

Role of arbuscular mycorrhizal fungi in enhancing soil health and plant resilience

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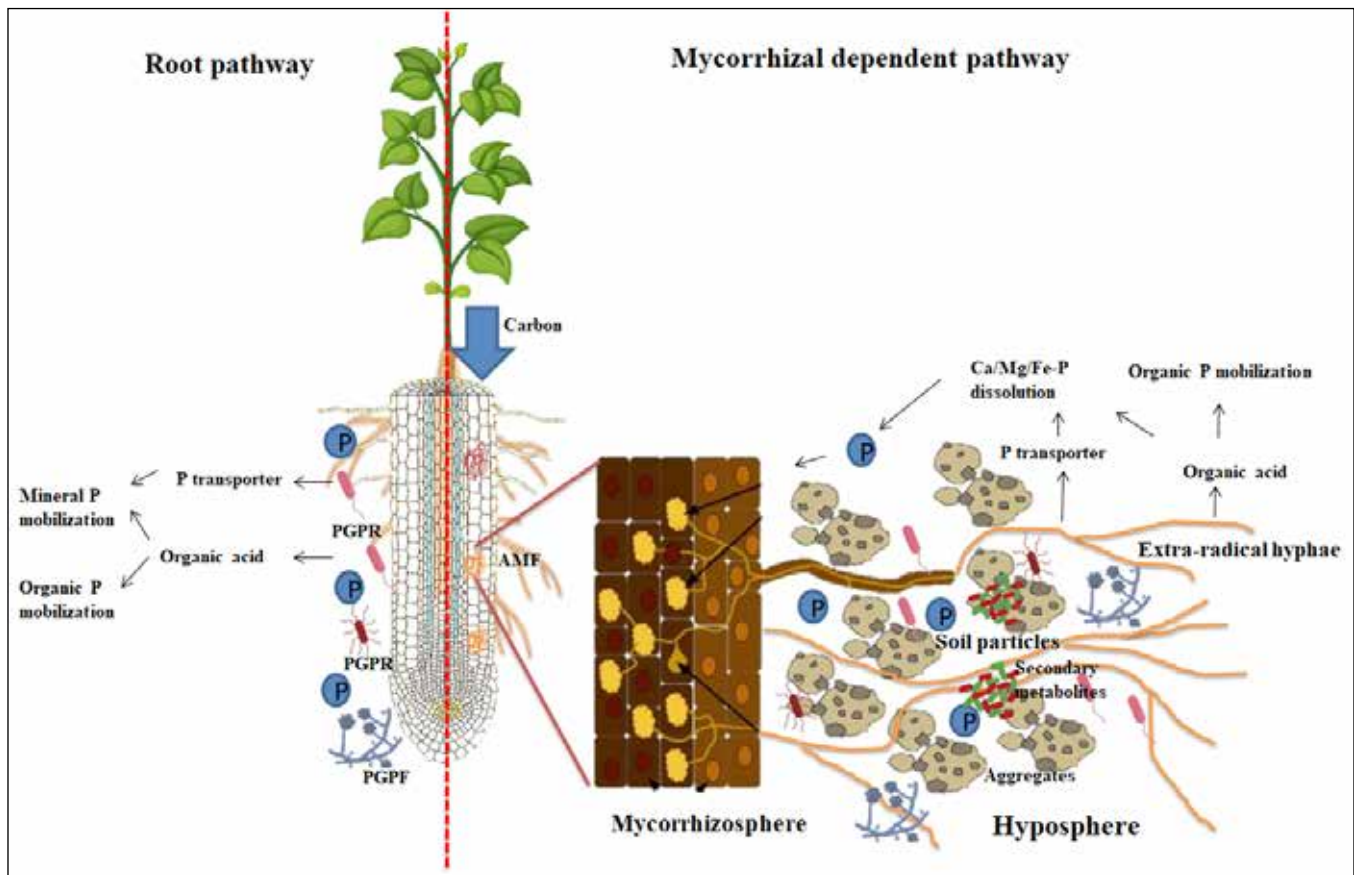
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Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with the roots of most terrestrial plants and play a pivotal role in maintaining soil health and ecosystem stability. Through their extensive hyphal networks, AMF enhance plant access to key nutrients particularly phosphorus and nitrogen while receiving carbohydrates in return, thus, supporting a mutualistic exchange. Their role in improving soil structure is mediated by glomalin production, which stabilizes soil aggregates, enhances porosity, and fosters microbial activity. AMF also contribute to organic matter decomposition and carbon sequestration, further influencing nutrient cycling. Importantly, AMF have emerged as effective agents for mitigating salinity stress in plants by improving phosphorus acquisition, reducing sodium uptake, and maintaining optimal K^+/Na^+ and Mg^{2+}/Na^+ ratios in plant tissues. Despite observed genotype-dependent variability in AMF effectiveness, their integration into sustainable agricultural practices such as reduced tillage, crop rotation, and inoculation offers a promising strategy for improving soil fertility, minimizing chemical inputs, and enhancing crop resilience under abiotic stress conditions. Understanding the functional mechanisms of AMF is thus vital for leveraging their potential in agroecological systems.

Keywords: Arbuscular mycorrhizal fungi, Carbon sequestration, Crop resilience, Ecosystem stability

ARBUSCULAR Mycorrhizal fungi (AMF) form symbiotic associations with the roots of the majority of terrestrial plants, playing a crucial role in shaping soil conditions and influencing soil health. AMF establish intricate networks within the rhizosphere, facilitating nutrient uptake, improving soil structure, and enhancing plant resilience to environmental stressors. As such, exploring the effects of AMF on soil conditions and soil health is essential for understanding the intricate relationships between plants, microbes, and their surrounding environment. AMF belong to the phylum Glomeromycota and form mutualistic relationships with a wide range of plant species, including crops, grasses, and trees. Through these symbiotic associations, AMF extend the reach of plant roots, increasing their access to water, nutrients, and minerals, particularly phosphorus and nitrogen. In return, plants provide AMF with carbohydrates synthesized through photosynthesis, sustaining their

growth and reproduction. This mutualistic exchange benefits both partners and contributes to the overall productivity and resilience of terrestrial ecosystems. One of the key contributions of AMF to soil conditions is the enhancement of soil aggregation and structure. By secreting glomalin, a glycoprotein that acts as a binding agent, AMF promote soil aggregation, leading to the formation of stable soil aggregates. These aggregates improve soil porosity, water infiltration, and aeration, creating a favourable environment for root growth and microbial activity. Additionally, AMF play a vital role in organic matter decomposition, accelerating the breakdown of organic residues and contributing to soil carbon sequestration. Moreover, AMF influence soil nutrient cycling and availability, particularly phosphorus cycling. Through their extensive hyphal networks, AMF scavenge phosphorus from the soil, making it accessible to plants with high phosphorus requirements. This nutrient mobilization not only



Description of functioning of AMF in the rhizosphere (Chandra *et al.* 2025)

benefits mycorrhizal plants but also enhances the nutrient status of the soil, supporting the growth of associated plants and promoting ecosystem diversity.

As key components of soil-plant ecosystems, AMF play a crucial role in improving plant responses to salinity, benefiting both growth and yield. This makes AMF valuable candidates for mitigating salt stress through bio-amelioration. The enhanced growth observed in mycorrhizal salt-stressed plants is largely attributed to AM fungi-mediated improvements in nutrient acquisition, particularly phosphorus, as Pi absorption tends to decline under saline conditions.

AM symbiosis has also been shown to reduce sodium (Na^+) uptake and translocation while promoting the absorption of essential cations such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). This interaction leads to an increase in K^+/Na^+ and $\text{Mg}^{2+}/\text{Na}^+$ ratios in plant shoots, which contributes to improved physiological stability under salt stress. However, significant variability has been reported in the effectiveness of AM symbiosis in addressing salinity and phosphorus deficiency, depending on the specific plant and AM fungi genotypes involved.

In recent years, there has been growing interest in harnessing the potential of AMF to improve soil health and agricultural sustainability. By inoculating soils with AMF or adopting practices that promote their proliferation, such as reduced tillage and cover cropping, farmers can enhance soil fertility, reduce nutrient leaching, and reduce the need for chemical fertilizers and pesticides. Understanding the mechanisms underlying

the effects of AMF on soil conditions and soil health is essential for optimizing their use in agroecosystems and maximizing their benefits for sustainable agriculture.

Functioning of AMF

- **Nutrient uptake:** AMF enhance nutrient uptake by extending the root system's reach into the soil, increasing the surface area available for nutrient absorption.
- **Nitrogen uptake:** AMF enhance nitrogen uptake plants, particularly in nitrogen-poor soils, through increased root exploration and nutrient absorption.
- **Phosphorus solubilization:** AMF release organic acids and phosphatase enzymes into the rhizosphere, which solubilize phosphorus from minerals such as apatite and rock phosphate.
- **Induced systemic resistance:** Mycorrhizal associations induce systemic resistance in plants, activating defence mechanisms that enhance plant resilience to pathogen attack.
- **Disease suppression:** AMF protect plant roots from infection by soil-borne pathogens, forming a physical barrier and enhancing plant defence against pathogen invasion.
- **Water relations:** AMF improve water uptake efficiency by accessing water from deeper soil layers and transporting it to the plant host.
- **Enhanced root exploration:** AMF hyphae extend into the soil, accessing micronutrients from mineral sources and soil organic matter.
- **Soil structure:** By secreting glomalin and

promoting soil aggregation, AMF contribute to soil structure formation, enhancing soil fertility and plant growth.

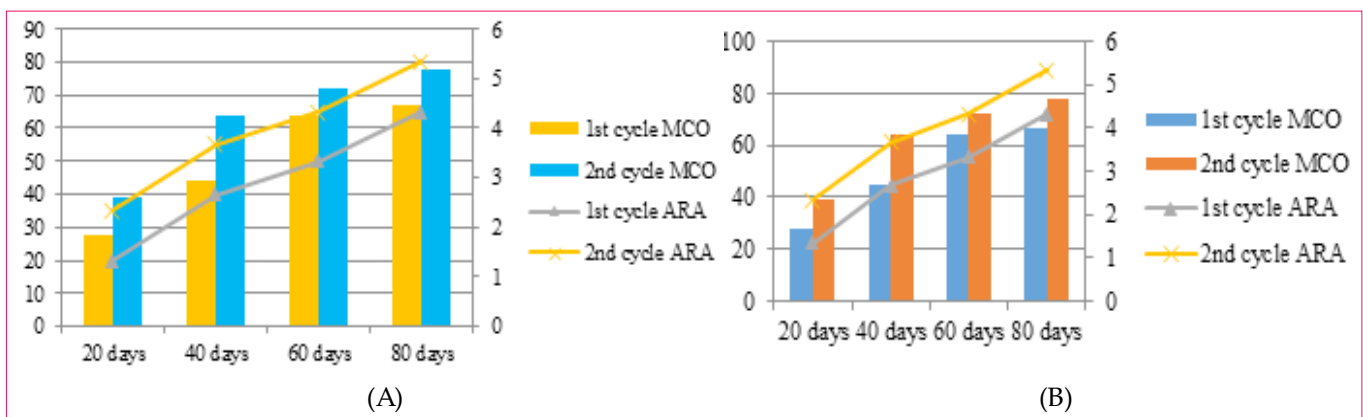
- **Stress tolerance:** AMF enhance plant resilience to environmental stressors such as drought, salinity, and nutrient deficiency, through improved nutrient acquisition and water relations.
- **Drought tolerance:** AMF enhance plant drought tolerance by improving water uptake efficiency, regulating stomatal conductance, and enhancing plant osmotic adjustment mechanisms.
- **Salinity tolerance:** Mycorrhizal associations can alleviate salt stress in plants by enhancing ion homeostasis, facilitating sodium exclusion, and promoting osmotic adjustment, thereby improving plant growth and productivity in saline soils.
- **Heavy metal remediation:** AMF contribute to heavy metal remediation by immobilizing toxic metals in the soil, facilitating metal uptake by plants, and promoting metal detoxification and sequestration in plant tissues and rhizosphere microorganisms.
- **Carbon sequestration:** AMF play a significant role in soil carbon sequestration by enhancing plant productivity, promoting root biomass accumulation, and increasing soil organic matter content.

Case study in salt affected soils

Suitable host: Propagation of native AMF by soil trapping method was studied using sorghum and maize as trap crops in two cycles. For the first cycle, both the crops were grown in pots for 60 days and the plants were uprooted and some roots were collected for confirmation of mycorrhizal associations. For the second cycle, the roots obtained from first cycle were chopped and mix as inoculum in the same pots. Sorghum and maize seeds were sown in the same pots. Again after 2 months, the plants were uprooted and roots were examined for mycorrhizal associations. Sorghum and maize are the two distinct host plants which possess the ability to associate with arbuscularmycorrhizal fungi (AMF), both are also commonly used for AMF propagation. In the study, mycorrhizal association and colonization increased in both cycles of propagation for both hosts. However, maize exhibited higher propagation and colonization

compared to sorghum. Previous studies, have also indicated that maize facilitates AMF propagation. The higher percentage of root colonization in maize is largely attributed to the unique composition of its root exudates. Some flavones, exclusively produced by maize roots, play a significant role in plant-fungal interactions and symbiotic relationships. These compounds are known to attract mycorrhizal germ tubes to the roots, potentially enhancing AMF colonization by promoting spore germination and germ tube growth. Mycorrhizal colonization varies depending on AMF communities, crop type, variety, and environmental factors such as soil and climate conditions. The primary factor influencing these interactions is the fungal requirement for photoassimilates, which affects both root associations and fungal reproduction. In the second cycle of propagation, both colonization levels and arbuscule abundance were higher than in the first cycle. The extensive root density, branching, and spread of sorghum and maize roots support a broad proliferation of AMF within their root systems. This facilitates a richer and more diverse fungal community, increasing the number of infection points and enhancing contact with spores, ultimately leading to improved colonization.

Plant growth, and phosphorus status: Plants inoculated with AMF exhibited significantly improved growth compared to control plants in terms of various growth parameters highlighting the role of AMF colonization in enhancing plant growth and nutrient uptake. The findings further suggested that AMF exert a positive effect under salt stress conditions. AMF inoculation also enhanced P uptake in sorghum plants under stressed conditions. AM fungi possessing specialized phosphorus transporters with high affinity, which help solubilize P under moderate and severe salinity conditions and when P availability is low. These fungi achieve this by producing organic acids that facilitate P absorption, making it more accessible to plants. AMF inoculation also reduced Na^+/K^+ ratio in sorghum plants under stressed conditions. Studies have shown that AM symbiosis increases sodium (Na^+) exclusion by sequestering it within intraradical hyphae, thereby preventing its translocation to the shoots. This enhanced Na^+ exclusion capacity is likely

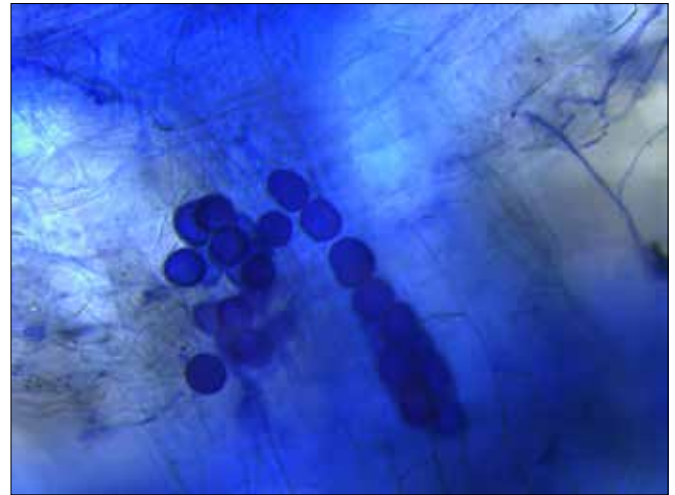


The interaction of AMF colonization (MCO) with the roots of maize (A) and sorghum (B) in first and second cycle of propagation of and number of arbuscules (ARA) formed with respect to time

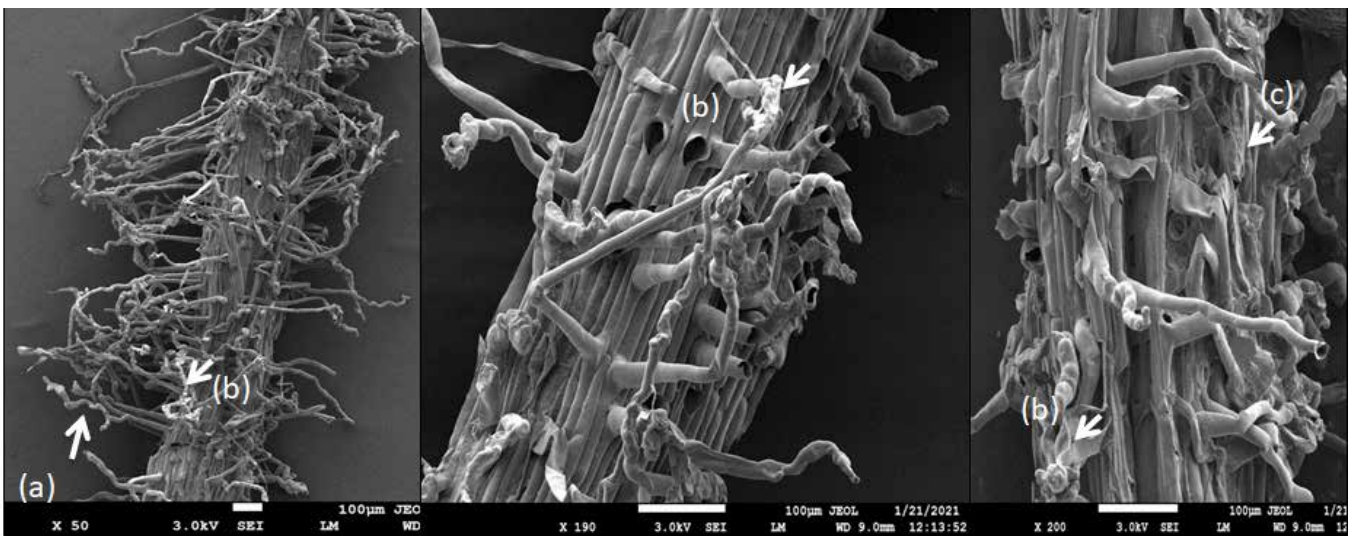
a contributing factor to the improved growth observed in AM-inoculated plants. Additionally, AM fungi have been proposed to limit Na⁺ uptake either by selective absorption from the soil or by controlling its transfer within the plant.

Mycorrhizal colonization and soil properties:

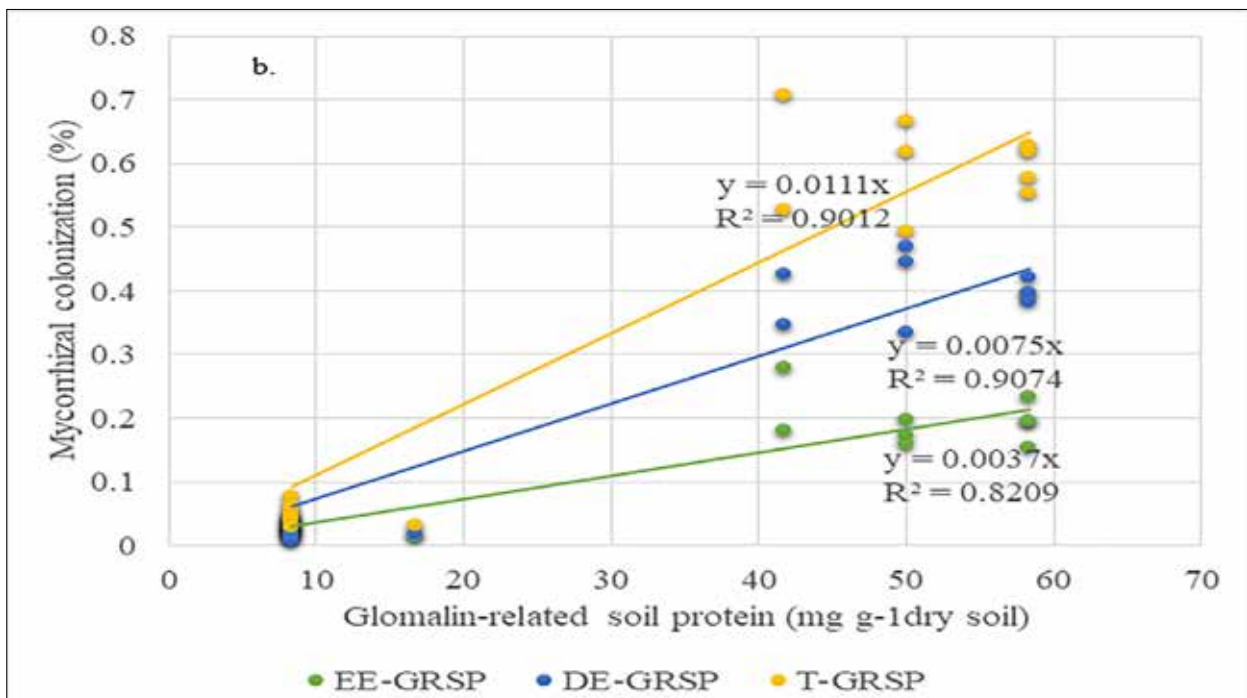
Microscopic observations confirmed the presence of various growth stages of mycorrhizal development within plant roots, including intraradical and extraradical hyphae, arbuscules at different formation stages, and vesicles. The overall colonization of sorghum roots inoculated with AMF ranged from 8.3% to 58.3%. Arbuscularmycorrhizal fungi (AMF) generally exhibit a higher tolerance to salinity compared to plants. Under stress conditions, plants reduce root biomass and invest more in AMF associations, allowing the fungi to take over essential water and nutrient acquisition. AMF's beneficial role is closely linked to the production of a fungal protein



Roots of AMF-inoculated sorghum plants demonstrated AMF colonization and abundance as their typical fungal structures were found under microscope



Electron micrograph (5000X) of root with visualization of (a) root hairs (b) mycorrhizal hyphae coiling the root hairs (c) root exudates through Scanning Electron Microscope (SEM)



Relationships between arbuscular mycorrhizal (AM) colonization and Glomalin related soil proteins content in soil



View of the experiment at experimental farm Nain, Haryana



Propagation of mycorrhiza in sorghum roots

called glomalin, which is quantified in soil as glomalin-related soil protein (GRSP). In this study, GRSP content was significantly higher in AM-inoculated soil compared to non-inoculated soil. The presence of AMF strongly correlates with microbial activity in the soil, as inoculated treatments exhibited higher microbiota populations. This suggests that AMF colonization efficiency may be influenced by bacterial communities acting as a third symbiotic partner. Soil microbial enzymes serve as indicators of microbiological activity, and the significantly higher dehydrogenase and phosphatase enzyme activity in AMF-inoculated soil can likely be attributed to increased microbial populations. These findings further highlight the role of phosphatase enzymes released by AMF in enhancing plant phosphorus nutrition through hyphal transport.

SUMMARY

Arbuscular mycorrhizal fungi (AMF) are integral part of soil ecology in the maintenance and improvement of soil health, plant nutrition, and ecosystem resilience.

Their symbiotic associations with plant roots facilitate enhanced nutrient acquisition particularly phosphorus and promote soil structural stability through glomalin-mediated aggregation. AMF also play a significant role in mitigating salt stress by regulating ion uptake and improving physiological balance in plants. Although the efficiency of AM symbiosis can vary depending on host plant and fungal genotypes, the ecological and agricultural benefits of AMF are well-documented. Harnessing their potential through targeted inoculation strategies and AMF-friendly agronomic practices offers a sustainable pathway for enhancing soil fertility, reducing reliance on synthetic inputs, and improving crop productivity under both normal and stress-prone conditions. Continued research into the functional dynamics of AMF will be critical for optimizing their application in diverse agroecosystems and advancing sustainable agricultural practices.

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