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Arbuscular Mycorrhiza and Its Microbiome: Could This Be Nature's Key to Food Security?

Seema Sangwan
Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi, India
**Corresponding author - cmasangwan123@gmail.com*

In the intricate web of life beneath our feet lies an intricate symbiotic association between plants and fungi, one that has quietly sustained ecosystems for millennia. This tripartite symbiotic association Arbuscular Mycorrhiza (AM) fungi between plant and arbuscular mycorrhiza fungi with its microbiome, represents not only a marvel of nature, but also a beacon of hope for addressing one of humanity's most pressing challenges: food security.

The Hidden Network: What is Arbuscular Mycorrhiza and its microbiome?

These fungal allies have evolved together with terrestrial plants for past 400 million years or more, and form highly specialized, tree-like structures called arbuscules within the roots of their host plants. Through these structures, plants and fungi engage in a mutually beneficial exchange. Plants provide AM fungi with carbohydrates synthesized through photosynthesis, while AM fungi, with their vast hyphal networks, absorb essential nutrients-particularly phosphorus and nitrogen-from the soil, which they channel back to the plants. AM fungi extend far beyond the root zone, accessing nutrients in regions of the soil that plant roots cannot penetrate. What is particularly amazing about this partnership is the metabolic efficiency and widespread nature of the fungal network. In essence, AM fungi act as an expanded root system, amplifying the plant's ability to thrive in nutrient-poor environments and adapting to environmental fluctuations.

Beneath the surface, the influence of AM fungi does not end with the fungi themselves, rather they host a thriving microbiome which is often considered the invisible virtuosos in this mutually beneficial alliance between AM fungi and plants, playing a pivotal role in orchestrating the establishment of mycorrhizal associations and its effective functioning (Fig. 1). Comprising a diverse assemblage of bacteria, archaea, and additional fungi, these microscopic organisms dynamically interact with AM fungi, enhancing their capacity to facilitate nutrient and water uptake, fortify disease resistance, and improve soil architecture thus act as the tiny helpers in this symbiotic relationship. But here a question arises:

Can this hidden association of microbes offer a solution for sustainable food production?

Harnessing AM fungi and Microbiome Synergy: A Sustainable Path to Food Security

Arbuscular mycorrhizal and their microbiome represent a powerful synergistic association, representing a nature-based solution for food security, particularly in the face of soil degradation and climate change, allowing crops to thrive in unpredictable environments and nutrient-poor soils (Fig. 2).

- **Vital Nutrient Acquisition Hubs**

AM fungi function as indispensable symbiotic microorganisms, mediating the uptake of essential edaphic nutrients that are otherwise recalcitrant to plant assimilation. A meta-analysis encompassing 187 studies demonstrated significant enhancement in plant growth and nutrient assimilation following AM fungal inoculation. Enrichment to the tune of 47% increase in biomass, a 16% elevation in nitrogen (N) concentration, a 27% improvement in phosphorus (P) concentration, and remarkable increases of 67% and 105% in total nitrogen and phosphorus uptake, respectively were documented. Specific reports are available on *Glomus mosseae* inoculation enhancing nutrient uptake, with increase in phosphorus (35%), nitrogen (24%), potassium (4%), iron (24%), and manganese (13%) in *Salvia rosmarinus*, *Amaranthus* sp., and *Brassica oleracea.* The capacity of AM fungi to enhance nutrient acquisition is ascribed to their extensive extraradical hyphal networks, which

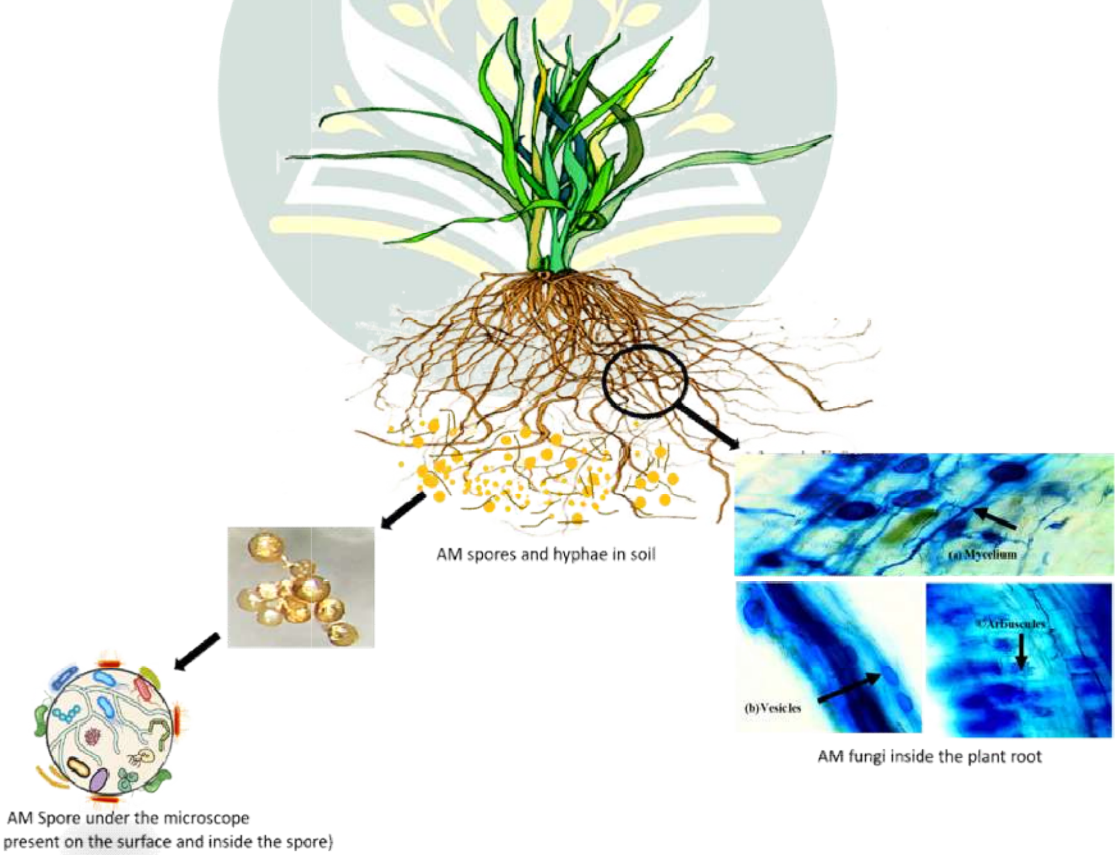

Fig 1: Symbiotic Hidden Network: plant roots intertwined with AM and associated microbial life

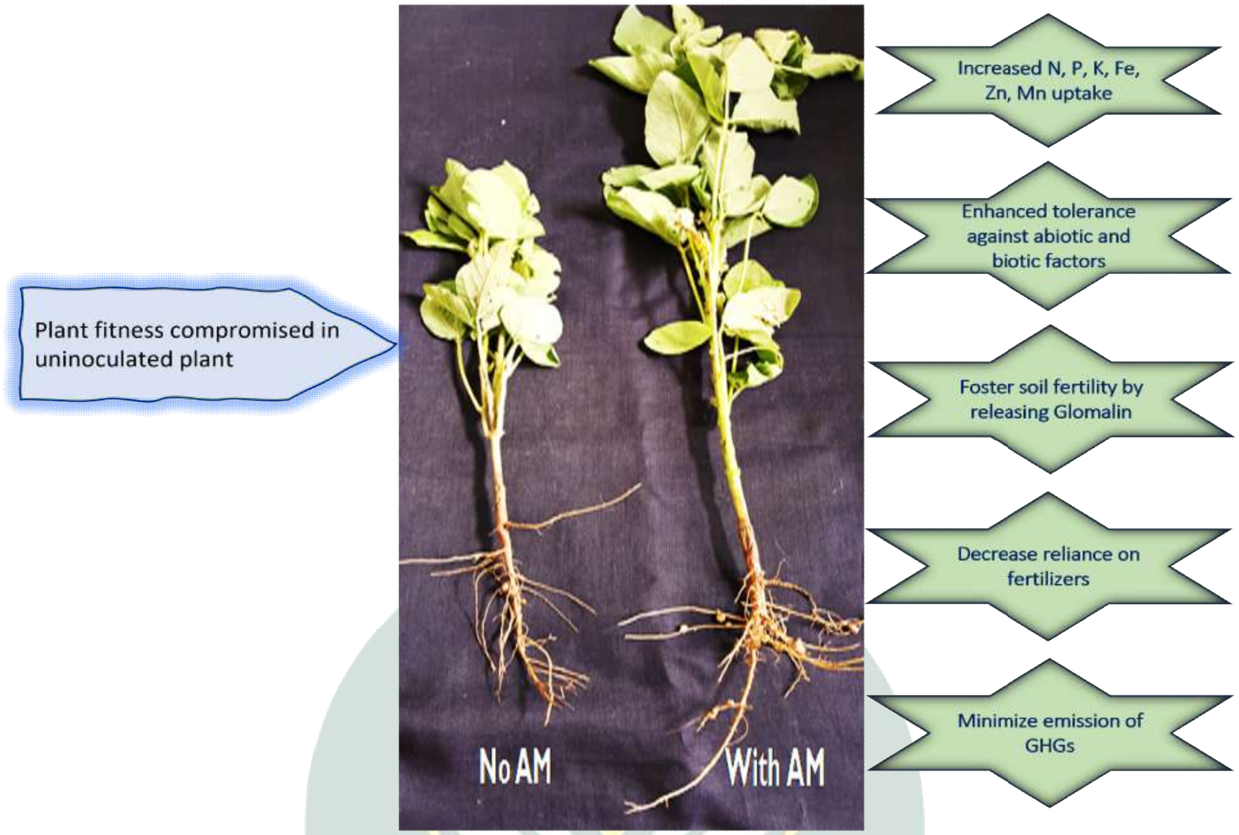

Fig 2: Thriving with AM and its microbiome: Insights into stimulated plant health and productivity

substantially increase the soil volume accessible to plant roots, thereby serving as an efficient biological nutrient mobilizer. The greater availability of nutrients for plant growth reflects the reduced need for chemical fertilizers in agriculture.

- **Key Drivers of Robust soil matrix formation**

AM fungi enhance soil structure through the secretion of glomalin-related soil proteins (GRSP), comprising 20–43% carbon (C) and 3–5% nitrogen (N). GRSPs promote carbon sequestration, microbial activity, and heavy metal detoxification while their recalcitrance, hydrophobicity, and iron-binding capacity strengthen soil integrity. These multifunctional traits establish AM fungi as **natural architects** of soil health and resilience.

- **Reinforcing Plant Adaptability and Resilience**

AM fungi boost plant resilience to environmental stresses (drought, salinity, and heavy metals) and biotic stresses (pathogens) by optimizing nutrient uptake and modulating physiological processes. *Glomus fasciculatum* improves biomass and reduce leaf browning under heat stress through antioxidative activity, while *Glomus intraradices* alleviate dehydration in soybean under drought and salinity by maintaining higher relative water content. AM fungi activate immune responses, boosting resistance to pathogens and nematodes, thereby sustaining crop health. *Glomus vismiae* in *Cynara carduncululus* upregulated defence enzymes (APX, MDHAR, SOD) and reduced H_2O_2 and lipid peroxidation, enhancing fungal resistance. *Glomus species* promotes growth and activates disease resistance in banana seedlings, protecting against *Fusarium wilt*, with *Glomus cerebrosum* outperforming *Glomus clarum* in root rot resistance.

- **Guardians of the Planet**

AM fungi are positioned as **catalysts** for global environmental transformation because they are mitigating greenhouse gas (GHG) emissions through complex interactions within soil ecosystems. First, they enhance host plant biomass and transpiration, increasing nitrogen uptake and reducing soil nitrogen available for denitrification. Second, AM fungi promote the formation of water-stable aggregates, improving soil aeration and inhibiting anaerobic denitrification, thereby reducing N_2O production. Third, AM fungi alter the microbial community by stimulating *nosZ*-carrying microbes, which reduce N_2O, and suppressing *nirK*-carrying microbes, which produce N_2O. AM fungi improve soil carbon storage, aiding in climate change mitigation. AM fungi inoculation has been reported to stimulate plant photosynthetic rates in coalfields by 15.3% to 33.1% leading to a 17.2% increase in soil carbon storage and limits its release in environment. By modulating microbial communities and nutrient cycling, AM fungi not only influence greenhouse gas dynamics but also significantly enhance soil carbon storage, highlighting their role in sustainable agriculture and climate change mitigation.

The path forward

In the pursuit towards a more secure and sustainable future in terms of food security, leveraging the untapped potential of arbuscular mycorrhiza and its microbiome offers a path forward that is both grounded in natural processes and deciphered by cutting-edge science. By integrating advances in biotechnology and microbiome engineering, this ancient symbiosis can be used to develop specific mycorrhizal inoculants to establish a resilient, ecologically sound foundation for food production that meets the needs of the growing population while preserving our planet's health. This holistic approach will transform farming into a cohesive ecosystem, where every organism plays an indispensable role in maintaining the balance and health of the environment making it more resilient and sustainable compared to conventional monoculture approaches.

Conflicts of interest

The authors report no conflict or competing interests.

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