The Role of Arbuscular Mycorrhiza in Sustainable Agriculture

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Abstract

Eighty percent of plants, including field crops, vegetables, fruit trees, and ornamental and medicinal plants, have arbuscular mycorrhiza. Arbuscular mycorrhizal fungi form arbuscules in the endodermis of root tissue, and an extramatrical fine hyphal net. Arbuscular mycorrhizal fungi help in the management of diseases caused by fungi, fungal-like organisms, nematodes, bacteria, phytoplasmas, and physiological disorders by increasing the absorption of water and nutrient elements for plants, competing with pathogens for nutrients and establishment site, making changes in chemical constituents of plant tissues, changing the root structure, alleviating the environmental stresses, and increasing the population of useful bacteria in soil. They also contribute to optimum plant growth and improved nutrient absorption in heavy metal-contaminated soils. As a result, in disturbed lands, arbuscular mycorrhizal fungi are powerful biological restoratives. They will help to minimize the use of chemical fertilizers and pesticides, which are both detrimental to the environment and agricultural product consumers. The use of these beneficial fungi can increase crop production and establish sustainable nonchemical agriculture.

Keywords

Funneliformis · Glomeromycota · *Glomus* · Phosphorous

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4.1 Introduction

Arbuscular mycorrhiza is found in 80% of plants, including field crops, fruit trees, vegetables, and ornamental and medicinal plants (Avazzadeh-Mehrian and Sadravi 2017; Błaszkowski et al. 2010; Smith and Read 2008). Arbuscular mycorrhizal fungi (AMF) spores usually have plentiful storage lipid, some carbohydrate, and thick walls with chitin and at some instances with β1–3-glucan (Driver et al. 2005). The growth of hyphae as spore germination involves some reserves of carbohydrates and lipids, nuclear division, and production of limited amounts of branching coenocytic mycelium. Signal molecules from the roots of an associated plant will stimulate hyphal branching. Low soil phosphorus concentrations increase the growth and branching of the hyphae as well as induce plant exudation. The hyphae penetrate into the hairy and lateral roots and grow between epidermal cells. Most of these fungi appear between the cells of the root parenchyma, producing oval or ovoid "vesicles" with a thin wall in the middle or at the end of the hyphae (Fig. 4.1a). Due to the fact that these vesicles are rich in fat and their number increases in old roots, they are considered as a source of food storage and energy of the fungus and are durable after plant death in the soil. In this way, the fungus can survive in the root tissue for a long time if the roots are not removed from the soil. All of these fungi, inside the cells of endodermis, produce a shrub-like structure called "arbuscule" between the plasma membrane and the cell wall, which is rich in nuclei, glycogen particles, fat globules, and vacuoles. Arbuscules are the specific structures of arbuscular mycorrhizal fungi and the sites for the interchange of nutrients such as phosphorus, water, and carbohydrate (Fig. 4.1b). AMF produce a delicate network of "extraradical hyphae" on the root surface, after establishment in the root tissue. This hyphal network absorbs water and nutrients and transfers them to the root tissues and arbuscles. Spores are produced at the tips of extraradical hyphae branches, and after being released from the mother cell and germinating, they mutualize with other parts of the same plant's root or adjacent plants (Peterson et al. 2004).

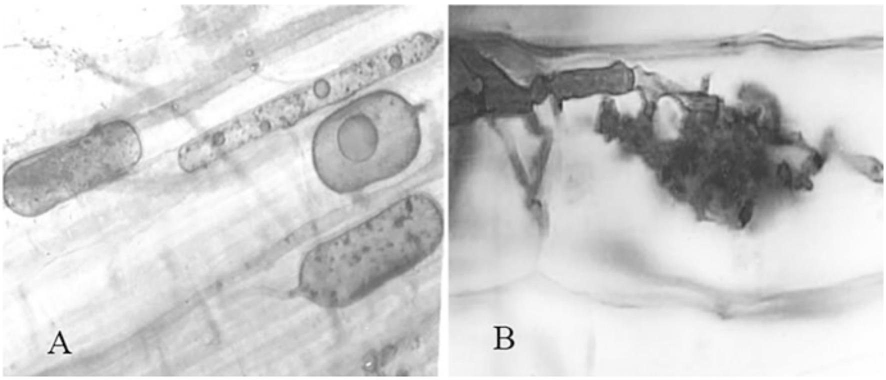

Fig. 4.1 Arbuscular mycorrhizal structure: (**A**) vesicles between the cells of the root parenchyma, (**B**) arbuscule inside the cell of root endodermis

Arbuscular mycorrhiza or endomycorrhiza is associated with mutual benefits, which means that the fungus provides more water and nutrients, and in return the plant supplies necessary carbohydrates for the fungus. AMF increase plant resistance to drought, environmental stresses, soil and water salinity, and soilborne pathogens. They also increase the activity of nitrogen-fixing bacteria leading to increase in agricultural yield and also uplift the efficiency of plants to grow in deserts, sand dunes, and contaminated soils (Sadravi 2000, 2005; Ray 2020).

4.2 The Range of Symbiotic Plants

The range of symbiotic plants of AM fungi is extremely wide, viz. wheat, barley, corn, sorghum, alfalfa, soybean, sunflower, sesame, cotton, apple, grape, olive, jujube, peace lily, ceriman, syngonium, pothos, sansevieria, asparagus fern, and spineless yucca (Avazzadeh-Mehrian and Sadravi 2017; Błaszkowski et al. 2010; Sadravi 2002, 2003, 2004, 2006a, b, c, d, 2007, 2010; Sadravi and Gharacheh 2015; Sadravi et al. 1999, 2000; Sadravi and Moshiri-Rezvany 2019; Sadravi and Seifi 2002). Moreover, arbuscular mycorrhiza has been reported in most herbaceous plants, and some valuable trees such as *Acer*, *Araucaria*, *Podocarpus*, and *Agathis*, as well as all members of *Taxodiaceae*, *Cupressaceae*, *Cephalotaxaceae*, and *Taxaceae* in addition to most tropical hardwoods. Reports available on plants in several major families, including *Brassicaceae*, *Chenopodiaceae*, *Polygonaceae*, *Caryophyllaceae*, *Proteaceae*, and *Juncaceae*, do not show any mycorrhizal symbiosis (Smith and Read 2008).

4.3 Taxonomy of Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhiza is thought to have formed about 1000 million years ago, at the same time as plants began to emerge on land (Fortin et al. 2005). AM fungi were probably important in plant colonization of land due to their roles in nutrient uptake. The first species of AM fungi were introduced in the genus *Glomus* in 1845, followed by the genera *Sclerocystis*, *Acaulospora*, *Gigaspora*, *Entrophospora*, *Scutellospora*, and others (Schenck and Perez 1990). Arbuscular mycorrhizal fungi were placed in the *Endogonales* (*Zygomycota*) due to their aseptate hyphae and similar spores to the zygospores of *Endogone* species, more than two decades ago (Morton and Benny 1990; Morton and Redecker 2001). The first attempt at representing phylogenetic relationships was made using cladistic tools and assuming a new monophyletic order *Glomales* (*Zygomycota*), containing only those fungi for which carbon is acquired obligately from their host plants via arbuscules. Then by genetic analysis, arbuscular mycorrhizal fungi were placed in the independent new phylum *Glomeromycota* (Schüβler et al. 2001). Since then, the taxonomy of arbuscular mycorrhizal fungi has greatly progressed (Oehl et al. 2008; Krüger et al. 2012; Wijayawardene et al. 2020). The latest taxonomy of AMF is given in Table 4.1.

Table 4.1 Taxonomy of arbuscular mycorrhizal fungi (Phylum: *Glomeromycota*)

Class	Order	Family	Genus	Species (type)
Glomeromycetes	*Glomerales*	*Glomeraceae*	*Glomus*	*G. macrocarpum*
			Funneliformis	*F. mosseae*
			Dominikia	*D. minuta*
			Halonatospora	*H. pansihalos*
			Kamienskia	*K. bistrata*
			Oehlia	*O. diaphana*
			Rhizophagus	*R. populinus*
			Sclerocystis	*S. coremioides*
			Sclerocarpum	*S. amazonicum*
		Claroideoglomeraceae	*Claroideoglomus*	*C. claroideum*
	Diversisporales	*Acaulosporaceae*	*Acaulospora*	*A. laevis*
			Entrophospora	*E. infrequens*
		Diversisporaceae	*Diversispora*	*D. spurca*
			Corymbiglomus	*C. corymbiforme*
			Desertispora	*D. omaniana*
			Otospora	*O. bareai*
			Redeckera	*R. megalocarpa*
			Tricispora	*T. nevadensis*
		Gigasporaceae	*Gigaspora*	*G. gigantea*
			Scutellospora	*S. calospora*
			Bulbospora	*B. minima*
			Cetraspora	*C. gilmorei*
			Dentiscutata	*D. nigra*
			Intraornatospora	*I. intraornata*
			Paradentiscutata	*P. baiana*

			Racocetra	*R. coralloidea*
		Pacisporaceae	*Pacispora*	*P. scintillans*
		Sacculosporaceae	*Sacculospora*	*S. baltica*
Archaeosporomycetes	*Archaeosporales*	*Archaeosporaceae*	*Archaeospora*	*A. trappei*
			Palaeospora	*P. spainiae*
		Ambisporaceae	*Ambispora*	*A. fennica*
		Geosiphonaceae	*Geosiphon*	*G. pyriformis*
Paraglomeromycetes	*Paraglomerales*	*Paraglomeraceae*	*Paraglomus*	*P. occultum*
			Innospora	*I. majewskii*
		Pervetustaceae	*Pervetustus*	*P. simplex*

4.4 The Role of AM Fungi in the Management of Plant Diseases

4.4.1 Impact on Fungal and Fungal-Like Diseases

Symbiosis of *Funneliformis mosseae* (T.H. Nicolson and Gerd.) C. Walker and A. Schüßler with barley root provides significant protection against infection with *Gaeumannomyces graminis* (Sacc.) vonArex and Olivier var. *tritici* Walker, the cause of take-all disease (Castellanos-Morales et al. 2011). *Rhizophagus intraradices* (N.C. Schenck and G.S. Sm.) C. Walker and A. Schüßler symbiosis with chickpea root increased growth, number of pods, nitrogen, potassium, and phosphorus content, stem dry weight, and number of nitrogen-fixing bacterial nodules in the root, and reduced root rot caused by *Macrophomina phaseolina* (Tassi) Goidanich (Akhtar and Siddiqui 2010). In greenhouse, inoculating a mixture of several arbuscular mycorrhizal fungi into cucumber roots increases growth and controls vascular wilt caused by *Fusarium oxysporum* f. sp. *cucumerinum* J.H. Owen (Hu et al. 2010). The combination of a mixture of two AM fungi, and *Pseudomonas fluorescens* (Flugge 1886) Migula 1895, significantly reduces root rot of French bean (*Phaseolus vulgaris* L.) caused by *Rhizoctonia solani* J.G. Kühn and increases growth and yield (Neeraj 2011). The mixture of *F. mosseae* and *R. intraradices* significantly protected strawberry against wilt disease caused by *Verticillium dahliae* Klebahn, as well as showed a 60% increase in yield (Tahmatsidou et al. 2006). *R. intraradices*, *Trichoderma harzianum* Rifai, and *P. fluorescens* were inoculated alone or in combination with tomato in greenhouse and field conditions, to control Fusarium wilt disease caused by *Fusarium oxysporum* f. sp. *lycopersici*. All treatments significantly reduce disease severity, but the combination of these fungi and bacterium has the best effect, as this treatment reduces the disease severity by 74% and provides a 20% increase in yield (Srivastava et al. 2009). Cucumber inoculation with *F. mosseae*, *Penicillium simplicissimum* (Oudem.) Thom, and *T. harzianum*, alone or in combination with control seedling damping-off by *R. solani*, showed that although each of these fungi can reduce disease severity, the best effect has been the mixture treatment of *F. mosseae* + *T. harzianum* (Chandanie et al. 2009). Inoculation of pea root with *R. intraradices* increased phosphorus in plant tissues and significantly reduced the severity of root rot caused by *Aphanomyces euteiches* Drechsler (Bodker et al. 1998). Inoculation of three citrus cultivars' seedling roots with the inoculum of *Acaulospora tuberculata* Janos and Trappe, and *Claroideoglomus etunicatum* (WN Becker and Gerd.) C. Walker and A. Schüßler for root rot disease control, caused by *Phytophthora nicotianae* Breda de Haan, significantly decreased dieback and increased the amount of phosphorus in leaves (Watanarojanaporn et al. 2011).

4.4.2 Impact on Plant Parasitic Nematodes

A review of 65 research articles on the effect of AM fungi on plant parasitic nematodes has shown that among the AM fungi *R. intraradices*, *C. etunicatum*, and *F. mosseae* have the ability to reduce damage of root-knot nematodes (*Meloidogyne* sp.) and *Tylenchorhynchus* sp. (Gera Hol and Cook 2005). Cherry seedlings inoculated with *R. intraradices* showed significantly higher weight (in wet) and stem diameter than non-mycorrhizal seedlings and were more resistant to *Pratylenchus vulnus* Allen and Jensen (Pinochet et al. 1995). Apple seedlings inoculated with *F. mosseae* showed more resistance to *P. vulnus*, and their wet root weight and branch length were significantly higher than non-mycorrhizal seedlings (Pinochet et al. 1993). Symbiosis of *F. mosseae* with citrus roots has protected the roots against *Radopholus similis* Cobb and reduced the nematode population by 50% (Elsen et al. 2001). While stimulating plant growth, inoculation of tomato rootstocks with *Funneliformis coronatus* (Giovann.) C. Walker and A. Schüßler significantly reduced infection with the root-knot nematode *Meloidogyne incognita* (Kofoid and White) Chitwood (Diedhiou et al. 2003).

4.4.3 Impact on Plant Bacterial Diseases

Tomato plants colonized with an arbuscular mycorrhizal fungus, that were inoculated by the wilt-causing bacterium *Pseudomonas syringae* pv. *syringae* van Hall 1902, after 3 weeks showed higher growth than non-mycorrhizal plants (Garcia-Garrido and Ocampo 1989).

4.4.4 Impact on Phytoplasmas

Inoculation of tobacco root with an arbuscular mycorrhizal fungus to investigate its effect on aster yellows disease has also showed that this symbiosis significantly increases root length and photosynthesis of diseased plants (Kaminska et al. 2010).

4.4.5 Impact on Plants' Physiological Disorders

In a greenhouse experiment, inoculating tomato seedlings with *F. mosseae* significantly improved their growth and yield in saline soil compared to uninoculated plants (Zhong Qun et al. 2007). Inoculation of the roots of coffee seedlings with *Glomus* sp. increased their resistance to drought and salinity of water and soil (Andrade et al. 2009).

4.5 Arbuscular Mycorrhizal Fungi's Mode of Action

4.5.1 Greater Water and Nutrient Uptake, and Minimizing Environmental Stresses

Arbuscular mycorrhizal fungi increase water uptake and transfer into the roots of symbiotic plants due to an increase in root absorption area by an extramatrical hyphal net. Also, the penetration of their arbuscules to endodermis cells provides a suitable path across the root for water to move and reach the woody vessels. These fungi also increase root growth, which in turn provides an extensive root system for water uptake. These fungi increase the uptake of inactive nutrients such as phosphorus from the soil, by secretion of enzyme phosphatase. Increased phosphorus absorption by these fungi for plants contributes to increased growth rate and faster passage of the plant through the critical stage of youth, as well as the ability of cells to proliferate and repair damaged tissues from soilborne pathogens. Arbuscular mycorrhizal fungi increase the absorption of water and nutrients, making plants more resistant to environmental stresses such as drought and nutrient deficiency (Pfleger and Linderman 1994).

4.5.2 Changes in Plant Tissue Chemicals

Colonization of peanut (*Arachis hypogaea* L.) and leek (*Allium porrum* (L.) J. Gay) roots by an arbuscular mycorrhizal fungus increased levels of ortho-dihydric phenol, a potent inhibitor of soilborne pathogens (Mahadevan 1991). An increase in isoflavonoid phytoalexin-like substances has been reported in soybean arbuscular mycorrhizal roots, which have shown resistance to infection by pathogenic fungi and nematodes (Pfleger and Linderman 1994).

4.5.3 Compete with Pathogens for Location and Nutrients

Plant parasitic nematodes usually attack roots and require plant-produced nutrients for growth and reproduction. Earlier establishment of arbuscular mycorrhizal fungi prevents nematodes from developing and absorbing nutrients (Gera Hol and Cook 2005).

4.5.4 Structural Changes in Roots

Increased lignification has been observed in mycorrhizal root cells of cucumber and tomato, which is considered to be the main factor in their resistance to vascular Fusarium wilt (Pfleger and Linderman 1994; Tahat et al. 2010).

4.5.5 Increasing the Population of Beneficial Soil Bacteria

Mycorrhizal roots have richer exudates that provide a suitable environment for the growth of beneficial soil bacteria. The extramatrical hypha of AM fungi also causes fine soil particles to aggregate and improve airflow in the soil, which is essential for the growth and propagation of soil bacteria. As a consequence, the population of nitrogen-fixing bacteria, plant growth-promoting rhizobacteria (PGPR), and a number of gram-positive bacteria in the rhizosphere increases, and the population of pathogens from the genus *Fusarium* or *Phytophthora* decreases significantly (Tarkka and Frey-Klett 2008).

4.6 AM Fungi's Importance in Phytoremediation of Polluted Soils

The expansion of cities and industrial factories has increased the contamination of limited agricultural lands with harmful substances from industrial wastewaters or urban wastes, posing a serious threat to society's sustainable production of agricultural products and food security. Toxic elements such as lead, copper, zinc, mercury, arsenic, cadmium, and nickel can enter water or soil through industrial and urban wastewater or through the extensive use of chemical fertilizers or herbicides, and pesticides. These heavy metals also increase the risk of oxidation of plant tissues, resulting in symptoms of root rot, plant yellowing, and stunted growth. The presence of these heavy metals in water and soil resource reduces the activity of beneficial microorganisms such as PGPRs and soil fertility, ultimately leading to significant yield reduction. Cadmium, one of these toxic heavy metals, prevents the growth of roots and stems, affects the absorption of essential nutrients from the soil, and often accumulates in the product. Refining soils contaminated with heavy metals requires a lot of energy and money. Methods such as excavation or soil leaching can damage the structure and soil fertility and transfer contaminants to groundwater. Green refining has been proposed as a low-cost, environmental-friendly alternative technology. Phytoremediation is a technology that uses plants to remove, decompose, or produce less hazardous materials in soil and water. This method uses plants that have the ability to tolerate or store large amounts of metal in the rhizosphere and their tissues. Plants that are symbiotic with AM fungi show a greater ability to regenerate contaminated soil (Schutzendüble and Polle 2001; Gaur and Adholeya 2004). AM fungi cause selective permeability of roots by forming extraradical hypha (Sudova and Vosatka 2007). The mechanisms that these fungi use to reduce the stress of heavy metals on plants include chelating of heavy metals, improving mineral nutrition (especially phosphorus) for the plant and accelerating growth, changing the pH of the rhizosphere, and regulating the expression of metal transporter genes (Gonzalez-Guerrero et al. 2005). The cell wall materials of AM fungi have compounds (e.g., hydroxyl and carboxyl and free amino acid groups) which can bind to toxic heavy metals and immobilize them. Cell wall proteins of AM fungi such as glomalin also show the ability to combine with heavy metals and inactivate them. In a cadmium-contaminated soil, *F. mosseae* symbiosis with clover has inhibited its impact on optimal plant growth and production (Biro and Takacs 2007). Arbuscular mycorrhiza of sorghum in lead-contaminated soil stabilizes and inactivates this heavy metal in fungal organs by polyphosphate granules (Wong et al. 2007).

4.7 Conclusion

The increased use of chemical fertilizers and pesticides presents significant risks to human society and the environment. Arbuscular mycorrhizal fungi have symbiosis with most field crops, fruit trees, vegetables, and ornamental and medicinal plants. Some of the AMF can increase water and nutrient uptake for plants and resistance to pathogens and decrease soil pollution. Therefore, through sufficient inoculation with efficient AM fungus, plants can be well protected against diseases, environmental stresses, and soil contamination with toxic elements. The following factors should be considered when using them: (a) efficiency of the arbuscular mycorrhizal fungus used; (b) sufficient amount of inoculation of these fungi; (c) suitability of the symbiotic plant genotype (although these fungi do not have a specific host, in terms of root tissue establishment and multiplication in it, there may be differences between different cultivars of a plant, which affects their efficiency); (d) inoculation and their establishment before the attack of pathogens; and (e) suitability of physical and chemical conditions of soil and environmental conditions for their maximum efficiency and deterrence of pathogens. Also, for the survival of AM fungi in the soil, need to be performed agricultural operations with minimal tillage after harvesting, and set up a crops rotation with well symbiotic plants including cereals and legumes to increase their population. In this way, while increasing their efficiency, their inhibitory power from pathogens will be stable. The use of these beneficial fungi can increase crop production and establish sustainable nonchemical agriculture.

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