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Mycorrhiza: An under earth revolution for sustainable food production

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Abstract
After green revolution the use of chemical fertilizers and pesticide has increased substantially throughout the world which deteriorated quality and health of our natural resources like soil, water and air (Abbasi *et al.,* 2015). So, the production and productivity growth rate of major crops are also stagnated or even declined during this green revolution era. Mycorrhizal associations are extremely abundant in the plant kingdom. Estimates suggest that 74% of all plant species form AMs with fungi of the Glomeromycota clade (Smith & Read, 2008; Brundrett, 2009). Mycorrhizas improve the availability of nutrients which are immobile and have very low diffusive movement. The increase in inorganic nutrient uptake in mycorrhizal plants is mainly because fungal hyphae provide the large surface area for nutrient acquisition to external root surface as compared to uninfected roots (Aggarwal *et al.*, 2011). The combination of an extensive hyphal network and the secretion of glomalin is considered to be an important element in stabilization of soil aggregates (Rillig and Mummey 2006), thereby leading to increased soil structural stability and quality (Bedini *et al.,* 2009; Caravaca *et al.,* 2006). Some of the strains of Mycorrhizal fungi can tolerate heavy metal stress, among which, *Glomus intraradices*, *Glomus mosseae* and some other species of *Glomus* are important (Bano and Ashfaq, 2013). It is also becoming evident that the AM symbiosis can stimulate the synthesis of plant secondary metabolites, which are important for increased plant tolerance to abiotic and biotic stresses or beneficial to human health through their antioxidant activity (Seeram, 2008). Thus Arbuscular mycorrhiza is a holistic approach for sustainable agriculture production, disease management addressing different environmental issues, including 'carbon-neutral' energy, ecologically sustainable land.

Keywords: Arbuscular mycorrizal fungi, carbon sequestration, abiotic stresses, soil stabilization

Introduction

The intensification of agriculture is requisite for production of food for growing population. However this intensification impose some serious threats on environment like climate change; a high rate of biodiversity loss; land degradation through soil erosion, compaction, salinization and pollution; depletion and pollution of water resources; rising production costs; an ever decreasing number of farms and, linked with that, poverty and a decrease of the rural population (Velten *et al.*, 2015) [52]. After green revolution the use of chemical fertilizers and pesticide has increased substantially throughout the world which deteriorated quality and health of our natural resources like soil, water and air (Abbasi *et al.*, 2015). So, the production and productivity growth rate of major crops are also stagnated or even declined during this green revolution era.

The sustainable agriculture has been proved as an alternative for conventional intensified agriculture which hold soil and crop productivity by using of farming techniques that protect the environment, public health, human communities, and animal welfare (Siddiqui and Pichtel, 2008) [44]. In this concern, maintenance of quality and health of soil, a nonrenewable resource, is important issue which performs many social and environmental functions, some of them performed by soil microbes (Zacarini *et al.*, 2013). Among these microbes, arbuscular mycorrhia is a low input strategy which benefits the plant by number of ways and increase overall production and productivity. Arbuscular mycorrhizal fungi (AMF) or endomycorrhizae, including fungi belongs to the recently established phylum Glomeromycota (Schüßler *et al.*, 2001) [41]. AMF are crucial for the functioning of terrestrial ecosystems and terrestrial plants form symbiotic interactions with AMF and colonize more than 80% of plant roots (Brundrett, 2004) [7]. Mycorrhiza is one of the most widely occurring soil microbe which improve soil microbial biomass carbon and helpful in nutrient cycling (Harley and Smith, 1983) [13]. They improve nutrient uptake, especially P, and also uptake of micronutrients such as zinc or copper; they stimulate the production of growth substances and may reduce stresses, diseases or pest attack (Sylvia and William, 1992; Davet, 1996; Smith and Read, 1997) [47].

Biodiversity of Am Fungi

The seven types of mycorrhizae described are arbuscular, ecto, ectendo, arbutoid, monotropoid, ericoid and orchidaceous Mycorrhizae. Among them, arbuscular mycorrhizae and ectomycorrhizae are the most abundant and widespread (Smith and Read, 1997; Allen *et al.,* 2003) [47, 2]. Mycorrhizal associations are extremely abundant in the plant kingdom. Estimates suggest that 74% of all plant species form AMs with fungi of the Glomeromycota clade (Smith & Read, 2008; Brundrett, 2009) [46]. The Glomeromycota is divided into 4 orders, 8 families, 10 genera and 150 species. The common genera are *Acaulospora*, *Gigaspora*, *Glomus* and *Scutellospora* (Schüßler, 2005) [40]. They are characterized by the presence of extra radical mycelium branched haustoria-like structure within the cortical cells, termed arbuscules, and are the main site of nutrient transfer between the two symbiotic partners (Hock and Verma, 1995; Smith and Read, 1997) [47]. AM fungi colonize plant roots and penetrate into surrounding soil, extending the root depletion zone and the root system. The arbuscular mycorrhizal fungi are the most complex group of mycorrhizas which forms:

1) Intracellular hyphae forming coils, often found in the outer layers of cortical parenchyma.
2) The intercellular hyphae.
3) The intracellular hyphae with numerous ramifications, i.e., the arbuscules.
4) The inter or intracellular hypertrophied hyphae, i.e., the vesicles.
5) The extracellular ramified hyphae, i.e., branched-absorbing structures (BAS), and
6) Resistance propagules, i.e., the spores. There are plants, however, that have been shown to be mycorrhiza free, such as Proteacea, Cruciferae, Zygophyllaceae Dipterocaceae, Betulaceae, Myrtaceae and Fagacaeae. Although Cactaceae, Chenopodiaceae, Cyperaceae, Amarantaceae and Juncaceae were thought to be mycorrhiza free, most of the species were found to be infected under natural stressed rangeland conditions (Neeraj *et al.,* 1991 Olsson & Tyler 2004) [29]. The reason why some plants do not form mycorrhizas is not fully known, but it may be related to the presence of fungitoxic compounds in root cortical tissue or in root exudates (Quilambo, 2003) [33].

Table 1: Overview of the main roles that the AM symbiosis can play as an ecosystem service provider

AM function	Ecosystem service provided
Root morphology modification and development of a complex, ramifying mycelial network in soil	Increase plant/soil adherence and soil stability (binding action and improvement of soil structure)
Increasing mineral nutrient and water uptake by plants	Promote plant growth while reducing fertilizer requirement
Buffering effect against abiotic stresses	Increased plant resistance to drought, salinity, heavy metals pollution and mineral nutrient depletion
Secretion of ‘glomalin’ into the soil	Increased soil stability and water retention
Protecting against root pathogens	Increased plant resistance against biotic stresses while reducing phytochemical input
Modification of plant metabolism and physiology	Bio regulation of plant development and increase in plant quality for human health

Source: Gianinazzi *et al.,* 2010

Role of Am Fungi in Agriculture Sustainability

Nutrient Acquisition

Mycorrhizas improve the availability of nutrients which are immobile and have very low diffusive movement. The increase in inorganic nutrient uptake in mycorrhizal plants is mainly because fungal hyphae provide the large surface area for nutrient acquisition to external root surface as compared to uninfected roots (Aggarwal *et al.,* 2011) [1]. The most important benefit of mycorrhizae is the increase in the phosphorus uptake by the plant. The various mechanisms proposed to account for enhanced nutrient uptake include.

i) Increased exploration of soil.
ii) Increased translocation of phosphorus into plants through arbuscules.
iii) Modification of root environment.
iv) Efficient utilization of P within plants.
v) Efficient transfer of P to plant roots. and
vi) Increased storage of absorbed P (Rakshit, Bhadoria, 2009: Lambers *et al.,* 2011) [34, 19].

AM improves growth, nodulation and nitrogen fixation in legume-*Rhizobium* symbiosis. They also uptake NH_4^+readily from soil which forms the larger fraction of available nitrogen in many natural ecosystems. According to McFarland *et al.,* (2010) [27] more than 50% of plant N requirement is supplied by mycorrhizal association. The majority of nitrogen is thought to be taken up in the form of ammoniavia the action of fungal-encoded AMT1 family transporters such as the protein GintAMT1 characterized from *Glomus intraradicies* (López-Pedrosa *et al.,* 2006) [24]. AM symbiosis, due to its role in plant nutrition, could also have a positive impact on crop quality, thanks to the enrichment in both macro and micronutrients (Antunes *et al.,* 2012; Pellegrino and Bedini, 2014) [3, 31]. Focusing on Zn, Lehmann *et al.,* (2014) [22] concluded that AM symbiosis positively affected the Zn concentration in various crop plant tissues under distinct environmental conditions. Soil texture, pH, and soil nutrient concentration (i.e. Zn and P deficiency) have in fact an influence on the AM fungus-mediated Zn content in different plant tissues (Lehmann *et al.,* 2014) [22]. Moving attention to copper (Cu), iron (Fe), and manganese (Mn), the study by Lehmann and Rillig (2015) [21] has shown that there is a positive impact of AM symbiosis on these micronutrients.

Soil Aggregation and Soil Stabilization

AM fungal mycelial network can have a binding action on the soil and improve soil structure. Inaddition, the secretion by AM fungi of hydrophobic, ‘sticky’ proteinaceous substances, referred to as glomalin (Rillig *et al.,* 2002) [36], also contributes to soil stability and water retention (Bedini *et al.,* 2009) [35]. The combination of an extensive hyphal network and the secretion of glomalin is considered to be an important element in stabilization of soil aggregates (Rillig and Mummey 2006) [35], thereby leading to increased soil structural stability and quality (Bedini *et al.,* 2009; Caravaca *et al.,* 2006) [35, 8].

Alleviation of Abiotic Stresses

Mineral depletion, drought, salinity, heavy metals or heats are serious problems in many parts of the world, particularly in arid and semi-arid areas (Evelin *et al.*, 2009) [12]. It is predicted that two thirds of cultivable land may disappear in Africa, a third in Asia and one fifth in South America by 2025 and that arable land area per inhabitant in the world will be reduced to 0.15 ha in 2050 (Gianinazzi *et al.*, 2010). The potential of AM fungi to enhance plant tolerance in abiotic stress conditions has long been recognized (Smith and Read, 2008) [46] and their manipulation in sustainable agricultural system will be of tremendous importance for soil quality and crop productivity under severe edapho-climatic conditions (Lal, 2009) [18]. At the levels of both leaves and roots, the osmotic stress usually caused by drought or salinity is counteracted by mycorrhizal plants through biochemical changes that mostly include increased biosynthesis of metabolites (mainly proline and sugars) that act as osmolytes (Serraj and Sinclair, 2002) [43]. These compounds contribute to the lowering of the osmotic potential, and in turn, of the leaf water potential. These lower potentials allow the plants to maintain high organ hydration and turgor that sustain overall cell physiological activity, mainly related to the photosynthetic machinery (Khalvati *et al.*, 2005) [16]. AM plants with stand drought or salinity -induced oxidative stress by the increased production of antioxidant compounds that scavenge ROS and enhance the activities of antioxidant enzymes (Ruiz-Sánchez *et al.*, 2010) [38]. AM root colonization can enhance root growth, architecture, and hydraulic properties and can thus induce the formation of a highly functional root system for nutrient/water uptake. Some of the strains of Mycorrhizal fungi can tolerate heavy metal stress, among which, *Glomus intraradices*, *Glomus mosseae* and some other species of *Glomus* are important (Bano and Ashfaq, 2013) [4]. Heavy metals are mostly accumulated in fungal hyphae as well as in arbuscules. Many heavy metals are immobilized due to the binding capacity of fungal hyphae to metals. The translocation of toxic heavy metals to plants is reduced due to this binding capacity (Brown and Wilkins, 1985) [6]. Furthermore, many phosphate fertilizers are a major source of soil contamination by cadmium in agricultural systems (Lugon-Moulin *et al.*, 2006; Nziguheba and Smolders, 2008) [26, 28] which again pleas for the reduction of crop reliance on phosphate fertilizers. AM fungi, through their mycelium network, not only improve Pi uptake by roots but they also have a buffering effect on the cadmium uptake, reducing the toxic effect of cadmium on plant growth (Rivera-Becerril *et al.*, 2002; López-Millán *et al.*, 2009) [37, 23].

Alleviation of Biotic Stresses

Plants are attacked by various organisms ranging from fungi, bacteria, viruses and nematodes. The establishment of the arbuscular mycorrhizal (AM) symbiosis with plant host is able to reduce the attack of different insect pest and pathogen. The first mechanism proposed to be involved in mycorrhiza-induced protection was the improvement of plant nutrition and the consequent compensation of the damages caused by the pathogen (Pozo *et al.*, 2010) [32]. It is widely accepted that AM symbioses reduce the damage caused by soil-borne pathogens. Many studies revealed a reduction of the incidence and/or severity of diseases as root rot or wilting caused by diverse fungi such as *Fusarium, Rhizoctonia, Macrophomina* or *Verticillium,* bacteria as *Erwinia carotovora,* and oomycetes as *Phytophthora*, *Pythium* and *Aphanomyces.* Several mechanisms have been proposed to explain the protection extended by AMF to host plants against attackby pathogens. Several type of mechanism proposed to describe the mycorrhizal mediated biotic stress tolerance by host plant like increasing root thickenings, and causing chemical differences Amino acid content, particularly arginine has been found to be high in AM plants (Aggarwal *et al.*, 2011) [1]. The establishment of the arbuscular mycorrhizal (AM) symbiosis implies remarkable changes in the physiology of the host plant. The changes span from alterations in the hormonal balance and transcriptional profile to altered primary and secondary metabolism (Hause *et al*, 2007; Liu *et al.*, 2007; Schliemann *et al.*, 2008; López-Ráez *et al.*, 2010) [14, 39, 25].

Table 2: Effect of AM fungi on different plant pathogen

AM fungi	Pathogen type	Effect	References
Nematode			
G. fasciculatum	*M. incognita*	Reduced galling and nematode population on brinjal	Borah and Phukan, 2003
G. fasciculatum	*M. incognita*	Reduced nematode population on tomato	Pradhan *et al.*, 2003
G. intraradices	*M. hapla*	Reduced the no. of galls and egg sacs on tomato cv. ‘Hildares’ but bio control of nematode was not achieved in cv. ‘Tiptop’	Masadeh *et al.*, 2004
G. fasciculatum *G. constrictum* *G. mosseae* *G. intraradices* *Acaulospora* sp. *Sclerocystis* sp.	*M. incognita*	Individually all AM fungi reduced nematode reproduction but the greatest reduction was caused by *G. fasciculatum* on chickpea	Siddiqui and Akhtar, 2006
G. intraradices	*M. incognita*	Combined use of AM fungus with *Pseudomonas straita* and *Rhizobium* caused greater increase in chickpea growth	Akhtar and Siddiqui, 2008a [45]
Fungal disease			
G. mosseae *G. intraradices*	*P. parasitica*	*G. mosseae* was most effective in reducing disease symptoms produced by *P. parasitica* on tomato	Pozo *et al.*, 2002
G. fasciculatum	*F. oxysporum* f. sp. *Ciceris*	Reduced the disease severity in chickpea	Siddiqui and Singh, 2004
G. intraradices	*M. phaseolina*	Significantly reduced disease severity in chickpea	Akhtar and Siddiqui, 2007b
G. mosseae, *G. etunicatum,* *G. fasciculatum* *Gigaspora margarita*	*Phytophthora Capsici*	AM fungi significantly increased plant growth and reduced disease severity in pepper but *G. mosseae* reduced disease severity to a greater extent	Ozgonen and Erkilic, 2007
G. intraradices	*M. phaseolina*	Combined application of *G. intraradices* with *P. alcaligenes* and *B. pumilus* caused a greater reduction in the root-rot of chickpea	Akhtar and Siddiqui, 2008b [45]

Bacterial and viral disease			
G. etunicatum	Citrus tristeza Virus and Citurs urgose virus	Growth of *Citurs macrophylla* inoculated with tristeza virus (T-3 isolate) and Citurs urgose virus(CLRV-2) was not reduced by virus infection in mycorrhizal plants	Nemec and Myhre, 1984
G. mosseae	*P. syringae*	Neither growth of tomato nor percentage VA infection was negatively affected by pathogenic bacteria	Garcia-Garrido and Ocampo, 1989
G. intraradices	Tobacco mosaic virus	Higher incidence and severity of necrotic lesion in mycorrhizal than in non mycorrhizal plants	Shaul *et al.*, 1999
AM fungi	*P. solanacearum*	Disease decrease in eucalyptus seedlings injected with AM fungi	Ming Qin *et al.*, 2004

Source: Siddiqui & Futai, 2008 [44]

Am Fungi and Carbon Sequestration

AM fungi perform various ecological functions in exchange for host photosynthetic carbon (C) that almost always contribute to the fitness of hosts from an individual to community level (Willis *et al.*, 2013) [53]. A commonly known pathway by which AM fungi sequester C in soil is the transfer of photosynthates from the host plants to the AM fungal intraradical hyphae and subsequently to extraradical hyphae before release to the soil matrix (Leake *et al.*, 2004; Parniske 2008) [20, 30]. The turnover of hyphal cell walls, cytoplasm and extracellular polysaccharides represents a relatively labile organic C pool in soils. For example, the Glomeromycota fungi found in grassland soils represent a significant proportion of the fungal biomass pool, and it has been reported that 20-30% of microbial biomass C come from AM fungi (Leake *et al.*, 2004; Zhu and Miller, 2003) [20, 56]. AM fungi hyphae are responsible for the production of a glycoprotein-like substance, glomalin (Wright and Upadhyaya, 1998) [94], which is fairly stable in soils (Steinberg and Rillig, 2003) [50]. The close correlation of the amount of glomalin in soil, hyphallength and stability of soil aggregates is evidence that glomalin could influence soil carbon storage indirectly by stabilizing soilaggregates (Solaiman, 2014) [48]. The overall contribution of AM fungi to soil C sequestration could depend significantly on the quantity and quality of hyphae produced, the age and resilience of hyphal residues, the production of glomalin and the role played by AM fungi in the stabilization of soil aggregates.

Role of Am Fungi in Human Life

Plant produce different metabolites and other medicinal compounds include organosulfides, polyphenols (phenolicacids, anthocyanins, flavonoids), phytosterols, stilbenes, vitamins, lignans and terpenoids including carotenoids (Hooper and Cassidy, 2006; Kirby and Keasling, 2009; Stan *et al.*, 2008) [15, 17, 49] which can be beneficial in preventing diseases such as cancer, cardiovascular and neurodegenerative diseases or microbial infection (Cummings and Kovacic, 2009) [11]. It is also becoming evident that the AM symbiosis can stimulate the synthesis of plant secondary metabolites, which are important for increased plant tolerance to abiotic and biotic stresses or beneficial to human health through their antioxidant activity (Seeram, 2008) [42]. Approximately 30% of the world's soils are Zn deficient, particularly in tropical areas (Cavagnaro, 2008) [9] and this leads to reduced yields and Zncontent in crop products, resulting in inadequate dietary Znintake for many human populations and a negative impact on human health. Several studies have reported that AM can increase Zn uptake by plants even under field conditions (Cavagnaro, 2008) [9]. For example, the Zn content in shoots and fruits of field-grown wild-type mycorrhizal tomato plants was found to be up to 50% higher than in a mutant with reduced mycorrhizal colonisation (rmc) (Cavagnaro *et al.*, 2006) [10]. It is also reported that under field conditions AM fungi can enhance leaf, fruit or bulb accumulation of many molecules with medicinal interest. Although production of these medicinal metabolites not only dependent on AM fungi but also on plant genotype and crop management strategies (Toussaint *et al.*, 2007) [51].

Conclusion

Arbuscular mycorrhizal fungi area important group of microbewhich performs diverse role to improve plant health and nutrition. It is a cost-effective and non-destructive means of achieving high productivity leading to establishment of a viable, low-input farming system. The large scale use of AM fungi is restricted by using plant variety having non responsive to mycorrhizal inoculation, excessive use of fertilizers and adopting mono-cropping and intensive tillage. AM fungal bio fertilizer application and availability is very limited. Nevertheless, considerable progress has been made in the last decade towards the use of AM fungi, particularly for the production of high value crops such as ornamentals or fruit trees. Thus Arbuscular mycorrhiza is a holistic approach for sustainable agriculture production, disease management addressing different environmental issues, including 'carbon-neutral' energy, ecologically sustainable land management and used as a possible substitute to reduce the use of chemical fertilizers.

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