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Plant-arbuscular mycorrhizal fungal interaction: Insight into sustainable agroecosystems

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Sustainable agriculture is based on the understanding of ecosystem services. It includes environment-friendly methods of farming that allow the production of crops or livestock without damaging human or natural systems. Among the micro-organisms, the arbuscular mycorrhizal (AM) fungi play a vital role in increasing the crop yield without compromising the soil fertility and thus assist in sustainable agriculture. As President of the Mycological Society of India (MSI), I express my deep sense of gratitude to the esteemed members of MSI for their continued efforts over the years to promote the growth of mycology in our country and raise our Society to greater heights in the coming years.

This review focuses on plant-AM fungal interaction as well as provides an insight into sustainable agroecosystems. The rhizosphere microbiome comprises functionally diverse microorganisms ranging from plant pathogens to mutualists. Among the latter are AM fungi, which are considered the most prominent examples of interactions between plants and microorganisms. This plant-AM fungal interaction significantly affects the competence of the host plant's roots to absorb several nutrients, especially phosphorus (P), from the soil. Production and application of AM fungal inoculum are most easily recognized as an AM fungal technology. However, there is a need to determine the mechanism of plant-AM fungal interaction within given socio-economic constraints for the sustainable functioning of agroecosystems.

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INTRODUCTION

Recent research has focused more on understanding and interpreting the function and composition of microbiomes between plants and soil. The term "plant microbiome" refers to plants' association with various microorganisms that play a vital role in the niches inhabited. These microorganisms are found in the endosphere occupying the inner tissues of the host plant's roots. While the phyllosphere occupies the outer plant surfaces, such as stems, leaves, flowers, and fruits, the rhizosphere occupies the soil surrounding the host plant's roots (Thomas *et al.,* 2022). These microorganisms dwelling in the different niches of the host plant are involved in its ecology and physiology. They are known to significantly increase the soil nutrient availability to the host plant and increase its resistance to stress. These microorganisms living either in the endosphere or phyllosphere between plants and soil are predominantly bacteria and fungi (Berendsen *et al.,* 2012). Interestingly, the rhizosphere microbiome associated with plant roots has received inimitable attention in recent years due to its chief role in the host plant's growth, nutrition, immunity, development, and productivity. Prospective studies of the rhizosphere microbiome have been coupled with the need for more sustainable production for agroecosystems (Thomas *et al.,* 2022).

Rhizosphere microbiome

The rhizosphere microbiome is diverse with a wide range of microorganisms, including bacteria, oomycetes, fungi, algae, nematodes, viruses, protozoa, and archaea (Bonkowski *et al.,* 2009). The soil mycobiome, particularly in itself, contains functionally varied fungi, many of which are plant pathogens that reduce plant performance (Nilsson *et al.,* 2019). On the other side, mutualistic fungal taxa such as AM fungi are notable examples of interactions between plants and microbiota (Koide and Mosse, 2004; Jiang *et al.,* 2020). Plant-microbe interactions significantly impact plant functioning and plant community ecology (Moënne-Loccoz *et al.,* 2015). It is assumed that fungi are the most effective soil microorganisms involved in soil structure stabilization (Foster, 1994). AM fungi often comprise an extensive soil microbiome (Hayman, 1978). This plant-AM fungal interaction significantly affects the competence of the host plant's roots to absorb several nutrients from the soil.

Plant-arbuscular mycorrhizal (AM) fungal interaction

Rhizosphere communities are affluent in AM fungi. AM fungi are ubiquitous soil fungi that form a symbiotic association with plant roots (Smith and Read, 2008). Belonging to the phylum *Glomeromycota*, these fungi are a monophyletic lineage of obligate mycobionts with tight regulation of carbon for nutrients exchange between the host and the fungus (Schüßler *et al.,* 2001; Rillig *et al.,* 2016). As the phylum is an ancient form of symbiosis in plants, about 90% of extant plant species are mycorrhizal (Moënne-Loccoz *et al.,* 2015). The fungus penetrates plant root cell walls and develops intra-radical structures (hyphae, arbuscules, vesicles) in the cortical cells of the host root and extra-radical structures (hyphae, spores) in soil. A bidirectional nutrient flux characterizes this mutualistic association wherein the mycobiont helps the phytobiont in the acquisition of soil nutrients (mainly P.) while the phytobiont provides photo-assimilates (carbon sources) to the mycobiont (Buscot *et al.,* 2000; Brundrett, 2009).

AM fungi being vital components at the soil-root interface, their extra-radical hyphae and plant root hairs increase the soil-root contact area (Geelhoed *et al.,* 1997b). Therefore, AM fungi enhance the plant nutrient availability, particularly P, due to the presence of a large interface for P acquisition via an extensive mycorrhizal extra-radical mycelium network (Wang *et al.,* 2017). AM fungi also improve plant nutrient uptake of calcium (Ca) (Azcón and Barea, 1992), iron (Fe)

(Treeby, 1992), manganese (Mn) (Kothari *et al.,*1991), zinc (Zn) (Bell *et al.,*1989)*,* and nitrogen (N) (Näsholm *et al.,* 2009). AM fungi are most beneficial in improving plant nutrient acquisition in low-fertility soils (Brundrett, 2009). It is assumed that they can serve as a substitute for reduced fertilizer input (Galvez *et al.,* 2001), thereby leading to sustainable agriculture. Plant benefit other than nutritional attributed by AM fungi includes enhanced plant tolerance to biotic stress (pathogenic infection, herbivory) and abiotic stress (drought, metal pollution, salinity) (Augé, 2004; Al-Karaki, 2006; Bennett and Bever, 2007); Improved rooting of micro-propagated plantlets (Strullu, 1985) resulting in an overall increase in plant growth and development; Improved nutrient cycling, energy flow and plant establishment in disturbed ecosystems (Tiwari and Sati, 2008); Enhanced diversity of plant community. AM fungi through their extensive mycelial network interconnect a number of unrelated individual plant species consequently impacting the function and biodiversity of entire ecosystem (Smith *et al.,* 1997; Bonfante and Genre, 2010). Secretion of hydrophobic 'sticky' proteinaceous substance known as 'glomalin' by the AM fungal hyphae in the soil also results in improved soil stability, binding, and water retention thereby reducing soil erosion (Rillig *et al.,* 2002; Rillig and Mummey, 2006; Bedini *et al.,* 2009); Influencing microbial and chemical environment of the mycorrhizosphere (plant root-associated microbial communities especially mycorrhizae present in the rhizosphere) to contribute in plant nutrient acquisition (Azcón-Aguilar and Barea, 2015); more precisely the hyphosphere, the zone surrounding individual hyphae (Johansson *et al.,* 2004); Alleviating metal toxicity to plants by reducing metal translocation from root to shoot (Leyval *et al.,* 1997) and thus contribute in revegetation and restoration of disturbed or contaminated lands; and, Not only alter a plant's response to dynamic environmental fluctuations, but also modulate their metabolome through different pathways, affecting biosynthesis of phytochemicals that are vital for human health (Sbrana *et al.,* 2014). Thus, AM fungi also contribute to the earth's ecosystem services (Gianinazzi *et al.,* 2010).

Potential role of plant-arbuscular mycorrhizal (AM) fungal interaction in sustainable agroecosystems

The integral significance of soil life in agroecosystem sustainability, including plant-symbiotic associations, is increasingly appreciated (Mäder *et al.,* 2002; Wagg *et al.,* 2014; Bender *et al.,* 2016). Among these plant-symbiotic associations, a prominent player is arbuscular mycorrhiza, the predominant symbiotic association of fungi with plant roots (Smith and Read, 2008). The role of arbuscular mycorrhiza in agroecosystems is well known (Rillig *et al.,* 2016). The AM fungal association has been much considered in the context of agroecosystem sustainability, (i) because AM is the most common and dominant type of mycorrhiza formed by most crop plants (exception of *Brassicaceae* members); (ii) because of the potentially beneficial, multi-functional role of AM fungi in plant nutrition, pathogen protection, stress tolerance and soil structure maintenance (Hamel, 1996; Smith and Read, 2008; Gianinazzi *et al.,* 2010; Leifheit *et al.,* 2014); (iii) because many agricultural practices (e.g., tillage, fertilization, non-host crops) tend to negatively affect AM fungal abundance and diversity, thus possibly affecting their functioning; and (iv) because AM fungi can be managed (Rillig *et al.,* 2016).

Although native AM fungi have been demonstrated to be equally or even better performing than commercial isolates, most market inocula are composed of ubiquitous species in nearly all soils in the world (Smith and Read, 2008). Among 340 AM fungal species described so far, most commercial inocula in agriculture contain *Rhizophagus, Glomus,* and *Funneliformis* species because these genera are most prevalent in soils found in all climate zones (Smith and Read, 2008). AM fungal inocula can be effectively produced starting from indigenous soils, making the AM fungal technology more profitable for farmers and more ecologically friendly and supportive for natural biodiversity (Berruti *et al.,* 2016). Moreover, inoculation with AM fungal consortia, which co-evolves in local ecological niches, is more dynamic and sustaining than inoculation with a single species (Sharma *et al.,* 2017). Using a high-quality inoculum containing a combination of species with a high number of infective propagules dedicated to a particular host and growing conditions enable successful root colonization (Rouphael *et al.,* 2015). The most easily recognized AM fungal technology is the production and application of AM fungal inoculum directly addressing the decline of AM fungal abundance in agricultural fields (Gianinazzi *et al.,* 2002; Vosatka *et al.,* 2012; Solaiman *et al.,* 2014). However, this should not be the exclusive focus of AM fungal technology. The local AM fungal abundance and diversity should be optimized in yield and sustainability of ecosystem processes within given socio-economic limitations (Rillig *et al.,* 2016).

In conclusion, we need to ascertain the mechanism of plant-AM fungal interaction within given socio-economic conditions of the agroecosystem by assessment of indigenous AM fungal abundance, diversity, and functioning in the field, by proper management of agronomic practices with known effects on AM fungi, by promoting mycorrhizal fungi and their associated microbiota with desirable traits to develop the appropriate AM fungal technology for attaining sustainable functioning of agroecosystems.

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