REVIEW ARTICLE

The Potential Roles of Arbuscular Mycorrhizal Fungi in Soil Health and Conservation

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Abstract

Soil is an indispensable resource of the terrestrial ecosystem that provides manifold ecosystem services. Soil functions include regulation of nutrient cycle aided by armies of decomposers present in the soil, anchorage of plants and facilitation of their growth, sustenance of water quality, and regulation of water filtration, air quality, and temperature. Soil health is tightly correlated with sustainable agriculture, owing to the multitudinous microflora and fauna residing in the soil whose activity is instrumental to soil welfare. Maintenance of soil structure and quality is, thus, crucial for facilitating rapid plant growth so that the lag between food production and exponential population growth can be bridled. Regarding this, a major group of soil-dwelling fungus, i.e., Arbuscular mycorrhizal (AM) fungi (AMF), regulate soil quality and ecological interactions operating therein. This review pays attention to the AMF-secreted miracle glycoprotein –"glomalin" that considerably influences soil dynamics. The major takeaway is that mycorrhizal association in the rhizosphere improves soil quality by regulating soil aggregation, tilth and fertility, and enriching soil organic carbon pool. Besides, mycorrhiza-mediated amelioration of contaminated soil, which reflects a prominent role of AMF in ecosystem functioning, is also discussed. Along these lines, further studies should target the functional ecology of AMF in agro-ecosystems, and bioprospecting of more AMF strains should be done to completely harness their potential in biocontrol, bioremediation, and soil conservation.

Keywords: Arbuscular mycorrhizal fungi (AMF), Bioremediation, Glomalin, Soil aggregation, Soil conservation, Soil fertility, Soil organic carbon pool.

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Introduction

Soil is a fundamental resource of the terrestrial ecosystem and is essential for life on earth (Dumanski and Peiretti, 2013). It supports food security and environmental quality that is crucial to human existence (Blanco and Lal, 2008). A healthy ecosystem offers a steady production of environmental goods and services; hence soil quality directly impacts the food quality and quantity to all intents, construction and purposes. Soil ecosystem harbors armies of microscopic flora and fauna and furnishes essential nutrients and water to the plants growing therein.

The importance of soil and its role in human well-being are often ignored until there is a drop in food production resulting from severe soil erosion or degradation of soil to the level that it loses its inherent resilience. Intensive agricultural practices, over the years, have resulted in an altered physical and chemical nature of soil milieu, thereby severely affecting the floral and faunal composition of the soil. Unfortunately, soil responses to these practices have been overlooked in the past, resulting in unforeseen consequences, especially concerning soil health and sustainability. Since plant welfare is intimately connected to soil health, conservation and reinforcement of microfloral wealth will be instrumental in fortifying yield and quality of crops. Maintenance of soil structure is crucial for facilitating biogeochemical cycling, impedance to soil erosion, revitalization of soil carbon and water infiltration into the soil.

Concerning this, a major group of soil fungus, i.e., Arbuscular mycorrhizal fungi (AMF) exert a favourable influence on soil structure and ecological interactions (Rillig, 2004). AMF as a component of soil quality mirrors the significance of symbiosis at the level of community and ecosystem ecology level. AMF are ubiquitous soil-borne microorganisms that are symbiotically associated with the roots of more than 90% of plant species (Smith and Read, 2010) and are thus the vital components of soil ecosystem. This symbiosis is the most ancient and pervasive interaction of plants with fungi belonging to the monophyletic phylum, Glomeromycota (Schüßler *et al.*, 2001, Parniske, 2008). Mycorrhiza, the association between plant and AMF, is regarded as an evolutionary advancement that has facilitated the survival of plants on dry and hostile terrestrial habitat (Pirozynski and Malloch, 1975; Field *et al.*, 2015). Mycorrhizal association improves soil quality through its effects on soil structure and ecology. It plays important roles in soil formation, soil aggregation, soil fertility, nutrient availability and bio-geocycling, and reclamation of degraded ecosystems (Purin and Rillig, 2007; Wang *et al.*, 2019). The hyphal structure of AMF and glomalin secretions aid in soil aggregation and soil structure improvement (Purin and Rillig 2007; Leifheit *et al.*, 2014; Morris *et al.*, 2019). These group of fungi can also make direct contributions to the constitutional properties of soil by improving its water retention capacity, maintaining its pH, increasing soil enzyme activity and organic

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matter content, and also by boosting microfloral wealth in mycorhizosphere (Johansson *et al.*, 2004; Qian *et al.*, 2012; Zhang *et al.*, 2019). Additionally, AMF are also reported to enhance carbon sequestration by plants and recharge the organic carbon pool of the soil (Wang *et al.*, 2016).

In previous years, the impact of AMF on plant communities has turned out to be a primary focus, and possibly the next wave of research can be directed to study the contribution of AMF to ecosystem functioning and processes. AMF prominently contributes to soil quality at an ecosystem scale by regulating various fundamental aspects that govern soil health. However, studies devoted to the effect of AMF on soil quality and its conservation are still minuscule compared to the plethora of literature available on plant responses. In order to develop effective, sustainable soil conservation and management strategies it is imperative to understand AMF contributions to soil quality. This review primarily focuses on the major effects that have been associated with AMF in augmenting soil quality and its conservation. After providing an overview of glomalin, the miracle protein secreted by AMF, and its role in maintaining soil structure and stability, the review highlights the role of AMF in soil aggregation, fertility, resistance to erosion, and carbon sequestration. Further, the bioremediation capacity of mycorrhizae, termed as mycorrhiza-assisted remediation, and their role in the rapid amelioration of contaminated soil have also been acknowledged in the present review. Finally, the review highlights various research trajectories that need to be followed to reinforce the understanding of AMF in the sustainable development of agriculture.

AMF-secreted glomalin: A wonder protein for soil stability and conservation

The ability of AMF to regulate soil quality is ascribed to their beneficial effects on maintenance of soil structure and stability and soil ecological interactions. The improved structure and stability of soil are correlated with glomalin production, which is a persistent glycoprotein released by AMF hyphae and spores. Besides Glomeromycota, no other fungal groups synthesize glomalin in copious amounts. The structural and functional properties of glomalin are akin to fungal hydrophobins that are small, aggregating and insoluble (in water) proteins released by various types of fungi (Nichols and Wright, 2004). Glomalin, in soil, is operationally measured as Glomalin-related soil protein (GRSP) which consists of total glomalin fraction along with other soil proteins (Rillig, 2004). Biochemically, glomalin is an N-linked glycoprotein composed of carbon (36–59%), oxygen (33–49%), nitrogen (3–5%), hydrogen (4-6%), phosphorus (0.03–0.1%), and iron (0.8–8.8%). In 1998, Wright and Upadhaya established a tight correlation between glomalin and water retention and soil aggregate stability across different soil groups. Glomalin, being stable, hydrophobic, and impervious to heat damage, qualifies as an excellent soil binding and stabilizing agent as it forms stable soil aggregates and promotes organo-mineral complexes' development. This glycoprotein glues to the soil particles, forming homogenous aggregates comprising of humus and minerals. Essentially, these soil aggregates facilitate better water retention and root penetration into the soil. Hydrophobic nature of glomalin makes it recalcitrant to microbial decomposition and encourages the molecule's binding to soil surface. Besides hydrophobicity, microbial access to glomalin is denied by its iron-binding properties. Iron molecules bridge glomalin molecules to minerals and other types of organic matter in the soil. Iron concentrations (0.8-8.8%) in glomalin also impart stability to the molecule and prevent thermal degradation (Steinberg and Rillig, 2003; Fokon *et al.*, 2012). In addition to conferring thermal stability to the soil, glomalin has been found to potentially sequester heavy metals, such as, lead, zinc, iron, manganese, copper, and cadmium. This might reflect the capacity of AMF to sequester and immobilize heavy metals in the soil to preclude their entry into the plant system. Glomalin is purported to impart rigidity to the hypha and prevent its wear and tear as it grows between the soil particles. The protective glomalin sheath of senescing hyphae is sloughed off into the soil, where it associates with the organic matter and mineral particles, assembling into micro aggregates.

Glomalin is also believed to improve the tilth and texture of soil to make it stable enough to withstand erosion (by wind and water), but pervious enough to allow movements of air and water and penetration of roots growing through it. These properties of glomalin make it an "essential guardian" of soil and the hyphae dwelling therein (Wright and Upadhyaya, 1999).

Major roles of AMF in soil health and conservation

Soil Aggregation

Soil aggregation is an intricate ecosystem process that involves a relay of formation, stabilization and fragmentation of soil aggregates. It is a dynamic and complex phenomenon that involves physical and chemical interactions. The major factors contributing to soil aggregation include soil microorganisms, plant roots, environmental variables, soil fauna, and inorganic soil-binding agents, like glomalin (Fig. 1) (Golchin *et al.*, 1994; Rillig and Mummey, 2006). Soil aggregates are conglomerations made of soil particles (sand, silt, and clay) and minerals, microbial debris, organic matter, and bacteria that strongly adhere to each other and with the clay coatings (Kemper and Rosenau, 1986). The aggregates are bound by agents, such as fine roots, soil microbes, and fungal hyphae (Tisdall and Oades, 1982; Six *et al.*, 2004). Soil aggregates and the pores of diverse shapes and sizes within the aggregates are crucial in defining soil structure; and they primarily affect the fertility, quality, and sustainability of soil (Lehman *et al.*, 2019). For instance, soil pores maintain habitats of soil microbes, facilitate water infiltration, and promote gas exchange that altogether aid in nutrient biogeochemical cycling. In addition, a pore matrix facilitates penetration and growth of plant roots in soil. Soil erosion mediated by wind and water is reduced in well-aggregated soils (Lehman *et al.*, 2019). Thus, soil structure plays an important role in soil conservation and ecosystem functioning. In this context, a decent body of work has unfolded the contribution of AMF, the master players in various soil food webs, on the processes of soil aggregation. The role of AMF in soil structure and aggregation can be observed at various hierarchical levels of ecosystem, namely, the plant community, individual root system, and the extraradical mycelium (Rillig and Mummey, 2006). Glomalin produced by AMF on the external walls of extraradical hyphae and on abutting soil particles and serves as a durable soil-adhesive agent (Wright and Upadhaya, 1998). Consequently, the hyphae together with fibrous plant roots form a "sticky-string bag that results in enmeshment of soil particles into macroaggregates" (Miller and Jastrow, 2000). These macro aggregates form the structural foundation of the soil (Jeffries *et al*., 2003).

Significant pieces of evidence have demonstrated the role of AMF in influencing the composition and abundance of plant communities by rendering differential benefits to plants in terms of nutrient and water acquisition and mitigation of a/biotic stressors (Klironomos *et al*., 2000). Plant community differentially affects soil aggregation, as demonstrated for natural communities (Rillig *et al*., 2002; Piotrowski *et al*., 2004) and agro-ecosystems (Angers and Caron, 1998). Consequently, changes in the composition of plant community can, in turn, affect soil structure and aggregation. In addition, the net primary productivity of a plant community that directly controls the amount of carbon that may enter the soil as root or litter, determines soil aggregation rate (Rillig and Mummey, 2006).

Plant roots can influence soil structure through rhizodeposition and root decomposition—AM influences rhizodeposition by affecting the plant-cabon metabolism (Douds *et al*., 2000). Root exudates are considered major carbon providers that stimulate aggregate formation (Morel *et al*., 1991). This root-derived carbon is deposited in the rhizosphere where it serves as a fuel for the rhizosphere-dwelling microbes. These microbes further result in the humification of soil and cohesion of soil particles into macro-aggregates, which in turn serve as microhabitats for the soil microbes (Rillig and Mummey, 2006). Similarly, root decomposition also contributes to soil aggregation by delivering organic material. In addition to alteration of root morphology, AMF can also affect the quality of the below-ground litter by altering root chemistry (Langley and Hungate, 2003). This could affect the nature of decomposition products and decomposition rate, consequently affecting soil aggregation.

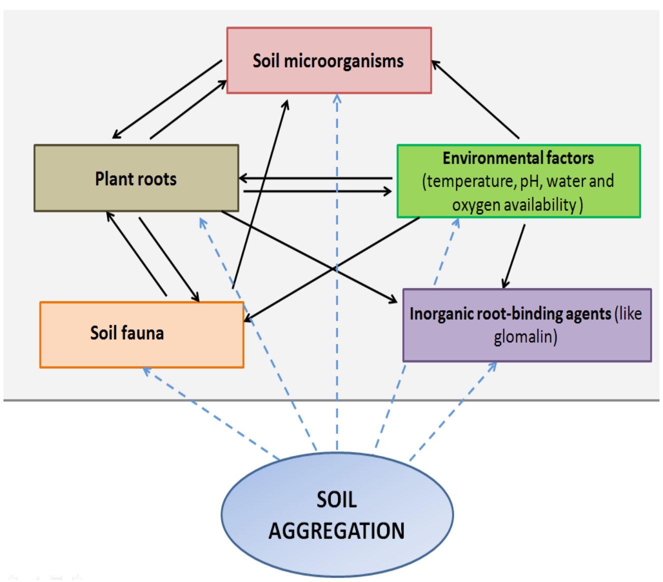

Fig. 1: Interaction and feedback among five major factors that govern the formation and stability of soil aggregates (Pal and Pandey, 2014).

The fundamental characteristic of AMF that helps stabilize soil aggregates is the extensive growth of their extraradical hyphae, which is responsible for the acquisition of nutrients beyond the host's roots (Parniske, 2008; Wilson *et al*., 2009) (Fig 2). The extraradical hyphae of AMF have often been reported to associate with soil stability parameters (Barto *et al*., 2010). Furthermore, the AMF species involved in the process determines the extent to which soil aggregation is formed. This is because different AMF can differentially produce extraradical hyphae (Hart and Reader, 2002). Consequently, various studies have reported variations in the ability of different AM fungal species to form soil aggregates (Piotrowski *et al*., 2004; Enkhtuya and Vosatka, 2005). The growth rate of mycelium exerts physical force in soil, thus pressing particles together and helping in aggregate formation. It also stabilizes soil aggregates by continuously delivering plant-derived carbon to the aggregate surfaces, thus rapidly bridging the planes of weakness (Rillig and Mummey, 2006). Till date, only a few studies have addressed the role of AMF richness and diversity in soil aggregation. Schreiner and Bethlenfalvay (1997) reported that a combination of three AMF species had a higher impact on plant growth and soil aggregation than using a single species.

Soil fertility

The capability of soil for the agricultural production of plants is determined by soil fertility. Fertile soil aids in provisioning the mineral nutrients for plant growth (Foth and Ellis, 1997). Three components can maintain soil fertility- physical, chemical, and biological (Abbott and Johnson, 2017). The physical component is concerned with soil texture, structure, and gaseous exchange; the chemical component deals with nutrient availability, pH, and salinity; and the biological component includes contributions from biotic communities (Abbott and Johnson, 2017). A balance of these three components is required for the long-term maintenance of soil fertility. However, in previous years, despite the well-known contributions of soil microorganisms to soil fertility, nutrient availability, and crop productivity, an emphasis on fertilizer-based soil nutrient amendments has increased tremendously (Lavelle *et al*., 2004; Abbott and Johnson, 2017). This has disturbed the balance among the three components. The incessant use of fertilizers is often associated with undesired environmental effects such as nutrient leaching and surface runoff, eutrophication of aquatic ecosystem, and disturbance of biogeochemical cycles (Perrott *et al*., 1992). Therefore, the current challenge is to maintain sustainable agricultural productivity to reduce dependency on fertilizers as nutrient amendments.

Mycorrhizal fungi functions at the nexus of soil's physical, chemical, and biological components and bridge them together (Jeffries *et al*., 2003; Abbott and Manning, 2015). Microbial inoculants such as AMF are promising alternatives to chemical fertilizers. Soil management by AMF inoculation favors biological fertility of soil and balance the contributions from soil's physical, chemical, and biological components of fertility by reducing the dependency on chemical fertilizers (Kalliokoski *et al*., 2010; Ekblad *et al*., 2013; Abbott and Lumley, 2014; Berrutti *et al*., 2016). Studies in the last decade have demonstrated that the soil of south-western Australia, a biodiversity hotspot, is severely weathered and has low physical and chemical fertility (Gibson *et al*., 2010; Lambers *et al*., 2013). However, the hotspot has been reported to support the diverse community through mycorrhizal symbiosis and other microbial associations that facilitate nutrient absorption by plants (Lambers *et al*., 2014).

Arbuscular mycorrhizal fungi promote plant growth by boosting nutrient uptake, as their extra-matrical hyphae penetrate deeper realms of soil nutrient reservoirs and acquire nutrients that are otherwise not accessible to the plant (Smith *et al*., 2003; Smith and Smith, 2012; Pellegrino and Bedini, 2014; Berruti *et al*., 2016) (Fig 2). Hence, these wonder fungi are increasingly gaining attention as biofertilizers. Characterization of high-affinity transporter proteins in AMF (Harrison and van Buuren, 1995) has led to extensive studies on nutritional aspects of AM symbiosis from physiological as well as molecular perspectives (Paszkowski *et al*., 2002; Nagy *et al*., 2005; Bucher, 2007; Smith and Smith, 2012). Several studies have reported the favorable effects of AMF on uptake of nutrients such as phosphorus, nitrogen, iron, zinc, calcium, potassium, sulfur, and magnesium (Marschner and Dell, 1994; Giri and Mukerji, 2004; González-Guerrero *et al*., 2005; Allen *et al*., 2009; Evelin *et al*., 2012; Lehmann and Rillig, 2015).

Resistance to Soil Erosion

Soil erosion is a naturally occurring phenomenon of soil degradation marked by drifting of top layers of soil due to the dynamic activity of biotic and abiotic erosive agents. It majorly takes place in arid and semi-arid areas (Shao, 2008). Anthropogenic interferences such as mining, urban sprawl, extensive agriculture, deforestation, among others, have amplified the frequency of soil erosion events and encouraged desertification (Mardhiah *et al*., 2016). Soil erosion and consequential desertification have become appalling environmental degradation processes, resulting in the barrenness of fertile soil. Vitiated soil quality ultimately impinges soil's productive capacity, reflecting reduced crop production and degraded underground water quality (Pimentel *et al*., 2006). Heavy rainstorms, wind, or a combination of both are the major abiotic erosive agents that ultimately result in loss of soil structure and organic composition (Mosse, 1986). In the long run, the degraded soil ecosystem has intense repercussions on food security and human health.

Establishing a healthy and perennial vegetation cover is considered the most successful strategy to prevent the recurring episodes of soil erosion and desertification. However, vegetation practices are challenged by high seedling mortality as the eroded soils do not provide a conducive environment for plant growth. Previous reports have indicated a growing interest of workers in utilizing AMF to overcome this problem (Miller and Jastrow, 1992; Perumal and Maun, 1999; Burri *et al*., 2013). Wind tunnel experiments have demonstrated the potential of AMF to significantly augment the safeguarding effect of freshly seeded plants against wind-induced soil drifting (Burri *et al*., 2013). They reported that high mycorrhizal root colonization could decrease seedling mortality in erosive soil by moderating the destructive effects of wind erosion on plantation cover.

Similarly, Karthikeyan and Krishnakumar (2012) determined the influence of AMF on the growth and survival of *Eucalyptus tereticornis* Sm. that were growing in the soil of thoroughly degraded origin (mining site). They observed enhanced seed viability and successful seedling establishment in mycorrhizal plants (Karthikeyan and Krishnakumar, 2012). However, seedlings in erosive soil are poorly colonized by mycorrhizal fungi since such soil lacks mycorrhizal spores, and the progression of root colonization is comparatively slow (Azcon-Aguilar *et al*., 2003).

Other potential roles of AMF in reducing soil erosion include increased soil aggregation by their extraradical hyphae (Rillig and Mummey, 2006), stimulated root growth (Bearden and Peterson, 2000) and increased cohesion due to dense root-hyphal network (Mardhiah *et al*., 2016) (Fig. 2). The stability of soil aggregates is an important factor that governs soil erodibility by wind and water. Several reports have shown that soil erosion decreases with an increasing degree of soil aggregation (Barthes and Roose, 2002; Eldridge and Leys, 2003). Size of soil aggregates is also a critical factor in controlling soil erosion; larger soil aggregates are less likely to be affected by winds than smaller soil particles. Hence, soil aggregate formation increases the non-erodible soil fraction of the soil and increases the soil surface's roughness, thereby decreasing near-ground wind velocities (Chepil, 1950; 1951).

Arbuscular mycorrhizal fungi are also reported to have important roles in reducing soil erosion by running water (Bearden and Peterson, 2000; Mardhiah *et al.* 2016). Mardhiah *et al.* (2016) reported the first study on the direct effect of AMF extraradical hyphae in reducing soil erosion due to surface water flow. The study reported that AMF treated soil showed a reduced soil detachment rate in comparison to the control soil. However, the effect of AMF inoculants on soil erosion is a newer realm that has not yet been extensively investigated.

Carbon Sequestration and Cycling

The soil organic carbon (SOC) is the wealthiest reservoir of the terrestrial carbon pool that bears an immense impact on the atmospheric climate (Stockmann *et al*., 2013). Therefore, it becomes very important to understand the carbon accumulation mechanisms in the soil that reside for a more significant period to estimate the climate change scenarios in the future (Parihar *et al*., 2020). The SOC repertoire predominantly depends on the plant's biomass production and distribution of photosynthates (fixed carbon) to the above- and below-ground plant parts (Zhu and Miller, 2003). This, in turn, regulates the structure and abundance of microbial communities in the soil and their related processes (Mohammadi *et al*., 2011).

It is recently being acknowledged and experimentally validated that AMF play an essential role in the replenishment and maintenance of the carbon pool of the soil (Treseder and Turner, 2007) (Fig. 2). Mycorrhizal fungi have been estimated to acquire >20% of the total plant carbon; and 50-70% of the total carbon held by AMF propagules (hyphae) and rhizospheric soil of the forest ecosystem (Rillig and Steinberg, 2002). Thus, it is proposed that plant-associated fungi play a vital role in carbon dynamics by regulating carbon sequestration and cycling in the soil (Fig. 2). Despite the retention of a significant amount of carbon by AMF, the average residence time of carbon in the soil and protection of its inherent physical form are climacteric for its extended storage in the soil (Parihar *et al*., 2020). The major

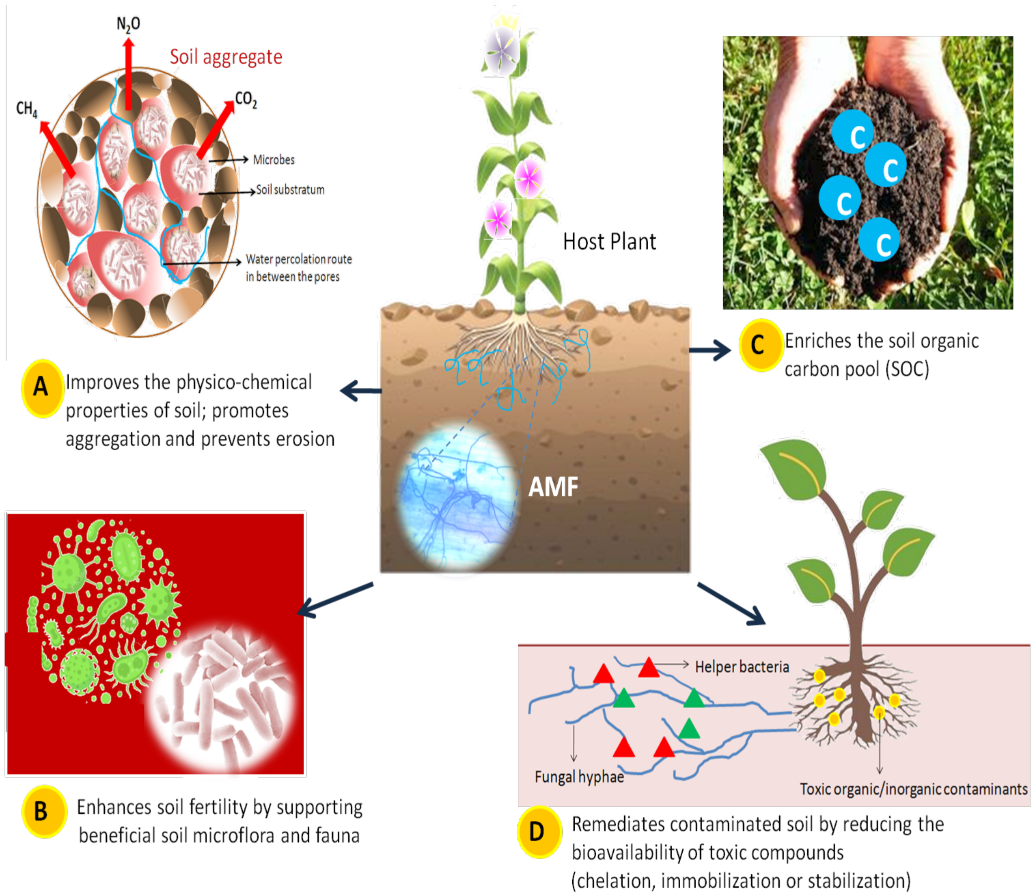

Fig. 2: Diagrammatic representation of the role of AMF in soil conservation and health. Arbuscular mycorrhizal fungus A) Improves the physicochemical properties of soil, stabilizes soil aggregates (due to glomalin), increases contact angle of H_2O penetration, and prevents soil erosion; B) Enhances soil fertility by fostering the growth of other beneficial microbes and replenishes the nutrient reservoir of the soil; C) Enriches the soil organic carbon pool by adding generous amounts of organic residue through hyphal biomass, GRSP, and release of various carbon-containing exudates, and D) Remediates soil containing persistent organic and inorganic pollutants.

portion of carbon received by AMF from the plants is accrued in the soil as fungal chitin or GRSP. The persistence of fungal-derived carbon is much more in the soil than that of plant origin (Prescott, 2010). Also, a large flux of soil organic carbon, i.e., 10-100 g/m^2/ year (Treseder and Turner, 2007), is represented by GRSP, which accounts for roughly 30-40% of the organic carbon undisturbed soils (Rillig and Steinberg, 2002). On the other hand, extraradical mycelia of AMF may account for 15% of the organic carbon reservoir of the soil (Leake *et al.*, 2004).

Arbuscular mycorrhizal fungi (AMF) regulates the cycling of roughly 5 billion tons of carbon per year that forms a sizeable proportion of carbon cycling (Bago *et al.*, 2000). AMF replenish the carbon pool of soil by adding generous amounts of organic residue through hyphal biomass, GRSP, and release of various carbon-containing exudates upon decomposition or senescence of the fungal hyphae. The composition, extent, and average turnover time of AMF hyphae directly influence the soil carbon dynamics. Even though the turnover period of extraradical hyphae is short, i.e., 5–6 days (Staddon *et al.*, 2003), the chitinaceous cell wall of hyphae (majorly composed of recalcitrant carbohydrates) may perpetuate in soil for up to 49 ± 19 years (Gleixner *et al.*, 2002). Furthermore, the close-knit interaction of soil particles with hyphal biomass, which contributes 54-900 Kg/ha soil organic carbon to both stable and recalcitrant carbon pools, provides physical protection to the soil carbon from microbial decay and damage (Zhu and Miller, 2003). Other than extraradical hyphae, the glycol-proteinaceous hyphal exudates such as GRSP also contribute substantially to SOC pool. The retention time of GRSP and related protein in the soil is as prolonged as 6–42 years (Rillig and Steinberg, 2002). The recalcitrance of GRSP is derived from the high content of aromatic carbon therein. Apart from its significant proportion and greater soil retention that accounts to carbon sequestration, GRSP also influences SOC pool by stabilizing the soil aggregates against thermal and structural damage. Greater the stability of soil aggregates, correspondingly higher will be the extent of carbon storage in the soil (Wright and Upadhyaya, 1996). In turn, soil aggregation physically protects the large fungal biomass, which would otherwise respire back to the atmosphere and invert the process of carbon sequestration (Parihar *et al.*, 2020). On that account, a distinct relationship between GRSP content and hyphal turnover and their combined impact on soil stability needs to be addressed. Although gross SOC storage depends on multiple factors such as hyphal architecture, production of GRSP and stability of soil aggregates, the intricacies of it still need to be considered and extrapolated in further studies.

Soil Remediation

Due to increased industrialization and mining activities, soil contamination has become a major concern; and soil pollution impact is pronounced in agriculture. Therefore, soil remediation is a key to ensure a healthy soil environment for constant food production. Soil remediation can be brought about by physico-chemical extraction and transporting the contaminated soil to other sites for treatment or disposal (ex-situ remediation). Other methods employ solvent extraction techniques, electro-kinetic separation, chemical oxidation, soil stabilization/solidification, and phytoremediation (Gong *et al*., 2005; Roach *et al*., 2009; Chibuike *et al*., 2013). The choice of above-mentioned methods depends on the type of pollutant (organic/inorganic) to be extracted, available time, and financial feasibility. However, besides being extremely expensive, these rigorous methods destroy all soil microorganisms residing in the soil substratum (Jeffries *et al*., 2003). Phytoremediation is, thus, a better alternative to these methods.

In the process of phytoremediation, many plant-associated microbes augment the metal detoxification capacity of the plants. AMF are an example of that, whose potential as ameliorator of heavy metal toxicity has been well proved and promoted (Christie *et al*., 2004; Sharma *et al*., 2017). Hence, Mycorrhiza Assisted Remediation (MAR) has been successfully used to remediate in/organic pollutants persisting in the soil (Table 1). Though both, ectomycorrhiza and endomycorrhiza can be used for MAR, AMF (endomycorrhiza) are a preferred choice as they colonize almost all the plants instead of ectomycorrhiza that is usually associated with woody species (Chibuike *et al*., 2013). Various recognized mechanisms deployed by AMF for prevention of heavy metal uptake by plants include metal immobilization, modulation of metal transporter activity, production of organic acids and glomalin, and boosting metal chelation by modulating phytochelatin synthase activity, among others. By immobilizing toxic metals and preventing their entry into the plants, AMF increases the net secondary value of the plant used in phytoremediation. Besides, due to the high retention time of AMF spores in the soil, these can easily colonize and aid the growth of newer vegetation planted on the remediated soils.

Mycorrhiza-assisted remediation improves the soil structure, recharges the nutrient pool, and ensures rapid vegetation on the redeemed soil (Fig. 2). AMF aid plant growth and survival in contaminated soil by protecting them against pollutant-induced phytotoxicity; besides, they also enhance soil amelioration by augmentation of soil microbiological processes and refining soil texture (Lenoir *et al*., 2016). Investigation of host responses to the presence of different strains of AMF in metalliferous soils can aid in selecting the best suitable combination of AMF-host plants for soil reclamation. Many other soil microorganisms can be used in conjunction with mycorrhizal fungi to vitiate the toxicity of metal contaminants, for instance, *Cunninghamella echinulata* and *Sphinomonas paucimobilis* (Alarcon *et al*., 2008), *Acinetobacter* (Yu *et al*., 2011), *Bacillus subtilis* (Xiao *et al*., 2012), among others. Furthermore, saprophytic fungi such as *Fusarium* sp. and *Trichoderma* sp. have been used in combination with MAR to redeem heavy metal contaminated soils (Arriagada *et al*., 2004, 2005, 2007). These studies demonstrate that the synchronous effect of these interacting fungi in MAR technique resulted in the efficient removal of copious amounts of pollutants vis-a-vis when used discretely. The interaction between these fungal species is poorly known. However, the efficiency of MAR and the amount of pollutants removed varies with the species of saprophytic fungi and AMF used for remediation.

Due to the voluminous tap root system of legumes, they have been used in many phytoextraction studies (Smith *et al*., 2006). *Rhizobia*, the nitrogen-fixing bacteria residing in the root nodules of legume roots, are found in most soils remediated with legumes. A huge body of evidence evinces the positive correlation between rhizobia and mycorrhiza. *Rhizobium* has been found to improve the growth and proliferation of mycelia in AMF in lieu of fungus-supplied phosphorus and other nutrients that aid nitrogen fixation in leguminous plants (Ma *et al*., 2006). Therefore, these interacting microorganisms indirectly improve the remediation of contaminated soils by stimulating microbial development and enhancing the soil enzyme activity (Ren *et al*., 2017) and boosting the abundance of phytochelatins and various organic acids (Ren*et al*., 2019). Besides, it has been found that interactions between soil-dwelling earthworms and AMF result in rapid remediation of soils polluted with heavy metals. Yu *et al*. (2005) reported a positive effect of earthworm activities on the colonization rate of *Lolium* sp. (ryegrass) by mycorrhizal fungi. This positive interaction amounted to the rapid removal of Cd from the contaminated soil. The authors suggested that phytohormone production by earthworms might have triggered mycorrhizal colonization that further augmented soil remediation. Earthworms also aid in the dissemination of fungal propagules and spores through their feeding habits.

Various advantages of MAR, as mentioned by Chibuike *et al*. (2013), include:

1. Rapid revegetation of redeemed soil due to pronounced AMF-mediated beneficial effects such as soil stabilization and aggregation, nutrient replenishment, increased water uptake by plants, and disease resistance.
2. The MAR process can be carried out *in situ*. Hence, the entire tedious process of transporting contaminated soil to landfills (ex-situ remediation) is eliminated and rules out the risk of contamination to humans.
3. It is an environmentally friendly and economically feasible process. It is easier to accomplish than other *in-situ* methods of soil remediation (such as electro-kinetic separation, chemical, and thermal remediation) since it does not involve sophisticated high-throughput technologies.
4. It can be used in complementation with conventional remediation techniques to obtain rapid and coveted results. For instance, MAR can be integrated with chemical remediation techniques wherein the chemicals are employed to achieve rapid remediation, while MAR fosters a restoration of the structural and functional properties for improved production and yield of crops.

Thus, MAR holds excellent potential for ameliorating contaminated soil; nevertheless, more exhaustive studies need to be devoted to optimizing this technique and addressing its limitations. Seemingly, the efficiency of MAR is governed, to a major extent, by differences in tolerance of AMF strains and their host to the pollutants present in the soil. The application of native fungal strains to plants rather than allochthonous inoculums should be promoted to obtain coveted results in phytoremediation. Besides, maneuvering the research trajectory

Table 1: Several studies demonstrating the role of AMF in the remediation of soil contaminated with organic and inorganic pollutants.

Host species	*AMF strain*	*Type of contamination*	*References*
Trifolium repens	Mixed inocula of *Glomus* species	Zinc contaminated soil	Zhu *et al.* (2001)
Hordeum vulgare	*Glomus* and *Gigaspora* species	Cadmium contaminated soil	Tullio *et al.* (2003)
Zea mays	*Glomus intraradices*	Lead contaminated soil	Malcova *et al.* (2003)
Lolium perenne	*Glomus mosseae*	Industrial soil contaminated with Polycyclic aromatic hydrocarbons (PAH) (400-2000 mg/kg)	Joner and Leyval (2003)
Zea mays	*Glomus caledonium*	Zinc-spiked (0-600 mg/kg) calcareous sandy andloamy soil	Chen *et al.* (2004)
Medicago sativa	*G. caledonium*	Benzo(a)pyrene contaminated soil	Liu *et al.* (2004)
Alnus glutinosa	*G. intraradices*	Soil extracted from acetylene and PVC (polyvinylchloride) factory	Oliveria *et al.* (2005)
Eucalyptus rostrata	*Glomus deserticola*	Lead-spiked sandy soil	Bafeel (2008)
Triticum aestivum and *Vigna radiata*	*G. mosseae*	Agricultural soil contaminated with PAH (500mg/kg)	Rabie (2004)
Chrysopogon zizanioides	*G. mosseae*	Lead contaminated soil	Punaminiya *et al.* (2010)
Saphora viciifolia	*Funneliformis mosseae*	Lead spiked soil	Xu *et al.* (2014)
Robinia pseudoacacia	*Rhizophagus intraradices*	Lead contaminated soil	Yang *et al.* (2016)

towards decoding signaling pathways operational between the interacting partners of mycorrhizal association in the presence of in/organic contaminants would be desirable (Rajtor and Piotrowska-Seget, 2016)

Concluding Remarks

The world is very close to a new phase of agriculture that involves the unification of plant biology with agroecology under the aegis of biotechnology and germplasm enhancement (Vance *et al.,* 2003). The low-middle-income developing countries are at the receiving end of the tremendous challenge of ensuring food security. To guarantee food security and ensure sustainable food production, boosting agricultural productivity is of dire importance. To achieve the endeavor of increasing food production, management of soil resources and agro-ecosystems is pre-eminent. Therefore, we need to strengthen our understanding and be better aware of the factors that govern the soil and plant welfare, including the root-soil interactions and understanding of the benefits of the microbes that reside in the rhizosphere (Martinez and Johnson 2010). The importance of AMF in organic farming represents an exciting subject.

AMF ensure sustainable soil welfare by improving soil structure, stabilizing soil aggregates against thermal and microbial damage, warding off soil-borne pathogens, replenishing soil organic carbon pool, rehabilitating soil microbial wealth, and contributing immensely to bioremediation of soil contaminated with organic and inorganic pollutants. It is conceivable that the distinguished benefits conferred by mycorrhizal colonization to the crop/horticultural plants are achieved by the concerted effect of AMF on soil structure, stability, function, and plant defenses against a/biotic stresses. On these grounds, future work should concentrate on optimizing AM effects on nutrient acquisition so that yield is maintained while improving output sustainability. By identifying and enhancing the traits associated with AMF receptivity, functionality in crop improvement, and soil conservation, leaps of progress can be made towards attaining global food security in sustainable agrological systems.

Although they constitute the most promising plant-microbe symbiosis, AMF interactions are just one dimension of the complicated multidimensional microbial interactions in the rhizosphere. Agro-ecologists and soil scientists must pay them condign attention while aiming to maintain and rehabilitate the soil ecosystem. Considering sustainable agriculture, the cost-effective development of viable AMF inocula to serve as biofertilizer holds enormous applications; however, limited research capacity and technical complexities are major handicaps to achieve their viable production. Promotion of AM-friendly management techniques should be made to ensure AMF biodiversity and hyphal networks thereof in the managed ecosystems (Berruti *et al.*, 2016). Large-scale field trials of tailor-made AMF inocula should be done at diverse topographical and edaphic locations to gauge their beneficial effects on soil and plant welfare and analyze the cost-economy (Ceballos *et al.*, 2013). Besides, isolation of native and adaptive ecotypes of AMF from soils harboring potentially toxic elements can offer a prospective tool for successful bio restoration of vitiated ecosystems.

Additionally, a practical understanding of the efficacy of combining different AMF isolates and other beneficial soil microbes in the augmentation of soil quality and texture will be consequential in harnessing AMF in sustainable agriculture. Moreover, to maximize the potential of AMF, research needs to be targeted to dissect their inherent complexities and multiple functionalities. A comprehensive understanding of the functional ecology of AMF is very much needed. Assessment of functional and genetic diversity between different AMF strains from different soil types should be done using advanced molecular techniques. Finally, understanding the interaction of AMF with important biotic and abiotic elements of the ecosystem should be consolidated to ensure notable progress towards this end.

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