing to wide-ranging environmental benefits such as phytoremediation and carbon sequestration. By simplifying nutrient uptake, improving soil structure and increasing plant resilience, AMF offer a sustainable alternate to chemical fertilizers and pesticides. However, the extensive adoption of AMF-based applies requires addressing practical challenges, such as cost, scalability and farmer education. Future research should focus on optimizing AMF inoculum formulations for specific agricultural contexts and exploring the potential of AMF in emerging areas such as precision agriculture and climate change mitigation. Through incorporating AMF into modern agricultural applies, it is probable to enhance the sustainability and productivity of agriculture, while also contributing to the restoration and preservation of natural ecosystems.

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Authors' contributions

SP, PG and SC design of work, interpretation, drafting the article, revision of the article, final approval of the version to be published. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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