Chapter 20
Arbuscular Mycorrhizal Fungi: Green Approach/Technology for Sustainable Agriculture and Environment

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Abstract To feed the growing population, global food production needs to be doubled by 2050. The fertilizers cost have increased several folds in the last few years, which necessitates agrarian community to be less reliable on chemicals to grow and protect their crops. Moreover, dependency on chemical fertilizers and pesticides has led to the deterioration of human health, disruption of ecosystem functioning and degradation of our environment. To overcome these problems, there is a need to explore and exploit the beneficial plant–soil microbe interactions to meet the food demand without affecting the relationship between the man and his environment. Arbuscular mycorrhizal fungi (AMF) are known to form symbiotic association with the roots of more than 90% of the terrestrial plants. They serve as biofertilizer and enhance the plant growth by accelerating nutrient uptake, particularly of inaccessible nutrients like phosphorus and nitrogen from the soil. Beside mineral nutrition, AMF also maintain the root hydraulic conductivity, increase the plant net photosynthetic capacity, improve stomatal conductance. The multifunctional extraradical hyphae of the fungus provide numerous ecological advantages like maintaining the soil health by influencing the beneficial microbes, aggregating soil particle and preventing soil erosion, conferring resistance to various stresses, enhance ecosystem productivity, bioremediation of degraded land, serving as soil carbon sink. In this chapter we attempt to discuss different role played by AMF, which make them potential tool for sustainable agriculture and environment. It is tempting to state that AMF served for 3E's i.e. eco-friendly, economic and enhanced yield.

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20.1 Introduction

The world's population is growing rapidly and has been predicted to reach around nine billion by the middle of this century (Rodriguez and Sanders 2015), which will put a tremendous pressure on the global agriculture to meet the growing demand for food. Therefore, the increase in crop production and land productivity in agriculture is necessary. It is beyond the doubt that due to the application of chemical fertilizers and agrochemicals, food production in agriculture has increased significantly. The use of these chemicals has been predicted to be increased significantly in future too (Weber 2014). However, the frequent use of chemical fertilizers along with other chemicals like pesticides and weedicides or herbicides has already generated environmental issues such as deterioration of soil quality, surface and ground water, soil biodiversity and ecosystem functioning. Any increase in the dosage of these chemicals to promote the agricultural productivity, however would severely deteriorate our environment and agriculture. Therefore, in order to safeguard the environment health as well as agriculture productivity, it is importance to reduce dependence of farmers on these agrochemicals to promote plant growth and yield.

Soil is an excellent habitat for a wide array of microorganisms, which could play specific role in maintaining soil productivity, ecological processes and environment health. These microbes could play a key role in sustainable agriculture as they improve the fertility and health of the soil. They safeguard plant from enemies, enhance nutrient cycling and assist host plant to acquire immobile nutrients like N and P from the plant (Aggarwal et al. 2011; Wagg et al. 2014; Bender et al. 2016; Hunter 2016a, b) also established symbiotic associations with a wide range of plant species (Rillig et al. 2016) and thereby benefit their partner plant. The application of beneficial soil microbes could be a potential source to sort-out the issue of intensive use of costly chemical fertilizers for agricultural production as they can increase nutrient availability, plant tolerance against various kinds of stresses and therefore can provide a sustainable way for agricultural practices (Aggarwal et al. 2011). In the soil, these microorganisms are present either in the free-living (Plant Growth Promoting Rhizobacteria, like *Azotobactor, Azospirillum, Pseudomonads*) state or may develop mutual association with plant roots (*Rhizobia*, mycorrhizas and mycorrhiza-like organisms like *Piriformospora indica*) (Prasad et al. 2015).

Amongst the diverse groups of soil microorganisms, mycorrhizas are the most ubiquitous soil fungi (Schüßler et al. 2001; Smith and Read 2008; Gianinazzi et al. 2010; Leifheit et al. 2014). It has been predicted that mycorrhizal fungi may have existed even when the first plants appeared on land, which is estimated around more than 400 million years ago (Brundrett 2002). They form a mutual symbiotic relationship with the roots of plant. They are called mycorrhiza originated from the Greek 'mukés', meaning fungus, and 'rhiza' meaning roots. So far, seven different mycorrhizal fungi have been discovered from natural soils, out of these arbuscular mycorrhizal fungi (AMF) are rather common amongst the wide range of plant species. More than 90% of terrestrial plant species are colonized by AMF (Gomes et al. 2017). AMF exist in two environments; in the soil, where they form an extensive extraradical mycelium, which scavenges mineral nutrients, and within the root, where they grow between and within cortical cells developing symbiotic interfaces-the finger-like profusely branched arbuscules or intracellular coils and balloon like structures, the vesicles (Smith and Smith 2011). Arbuscules are the functional sites of nutrient transfer and vesicles act as storage organs. Extraradical hyphae extend beyond the depletion zone and support host plant for acquiring mineral nutrients and water from the soil that are not easily accessible to the normal root system. This AMF–plant relationship encourages plant growth and development of root (Kaur et al. 2014). In return, fungus avail food/carbon from the partner plant. The fungus utilizes carbon/carbohydrate for its own growth and reproduction and also in the synthesis of excretory molecules like glycoprotein (known as glomalin), which release to the soil and helps in improving soil structure with soil organic matter content (Kaur et al. 2014; Sharma et al. 2017). AMF reproduce through asexual mode of reproduction. The sexual mode of reproduction in AMF has not yet well understood. AMF are potential components of sustainable management systems. These fungi are known to exist in a wide range of environment and play a vital role in maintaining plant–water relations, nutrient uptake and ionic balance and improve soil quality and health and productivity of plants (Ruiz-Lozano et al. 2012; Nadeem et al. 2014). Under abiotic stresses, they could improve accumulation of osmo-protectants, maintain membrane integrity and osmotic adjustment and prevent oxidative damages thereby reduce adverse effects of environmental stresses and improve plant growth (Wu and Xia 2006; Evelin et al. 2009). In addition, AMF notably enhance accumulation of active ingredients in several herbal medicinal plants (Mandal et al. 2013). It is estimated that AMF could reduce up to 50% usage of chemical fertilizers for optimal agriculture production depending upon plant species and environmental conditions. Therefore, AMF could be a potential tool for sustainable agricultural practices with improved agronomic strategies which can improve fertility, health and environment of the soil, thereby the plant growth and yield (Aggarwal et al. 2011; Bender et al. 2016; Rillig et al. 2016). In this review, we attempt to highlight the role of AMF as an essential component of sustainable agriculture and environment, due to their involvement in the increased nutrient uptake, biomass production, improved photosynthesis capacity, improving quality and quantity of plant secondary metabolites, reducing dependence on fertilizers and other agro-chemical and improving plant's tolerance to environmental stresses.

20.2 Green Approaches in Relation to Agriculture and Environment

The development of agriculture sector, defined in terms of increased production with decreased average cost along with healthy and safe environment. Sustainable agriculture includes four main objectives; (i) environmental health management (including plant and soil), (ii) economic effectiveness and (iii) enhanced yield, and

(iv) social and financial justice (Brodt et al. 2011). The techniques, which make products and processes more sustainable and environmental friendly may be considered as green or clean approaches. Green approaches aim to make the environment sustainable by reducing environmental degradation, conserving natural resources and reducing emissions of green house gases (CO_2, N_2O, CH_4 etc).

20.3 Potential Solutions for Sustainable Agriculture and Environment

In the previous decades, the consumption of chemical fertilizers and pesticides has been increased massively to increase the crop production to meet the growing demands of rising population for food, which has largely affected the environment and ecosystem of the agricultural fields in the form of deterioration of soil quality and fertility, contamination of surface and ground water, air pollution and decrease in ecosystem functioning and biodiversity (Schultz et al. 1995; Socolow 1999). A potential solution to fulfill current and future generation requirements could be efficient use of the community waste and sewage sludge, which is an inexpensive alternative as manure. However, these sources are having high amount of heavy metal content, which could impose negative impact on the soil microorganisms, and heavy metals may get accumulated in the crop itself and crop field (Giller et al. 1998; Graham 2000).

Soil contains the diverse groups of microorganisms, which could play specific roles in maintaining the soil productivity and ecological processes. To overcome the environmental and ecological issues along with increased crop yield, the application of soil microorganisms could be a cheaper, affordable and eco-friendly solution (Aggarwal et al. 2011). The utilization of beneficial soil microbes for the sustainable agriculture and environment could connect sustainability with enhanced productivity, and agricultural productivity could be efficiently maintained by careful planning of conservation as well as utilization of soils (managing soil fertility/quality). Transferring/minimizing existing agro-practices (use of chemical fertilizers and pesticides) with microbial applications is not only economical to grow safe and sufficient food but also for keeping the environment clean and contamination free. Further, sustainable agriculture with organic produce is paying attention of farmers, governments and development agencies. Organic farming is found in coordination with the local environment using land husbandry techniques such as soil-conservation measures, crop rotation, and the application of agronomic, biological and manual methods instead of synthetic inputs like mineral fertilizers and agro-chemicals for maximum outputs. Organic agriculture is a cost-effective approach for economically weaker farmers who cannot pay for expensive techniques of green revolution (Manimozhi and Gayathri 2012). Since arbuscular mycorrhizal fungi colonize roots of a majority of land plant species, provide them with many benefits and play a key role in ecosystem management and functioning, their application could be a potential approach for sustainable agricultural practices, and the improved agronomic strategies with AMF can improve the health of soil and environment (Schüßler et al. 2001; Aggarwal et al. 2011).

20.4 Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (also known as Endomycorrhizae or AMF) are soil fungi, which forms symbiotic association with roots of many vascular plants (including crop plants). AMF are obligate symbionts, belonging to the phylum Glomeromycota, which comprises many genera and species (Schüßler et al. 2001). They colonize all angiosperm families except Betulaceae, Utricaceae, Commelinaceae, Cyperaceae and Polygonaceae. AMF are present as a bridge between roots and soil, where they provide the host plant with mineral nutrients and water from the soil in exchange of carbohydrates from host plant for their own growth and reproduction (Fig. 20.1) (Smith and Read 2008). In this symbiotic

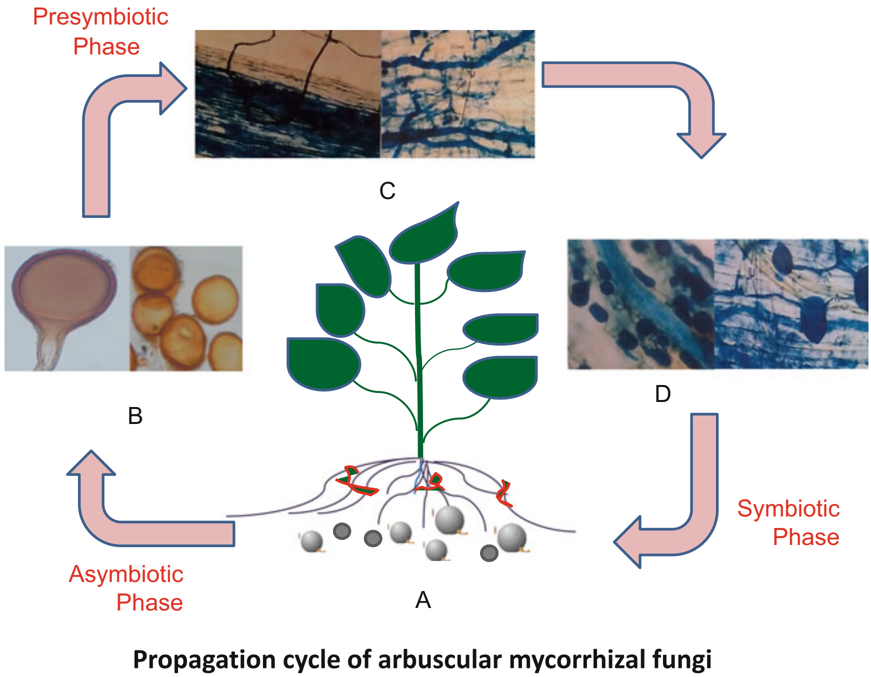

Fig. 20.1 Propagation cycle of arbuscular mycorrhizal fungi. They are considered asexual because sexual reproduction is remaining to be studied. The asexual life cycle includes three main phases, asymbiotic, presymbiotic and symbiotic phases. AM fungal spores present in the soil communicate with plant root (**A**), start germinating (**B**) subsequently develop dense extraradical hyphae, which grow through soil particles and eventually enter plant roots (**C**), forming a bulbous structure called appresorium. Inside plant root, fungal hyphae grow between and within cortical cells, forming intracellular arbuscules and intraradical vesicles (**D**)

association, the fungus develops different structures in soil and in root of host plant. They develop two types of hyphal network, the extraradical hyphae (present in soil) and intraradical hyphae (present in plant root). The extraradical hyphae extract important nutrients and forms dense branched filamentous structures in the soil (Smith and Read 2008). They extend several meters far from the root and are responsible for acquisition of mineral nutrients and water for host plant along with propagation of the fungal spore. AMF fungi produce different types of soil hyphae like thick or runner hyphae and thin or absorptive hyphae (Friese and Allen 1991). The hyphal network is long-lived, and is able to colonize new plant roots as they come in contact with.

Arbuscular mycorrhizal symbiosis initiates as the fungal hyphae start responding to the presence of a plant root, establishing a molecular communication and growing along its surface. Indeed, one or a few hyphae produce appressoria (a kind of swelling like structure), these appressoria penetrate epidermal cells of the root and proceed for entering the root (Brundrett 2008). These hyphae penetrate the hypodermis, start profusely branching in the root cortex region and spread in both directions and form a network. Where, the hyphae develop highly dichotomously branched structure called arbuscules. Arbuscules are formed between the cell wall and the cell membrane of root. They start to form about 2 days after root penetration and never come into the direct contact with the nucleus or other cell organelles of root cell (Brundrett et al. 1985). The exchange in this mutual association occurs in such a way that fungus facilitates plant to uptake nutrients from soil and plant supply carbohydrate to the fungus. This exchange of nutrients takes place at the cell membrane-arbuscule interface (Balestrini and Bonfante 2014). Indeed, AMF hyphae also produce balloon-like swellings in the root cortex known as vesicles, which accumulate the storage products. These arbuscules may be inter- or intracellular and may function as propagules by developing thick walls in older roots (Biermann and Linderman 1983; Brundrett 2008; Balestrini and Bonfante 2014). Due to the presence of vesicles and arbuscules these fungi were referred to as arbuscular mycorrhizal or AM, however, it has been observed that a few species of AMF do not produce vesicles; therefore, it was suggested to refer as arbuscular mycorrhizal fungi. AMF reproduce asexually through thick-walled spores produced on the extraradical hyphae, and stay in the soil for long periods.

20.5 Role of Arbuscular Mycorrhizal Fungi in Sustainable Agriculture

20.5.1 Plant Growth and Productivity

AMF supply amount of nutrients and water to crop plants, helping in overcoming stresses therefore lead to boost the productivity of various crops (Lekberg and Koide 2005; Suharno et al. 2017). Karagiannidis and Hadjisavva-Zinoviadi (1998) observed twofold increase in the biomass production of *Triticum turgitum* var. durum inoculated with *Glomus mosseae*, grow in ten different soils. Improved productivity and improved content of protein, Fe and Zn was recorded in mycorrhizal chick pea (Pellegrino and Bedini 2014). In alkaline soil, the synergistic effect of AMF and *Rhizobium leguminosarum* bv. *viciae* was observed on the growth of *Vicia faba* L. (Abd-Alla et al. 2014). Some of the AMF species, such as *Glomus geosporum* and *Glomus claroideum* accumulate heavy metals of soil into plant roots and prevent their translocation to shoot, acting as a filter (Sambandan et al. 1992; Del Val et al. 1999; Leyval et al. 2002; Meier et al. 2015). They enhance productivity and quality of plant in contaminated soils. Under saline condition, wheat varieties colonized with AMF have shown increased productivity, which may be attributed to the mycorrhiza-assisted reduced uptake of Na and Cl and improved uptake of mineral nutrients by wheat plants (Daei et al. 2009).

20.5.2 Mineral Nutrition

AMF provide host plant with mineral nutrients (Smith and Read 2008). The extraradical mycelium of AMF emerged out from the host root, extends into the soil and increases the surface area to acquire locked nutrients from the soil and alleviate nutrient deficiency by providing adequate supply of mineral nutrients to host plant (Marschner and Dell 1994; Johnson et al. 2010; Nouri et al. 2014). Phosphorus (P) and nitrogen (N) both are important determinants for the AM symbiosis and the colonization of the host plant is controlled by feedback mechanisms between both nutrients (Kytoviita 2005; Fellbaum et al. 2014).

Nitrogen is the most important nutrient for plant development and AMF assist plants to avail more than 50% of required nitrogen from soil and organic compounds by the way of N cycling and producing large amount of external hyphae (Hodge and Fitter 2010; McFarland et al. 2010; Veresoglou et al. 2012a). Studies suggest that AMF can obtain substantial amount of N from decayed organic matter/residue or accelerate N mineralization from organic matter (Atul-Nayyar et al. 2009; Hodge and Fitter 2010) and also affect the carbon supply through soil microbial communities during decomposition (Herman et al. 2012). AMF improves symbiotic nitrogen fixation, nodulation and increase the activities of pectinase, xylo-glucanase and cellulose which are involved in the nitrogen metabolism and increase the decomposition of soil organic matter (Barea 1991). AMF may exert a priming effect on the soil bacterial communities shifting denitrifying communities by reducing the availability of soluble N and can also reduce denitrification and N_2O emission rates (Ames et al. 1984; Amora-Lazcano et al. 1998; Scheublin et al. 2010; Veresoglou et al. 2012b; Bender et al. 2014).

AMF-inducible NO_3^- or NH_4^+ transporters have been identified in several plants including tomato and soyabean (Hildebrandt et al. 2002; Kobae et al. 2010). The NH_4^+ ammonium transporter has been found to be expressed in arbuscules, suggesting control of AMF on the supply of nutrients to host (Kobae et al. 2010).

Comparing with typical uptake systems of plants, the $NH4^+$ uptake system of AMF have a five times higher affinity for $NH4^+$, which enables the fungus to obtain $NH4^+$ from the soil even under low N supply conditions (Pérez-Tienda et al. 2012). Another important source of N in the soil is free amino acids. AMF influence the uptake of several of these amino acids such as aspartic acid, serine, glycine, glutamic acid, glutamine, cysteine or methionine (Cliquet et al. 1997; Nakano et al. 2001). Monoxenic root-organ culture experiments have shown that translocation of N in plant occurs as arginine but converts to $NH4^+$ before transfer to the plant across the symbiotic interface (Smith and Smith 2011). In *Sorghum bicolor*, AMF increase the uptake of phenylalanine, methionine, asparagine, tryptophan, and cysteine, along with increased uptake of the charged amino acids like arginine, lysine, and histidine, which seems to be possible with the help of such transporters only (Cappellazzo et al. 2008; Whiteside et al. 2012).

P is an essential nutrient for plant but difficult to be acquired from the soil (Lambers et al. 2015) due to its extremely low diffusion rate (Shen et al. 2011). Mycorrhizal fungi release phosphatases, which solubilize soil organic P and increase the uptake of P by both responsive and non-responsive plants (Smith et al. 2003; Li et al. 2006). Further, phosphatases act on phytate, a major source of organic P in the soil, and release the H_2PO_4 which is utilized by the plant (Joner et al. 2000). Mycorrhizal fungi increase the exploration of P in soil, increase its translocation to plants through arbuscules, help in efficient transfer of P to plant roots and increased storage of absorbed P (Bhat and Kaveriappa 2007). AMF–plant interaction specifically induces the expression of plant Pi transporters (Harrison et al. 2002; Balestrini et al. 2007; Walder et al. 2015). In sorghum (*Sorghum bicolor*) and flax (*Linum usitatissimum*) two genes coding for inorganic phosphate transporters are identified that were induced in roots colonized by AMF but acquisition of inorganic phosphorus (Pi) was strongly affected by the combination of plant and AMF species (Walder et al. 2016). The utilization of AMF along with phosphate solubilising bacteria and other soil microbes could improve plant productivity even with low grade rock phosphates as a source of P (Bagyaraj et al. 2015). However, the effectiveness of acquisition of P varies between fungal species and even between isolates within a species (Smith and Read 2008). Jansa et al. (2005) reported that *Glomus mosseae* and *Glomus intraradices* are more efficient in P uptake than *Glomus claroideum* and *Glomus mosseae*.

Along with N and P, AMF also help in transfer of sulfur (S) to the plants with the help of sulfate transporters (Allen and Shachar-Hill 2009; Giovannetti et al. 2014). Plants take up S primarily as the sulfate anion, which is often found in low concentrations in the soil (Leustek 1996; Allen and Shachar-Hill 2009). Several researchers have reviewed the uptake, transfer and utilization of S by plants (Allen and Shachar-Hill 2009; Rennenberg et al. 2007). Sulfur is a mobile element. It is commonly lost through soil leaching. Therefore, a large proportion of the soil S remains present in the organically bound forms such as sulfate esters, synthesized by soil microorganisms, which is difficult to utilize by the plant (Fitzgerald 1976; Scherer 2001; Allen and Shachar-Hill 2009). Mycorrhizal fungi have been found to increase the percentage of S in pot-grown onion and maize plants under the conditions of low S availability (Mohamed et al. 2014; Guo et al. 2007). However, very little is known about the mechanism of S assimilation and its regulation in mycorrhizal fungi. Allen and Shachar-Hill (2009) conducted research experiments to determine the role of AMF in acquisition of S, its metabolism and transfer to host roots and to identify effectors of S transfer to host roots. They found that sulfate was taken up by the AMF and transferred to AMF-colonized roots, increasing root S contents under moderate concentration of sulfate.

20.5.3 Water Uptake/Root Hydraulic Conductivity

Root hydraulic conductivity and permeability are the reliable indicators for water uptake activity in plants (Aubrecht et al. 2006). Mycorrhizal mycelium network affects moisture retention properties of soils and improves water uptake capacity of plant by regulating stomatal conductance (Augé et al. 2015). AMF inoculated plants have shown altered root morphology and hydraulic conductivity, demonstrating that increased root hydraulic conductivity is favorable for plant growth as it credits to improved water uptake by host plant (Augé 2001; Cseresnyés et al. 2013). Cseresnyés et al. (2014) observed that the mycorrhizal bean and cucumber plants exhibit higher rate of daily transpiration and root electrical capacitance than that of the non-mycorrhizal plants. Ruiz-Lozano (2003) revealed that to mitigate the water deficiency, AMF help to improve water uptake by enhancing the absorptive surface area of root (Aggarwal et al. 2011) which ultimately increase the soil water movement into root of plants and delay the decline in water potential (Porcel and Ruiz-Lozano 2004).

20.5.4 Role of AMF in Managing Rate of Photosynthesis

Mycorrhizal symbiosis increases photosynthetic capacity of plants by increasing the activity of hormones like cytokinin, gibberellins and of auxins which could elevate the rate of photosynthesis by influencing stomatal opening (Allen et al. 1982). Increasing colonization of *Boswellia papyrifera* seedlings resulted in greater stomatal conductance (Birhane et al. 2012). The inoculation of *Robinia pseudoacacia* L. (Black Locust) with AMF, *Funneliformis mosseae* and *Rhizophagus intraradices* grow in a lead toxic soil has shown increased photosynthetic pigment content in leaves and higher gas exchange capacity, non-photochemistry efficiency, and photochemistry efficiency (Yang et al. 2015). AMF greatly influence the photosynthesis of black locust seedlings with significantly greater leaf area, higher carboxylation efficiency, chlorophyll content and net photosynthetic rate. They significantly increase the photochemical efficiency of PS II and enhance the carbon content and calorific value of the seedlings (Zhu et al. 2014). Similarly, *Citrus tangerine* (tangerine) colonized by *Glomus versiforme* exhibited higher photosynthetic rates, stomatal conductance, transpiration rate and improve osmotic adjustments, substantiating influence of AMF on plant photosynthesis (Wu and Xia 2006).

20.5.5 Accumulation of Secondary Metabolites/Active Ingredients

Plant metabolites are divided into two broad categories, primary and secondary. The primary metabolites are vital for the basic processes of life including photosynthesis and respiration whereas secondary metabolites are important defense and specialized metabolites noteworthy for the plant interaction with its environment. Secondary metabolites play significant role in defense, and protection of plants against biotic and abiotic stress. AMF studies performed on herbal and aromatic medicinal plants showed that mycorrhizal symbiosis influences plant secondary metabolism in both above and belowground parts of the plants, increasing accumulation of active ingredients (Table 20.1). Farmer et al. (2007) observed accumulation of β-carotene in the tuber of *Ipomoea batatas*. Similarly, Sailo and Bagyaraj (2005) found increasing level of diterpene forskol in the roots of *Coleus forskohlii*. On mycorrhization of *Glycyrrhiza uralensis* plants, Liu et al. (2007) recorded higher concentration of glycyrrhizin. Mandal et al. (2013) carried out research experiments to examine the influence of AMF, *Rhizophagus fasciculatus* on the yield of secondary metabolites in *Stevia rebaudiana*, in relation to mycorrhiza-induced physiological changes in addition to improved P uptake. AMF inoculation of *Stevia* with P-supplementation produced higher concentrations of steviol glycosides in comparison to control plants. The higher content of stevioside and rebaudioside-A (steviol glycosides) in AMF inoculated plants could be attributed to increased nutrients uptake and biomass production, and carbohydrates and jasmonic acid, contributing to more biosynthesis of steviol glycosides. Enhanced nutrient uptake and sugar concentration due to increased photosynthesis in AMF inoculated stevia could control up-regulation of the transcription of steviol glycosides biosynthesis genes (Mandal et al. 2015). Mycorrhizal symbiosis also facilitates the accumulation of essential oils in plants like *Anethum graveolens*, *Trachyspermum ammi* and *Foeniculum vulgare* (Kapoor et al. 2002, 2004; Mandal et al. 2013). Inoculation of *Glycyrrhiza uralensis* with *Glomus mosseae* has been found to improve accumulation of flavonoids, liquiritin, isoliquiritin, isoliquiritigenin and glycyrrhizic acid (Chen et al. 2017) under nutrient stress condition. Marjoram and lemon balm inoculation with AMF considerably increased the yield of rosmarinic acid and lithospermic acid isomers (Engel et al. 2016). Similarly, in Lettuce they enhanced the accumulation of vitamins, nutraceuticals and minerals (Baslam et al. 2013). In *Dioscorea* spp., the inoculation of *Glomus etunicatum* increased content of polyphenols, flavonoids and anthocyanin (Lu et al. 2015). These observations substantiate the fact that the quantity and quality of

Table 20.1 Influence of AMF on accumulation of active ingredients in plants

Active ingredients produced	AMF species involved	Host plant	Family	Reference
Glycyrrhizin	*Glomus mosseae*	*Glycyrrhiza uralensis*	Fabaceae	Liu et al. (2007)
Hypericin and pseudohypericin	*Rhizophagus intraradices*	*Hypericum perforatum*	Hypericaceae	Zubek et al. (2012)
Polyphenols, flavonoids, and anthocyanin	*G. etunicatum*	*Dioscorea sp*	Dioscoreaceae	Lu et al. (2015)
Camptothecin	*G. diaphanum, Acaulospora mellea and Sclerocystis sinuosa*	*Camptotheca acuminata*	Nyssaceae	Zhao et al. (2007)
Flavonoids, lignin, DPPH activity and phenolic compounds	*Funneliformis mosseae*	*Cucumis sativus* L. seedlings	Cucurbitaceae	Chen et al. (2013)
Phenol	*Glomus aggregatum*	*Catharanthus roseus*	Apocynaceae	Srinivasan and Govindasamy (2014)
Chicoric and Caffeic acid derivative	*Rhizophagus intraradices*	*Ocimum basilicum*	Lamiaceae	Scagel and Lee (2012)
Stevioside and rebaudioside	*Rhizophagus fasciculatus*	*Stevia rebaudiana*	Asteraceae	Mandal et al. (2013)
Linalool and Methyl chavicol	*Glomus sp.*	*Ocimum basilicum*	Lamiaceae	Zolfaghari et al. (2012)
2-hydroxy-4-methoxy benzaldehyde	*Glomus sp.*	*Decalepis hamiltonii*	Asclepidaceae	Matam and Parvatam (2017)
Cinnamic acid, anthocyanin, Total phenol	*Glomus etunicatum and Glomus mosseae*	*Mentha spicata*	Lamiaceae	Bagheri et al. (2014)
Total phenol	*Glomus intraradices*	*Ocimum gratissimum L*	Lamiaceae	Hazzoumi et al. (2015)
Phytoalexins	*Glomus fasciculatum*	*Vigna unguiculata*	Leguminaceae	Sundaresan et al. (1993)
Rishitin and solavetivone	*Glomus etunicatum*	*Solanum tuberosum*	Solanaceae	Yao et al. (2003)
Trigonelline	*Gigaspora rosea*	*Prosopis laevigata*	Leguminaceae	Rojas-Andrade et al. (2003)
Cyanidin-3-glucoside	*Glomus intraradices*	*Fragaria x ananassa Duch.*	Rosaceae	Castellanos-Morales et al. (2010)

(continued)

Table 20.1 (continued)

Active ingredients produced	AMF species involved	Host plant	Family	Reference
Linalool, linalyl acetate	*Acaulospora morrowiae, Rhizophagus clarus, Scutellospora calospora*	*Mentha × piperita L. var. citrata (Ehrh.) Briq.*	Lamiaceae	Silva et al. (2014)
Artemisinin, Jasmonic acid	*Rhizophagus intraradices*	*Artemisia annua*	Asteraceae	Mandal et al. (2015)
Flavonoids, Carotenoids	*Glomus intraradices*	*Bituminaria bituminosa*	Fabaceae	Pistelli et al. (2015)
p-hydroxybenzoic acid, Rutin	*Rhizophagus irregularis*	*Viola tricolor L.*	Violaceae	Zubek et al. (2015)
Ferulic acid, Caffeic acid, Kaempferol and Luteolin, Quercetin	*Piriformospora indica*	*Brassica campestris ssp. chinensis L.*	Brassicaceae	Khalid et al. (2017)
Tanshinones, Salvianolic acid B	*Glomus mosseae, Glomus aggregatum, Glomus versiforme, Glomus intraradices*	*Salvia miltiorrhiza*	Lamiaceae	Yang et al. (2017)

active ingredients of plants could be improved by the application of optimized inoculum of arbuscular mycorrhizal fungi.

20.5.6 Abiotic Environmental Stress Tolerance

Salinity stress is one of the serious threats, limiting the plant growth and productivity by decreasing water uptake, adversely affecting nutrient absorbance, hydraulic conductivity, stomatal conductance and net photosynthetic rate (Al-Karaki et al. 2001; Koca et al. 2007). Mycorrhizal associations have been found to influence the physiological and morphological properties of plant, thereby help the plant to combat biotic and abiotic stresses (Miransari et al. 2008; Evelin et al. 2009; Saxena et al. 2017; Giri and Saxena 2017). Under environmental stresses like drought and salinity they play an important role in maintaining ionic balance and nutrient supply in plant and soil for proper functioning and productivity of crop plants (Porcel et al. 2012; Evelin et al. 2013; Augé et al. 2015). Availability of water is the major limitation in agricultural fields particularly in arid and semi-arid areas. Several studies have shown that presence of AMF in water-stressed plants increase leaf and root growth and positively maintain root to shoot ratio (Quilambo 2000). The extraradical hyphae increase the absorptive surface area of roots for the better uptake of mineral nutrients and water under stress conditions (Hampp et al. 2000). Moreover, AMF aid plant to overcoming the adverse effects of environmental stresses as they improve balance between K:Na and Ca:Na (Elhindi et al. 2017). AMF facilitate plant for the accumulation of osmo-protectants, osmotic adjustment and maintenance of membrane integrity, therefore preventing plant from oxidative damage during environmental stresses (Evelin et al. 2013). Molecular studies have shown that in AMF colonized plants like *Glycine max* and *Lactuca sativa* changes gene expression of gene encoding plasma membrane aquaporins in response to drought stress (Porcel et al. 2005). Similarly, AM symbiosis could regulate expression of genes involved in oxidative stress, proline synthesis and in dehydrin proteins (Porcel et al. 2005; Fan and Liu 2011). Several nutritional and non-nutritional mycorrhiza-mediated mechanisms, helping plants to overcome salinity stress may be programmed as (1) nutrient uptake (like P, N, Mg and Ca) (Evelin et al. 2009), (2) Biochemical changes like accumulation of proline, betaines, polyamines, carbohydrates and enzymatic and non-enzymatic antioxidants (Evelin et al. 2009), (3) Physiological changes like enhanced photosynthetic efficiency, gas exchange and water use efficiency (Ruiz-Lozano et al. 2012; Elhindi et al. 2017; Saxena et al. 2017).

20.5.7 Weed Control

In agricultural fields, weeds are a major hazard to the crops, as they compete with crops and negatively affect the crop productivity (Oerke 2006; Ampong-Nyarko and Datta 1991). Although the management of weeds is possible using herbicides, weedicides and toxic chemicals, but the drawbacks of using these techniques are (Heap 2015; Shakeel and Yaseen 2016); (i) they are expensive, (ii) not suitable for sensitive crops (iii) several weeds are resistant against the herbicides, (iv) not safe for ecosystem and environment. Arbuscular mycorrhizal fungi have been found effective against several weeds, hence could be considered as the potent microorganisms to control agricultural weeds (Rinaudo et al. 2010; Veiga et al. 2011). Lendzemo (2004) revealed that *Striga hermonthica* (witch weed), which seriously affects the cereal crops can be controlled by applying AMF inoculants, as they directly reduce growth of weed or suppress their growth by increasing the competitiveness of crop through increased nutrient uptake of crop for essential nutrients leaving weeds deprived of nutrition. Rinaudo et al. (2010) recorded about 47% reduction in biomass due to invasion of six weeds, which were grown together with a crop, which could be controlled using AMF (Veiga et al. 2011; Adeyemi et al. 2015). Another mycorrhizal approach in weed control can be inhibiting weed growth by changing the relative abundance of mycorrhiza-infected and nonmycorrhizal-infected weed species in agroecosystem (Jordan et al. 2000) most likely due to secretion of some substances from AMF extraradical mycelium (Veiga et al. 2012).

20.5.8 Disease Resistance

Through several mechanisms like damage compensation, direct competition for colonization sites or food, changes in root morphology and rhizosphere microbial community composition, biochemical changes associated with plant defense mechanisms and the activation of plant defense. AMF can induce control over various plant diseases (Huang et al. 2003; Whipps 2004). Shalaby and Hanna (1998) observed improved growth of AMF colonized Soyabean plant in a soil infested with pathogenic fungi *Fusarium solani* and other pathogens. Similarly, AMF colonization increased resistance in Poinsettia against pathogens like *Pythium ultimumon* (Kaye et al. 1984). Coffee plant infested with mycorrhizal fungi enhanced competitiveness against disease causing *Bidens pilosa* (França et al. 2016) whereas Tea plant inoculated with mycorrhizal fungi and other plant growth promoters provided resistance for rot disease (Chakraborty et al. 2016). *Fusarium* induces wilt disease in tomato worldwide, at large its control and management is difficult. Inoculation of tomato with AMF has shown control in the severity of the disease and enhanced overall growth in tomato seedlings (Mwangi et al. 2011).

20.6 Role in Ecosystem and Environment Management

20.6.1 Soil Health and Fertility

One of the most important functions of the mycorrhizal symbiosis is to enhance acquisition of nutrients from the soil with the help of fungal hyphae. The extraradical hyphae of AM fungi often acquire those nutrients, which are hard to be extracted by plant roots. Although phosphorus is an essential nutrient for plants but remain present in the immobile form in the soil. It can be solubilized with the enzymes released by AMF (Joner and Johansen 2000). Ecosystems instability severely influences the physical, chemical and biological properties of the soil. However, mycorrhizal fungi have been found to improve such properties/processes (Augé 2004). They not only indeed affect the individual plant, even actively engaged in the processes like soil aggregation at the ecosystem level and improve the soil health and quality (Rillig 2004a, b). Nonetheless, soil aggregation helps in improving soil porosity and gaseous exchange, and nicely maintains soil nutrient cycle, protects soil carbon in aggregates, and influences beneficial soil micro-fauna (Diaz-Zorita et al. 2002; Jastrow et al. 1998; Johansson et al. 2004). By acting as a biofertilizer, and biocontrol agent mycorrhiza benefits the overall soil health and productivity (Jeffries and Barea 2012; Abdel Latef et al. 2016). Although plants absorb both macro-and micronutrients from the soil to accomplish their metabolic activities, the excessive accumulation of heavy metals like Zn, Cu, Pb, As, Cd, Cu etc in soil due to various anthropogenic activities and deposition of agro-chemicals rigorously degrade the soil and its fertility and productivity (Liu et al. 1997).

Several researchers have observed that AMF could play important role in mitigating such effects by minimizing the negative impact of heavy metal contamination attributed to their enhanced adsorption and precipitation (Nadeem et al. 2014; Turnau et al. 2008; Malekzadeh et al. 2011).

20.6.2 Ecosystem Functioning and Biodiversity

The relationships between mycorrhizal fungi and plant is of great importance as they could play a major role in the ecosystem functioning and maintaining soil biodiversity (Gerz et al. 2016), contributing to biogeochemical cycles, food and timber production, and other benefits (Gianinazzi et al. 2010; van der Heijden et al. 2015; Bender et al. 2016). In fact, AMF are involved in many biogeochemical cycles, the most studied are C, N, and P (Smith and Read 2008; Prieto et al. 2012; Ekblad et al. 2013; Hodge and Storer 2015; Mayor et al. 2015; Lazcano et al. 2014). Moreover, their widespread distribution among a wide array of plant species makes them a powerful tool to manage agricultural and environment sustainability (Azul et al. 2014; Bhardwaj et al. 2014). Mycorrhizal fungi influence plant community structure and play a pivotal role in plant community assemblage and succession (Hartnett and Wilson 1999; Heneghan et al. 2008; Kikvidze et al. 2010; Lin et al. 2015). Further, AMF facilitate the regeneration and emergence of newly developed seedlings (Stanley et al. 1993; Barea et al. 2002), alter species interactions, and change the dynamics of plant communities' thereby increasing plant diversity in terrestrial ecosystems (van der Heijden et al. 1998; Klironomos et al. 2000; Dhillion and Gardsjord 2004; Simard and Austin 2010; Horn et al. 2017). AM association enhances plant's survival rate under unfavourable soil conditions, hence increasing the plant community diversity and ecosystem productivity (van der Heijden et al. 1998; Klironomos et al. 2000; Dhillion and Gardsjord 2004). It has been noticed that ecosystem instability is increasing in the modern agriculture system that might be due to lack of AMF interactions in soil (Helgason et al. 1998; Jeffries and Barea 2012). However, the incorporation of AMF could reverse the threat to biodiversity and ecosystem instability in the present day cultivation (Tilman 1996).

20.6.3 Reclamation of Degraded Land/Bioremediation

Increase in industrialization, urbanization, mining and several other human-induced activities across the globe have led to increased accumulation of toxic elements/ heavy metals in the groundwater and soil (Sharma et al. 2017), which largely affect both soil fertility as well as plant productivity (Whitmore 2006). AMF play an impending role in the restoration of degraded waste lands (Asmelash et al. 2016; Nicolson 1967). The extraradical hyphae of AMF improve the vegetation cover of the degraded lands by significantly enhancing the assimilation of nutrients (Jha et al. 1994; Khan 2006; Gohre and Paskowski 2006). AMF attribute to the seedlings emergence and their establishment and survival in the polluted areas/lands and maintain the diversity in severely heavy metals contaminated soils (Hassan et al. 2011; Karthikeyan and Krishnakumar 2012; Manaut et al. 2015). AMF alleviate the impact of heavy metals by immobilizing them in the soil, chelation upon absorption, adsorption on the cell wall, altering pH of the rhizosphere soil and by enhancing phytostabilization and phytoextraction ability of the plants (Gaur and Adholeya 2004; Malekzadeh et al. 2011; Abdel Latef et al. 2016). Garg and Singla (2012) observed that inoculation with AMF increased the chlorophyll and relative water content in pea plants growing in the arsenic contaminated soils. Shabani et al. (2016) reported reduced transportation of Ni from the root to shoot along with the enhanced level of ABC transporter and metalothein on inoculation with *Glomus mossae* and *Festuca arundinacea* growing in the Ni polluted soil. Several studies have demonstrated that molecular expression of genes like Zn (*GintZnT1*), As (*GiArsA*), Cu and Cd (*GintABC1*, *GmarMt1*) likely to play a crucial role in plant's heavy metal tolerance (Lanfranco et al. 2002; Gonzalez-Guerrero et al. 2005; Lenoir et al. 2016). AMF predominantly prevail in the stressed habitats and unusable soils, and establish a mutual relationship with the plant species growing on the toxic soil (Cabral et al. 2015; Lenoir et al. 2016). The glomalin produced by AMF adsorbs the heavy metal from the soil and reduce the soil toxicity (Gil-Cardeza et al. 2014; Wu et al. 2014a, b). Experimentation under axenic conditions has shown that AMF exhibit potential for bioremediation of contaminated soils (Mugnier and Mosse 1987; Declerck et al. 2005; Cabral et al. 2010). In the light of occurrence and importance of AMF in the degraded waste land, it may be tempting to state that AMF could prove to be a potential approach to reclaim disturbed/contaminated soils. However, to establish the fact further research, particularly at molecular level is required.

20.6.4 Preventing Soil Erosion

Increasing soil erosion due to anthropogenic activities has become a potential cause of land degradation and desertification. Besides, increasing applications of P fertilizers of which only a small amount is absorbed by the plant and rest of it gets washed-off due to the tillage-induced soil erosion and reduced water retention capacity of soil. Since AM symbiosis plays key role in ecosystem functioning, these fungi could be applied to overcoming the problem of soil erosion (Miller and Jastrow 1990; Perumal and Maun 1999; Enkhtuya et al. 2003; Estaun et al. 2007). Of all the processes involved, production of mucilage, glomalin related soil protein (GRSP) and other extracellular compounds are the most studied one. These compounds provide strength to soil particles to formulate aggregations (Wright and Upadhaya 1996; Rillig et al. 2002; Rillig 2004a, b). A positive correlation has been found between the length of AMF hyphae and water stable aggregate through the production of glomalin related soil protein (GRSP) (Miller and Jastrow 1990; Wright and Anderson 2000; Rillig et al. 2002). Glomalin related soil protein has also been found to maintain stability of soil. Mycorrhiza-induced GRSP fraction has a major role in aggregate stability in citrus rhizosphere (Wu et al. 2014a, b). However, soil aggregate stability may differ among the AMF species. Schreiner et al. (1997) observed a variation in the size of the aggregate formed by *Glomus mossae,* which were larger than those formed by *G. etunicatum* and *Gigaspora rosae*. Miller and Jastrow (1990) revealed a direct correlation between the spore density and water stable aggregate. Beside glomalin production, AMF-mediated dense hyphae production, entanglement of soil particles with hyphae, improved soil microbiota also play important role in soil aggregation (Rillig et al. 2002; Rillig and Mummey 2006; Sharma et al. 2017). Thus, in order to avail maximum benefits of AMF for a soil improvement program more studied are required to better understand, how AMF get involved in the formation of soil aggregation and what are other mechanisms behind it must be examined?

20.6.5 Mitigation of Global Warming and Climate Change

In addition to promoting plant growth, AMF can directly or indirectly contribute to the stabilization of carbon in the soil. AMF extraradical mycelium (AEM) has a carbon-rich component known as glycoprotein or glomalin that can stay in the soil for decades. AMF seem to have a priming impact on the other soil microbes to convert plant waste into stable soil carbon (Cheng et al. 2012), attributing to reduce atmospheric carbon-based green house gases (Giri and Saxena 2017). Research experiments conducted to study climate change impact have assessed that there is already too much GHGs in the atmosphere. To stop the progress of and reverse the effects of human-induced climate change, GHGs production must be reduced and controlled in the atmosphere. Plants have in built capacity, if harnessed appropriately, to fix carbon back into the soil in sufficient amount to make a significant contribution to combat climate change. AMF facilitate supply of the mineral nutrients to the host plant indeed increase the growth and biomass of the plant, harnessing more atmospheric carbon. Further, the sugar produced by the host is a prerequisite of AMF to meet their C requirement for own growth and life-cycle (Giri and Saxena 2017). AMF could play a vital role in the global carbon cycle, because these fungi can exploit a large percentage of the carbon fixed by their host (about 20%) under ambient atmospheric CO_2 conditions (Jakobsen and Rosendahl 1990, Drigo et al. 2010). They could help in depositing slow cycling organic compounds and protect organic matter from microbial attack (Smith and Read 2008; Verbruggen et al. 2013). This exhibits that AMF in fact promote aggregation of soil particles and help in managing soil erosion (Wilson et al. 2009). AMF help in soil C sequestration, particularly under elevated CO_2 concentration (Treseder 2016) as these fungi are the only producers of glomalin (a recalcitrant glue-like glycoprotein), which enters into the soil on the death of fungal mycelium and become a source of soil organic carbon sink (Wright et al. 1996, Wright and Upadhaya 1996).

In addition to atmospheric CO_2, nitrous oxide (N_2O) is another effective greenhouse gas involved in the destruction of the protective ozone layer in the stratosphere. It contributes to global warming with a several times higher global warming potential than atmospheric CO_2 (Forster et al. 2007; Ravishankara et al. 2009). Montzka et al. (2011) demonstrated that after carbon dioxide and methane, the nitrous oxide place highest impact on the greenhouse effect. The importance of N_2O is likely to increase due to its prolonged existence and a predicted increase in future emissions. However, the ecological processes regulating N_2O emissions from soil are not well known. Bender et al. (2014) revealed that the presence of AMF, which have a profound impact on a wide range of ecosystem functions, could shrink N_2O emissions from soil. They manipulated the abundance of AMF in two independent greenhouse experiments and two different soils and found that N_2O emissions increase by 42 and 33% in microcosms with decreased AMF abundance than microcosms with well-established AMF propagules. These results suggested that the N_2O emission from soil is controlled by AMF. They further explained that the reduced N_2O emission in the atmosphere could partially be attributed to the increased N immobilization into microbial or plant biomass and decreased level of soil N as a substrate for N_2O emission and altered water relations. Bender and his colleagues (2014) concluded that the intensification of agricultural practices may further contribute to increased N_2O emissions as it disrupts the development and proliferation of AMF hyphal network. At the high soil moisture levels AMF control N_2O emissions by increasing use of soil water (Lazcano et al. 2014).

20.7 Research Need and Approaches

AMF characteristics make them a potential tool to be utilized for the sustainable management of agriculture and environment (Rodriguez and Sanders 2015; Bhardwaj et al. 2014). Nevertheless, several agronomic practices including crop rotation, soil tillage, use of fertilizers and pesticides largely influence abundance and infectivity of mycorrhizal fungi (Jansa et al. 2002). These practices disturb AMF hyphal networks, destruct their colonization of roots and decrease the absorption of phosphorus from the soil (Douds et al. 1995). Further, conventional tillage significantly decreases mycorrhizal diversity (Alguacil et al. 2008) whereas in zero tillage condition AMF sporulation increased twofold, even in highly fertilized soil (Brito et al. 2011; Verzeaux et al. 2017). Further, land and air pollution, mining, deforestation, and many biotic and abiotic factors largely impacts mycorrhizal survivability, and cause severe loss to the viability of mycorrhizal propagules, resulting in a significant reduction in the mycorrhizal colonization of roots (Gehring and Bennett 2009; Zobel and Öpik 2014; Antoninka et al. 2015; Borriello et al. 2015; Klabi et al. 2015). Therefore, it important to understand that; (1) better understanding of the relative contribution of AMF to any aspect to sustainability by attaining a broad view of all the possible pathways by which they can influences sustainability, including their interactions with other soil microbial biome (Rillig et al. 2016), (2) Focus on the conservation and management of AMF diversity and abundance to accomplish the goal of sustainability. Special attention is required towards the sensitive ecosystems, which are directly affected due to inadequate soil management and climate change such as glaciers (Haeberli and Beninston 1998; Jiang and Zhang 2015), and highly exploited ecosystems like mountains (Kohler and Maselli 2009; Gurung and Bajracharya 2012) should also be prioritised for conservation.

Green technology/approach not only includes the decrease in use of chemical fertilizers but also the enhancement of the sustainable techniques. For the exploitation of AMF as a tool for green technology, we aim to optimize its benefits by increasing its abundance and diversity (Rillig et al. 2016) in the soil through various strategies including (1) Field study Assessment, (2) Analysis, (3) Management and Protection policies, (4) Advanced Improvement techniques, (5) Field trials with AMF (Fig. 20.2). In field study, various soil parameters like physical (structure), chemical (pH, moisture, etc), nutrient status and abundance and diversity of beneficial microorganisms (mycorrhiza and associated microbes) are monitored, as the abundance and diversity of AMF are influenced by the soil chemistry (Casazza et al.

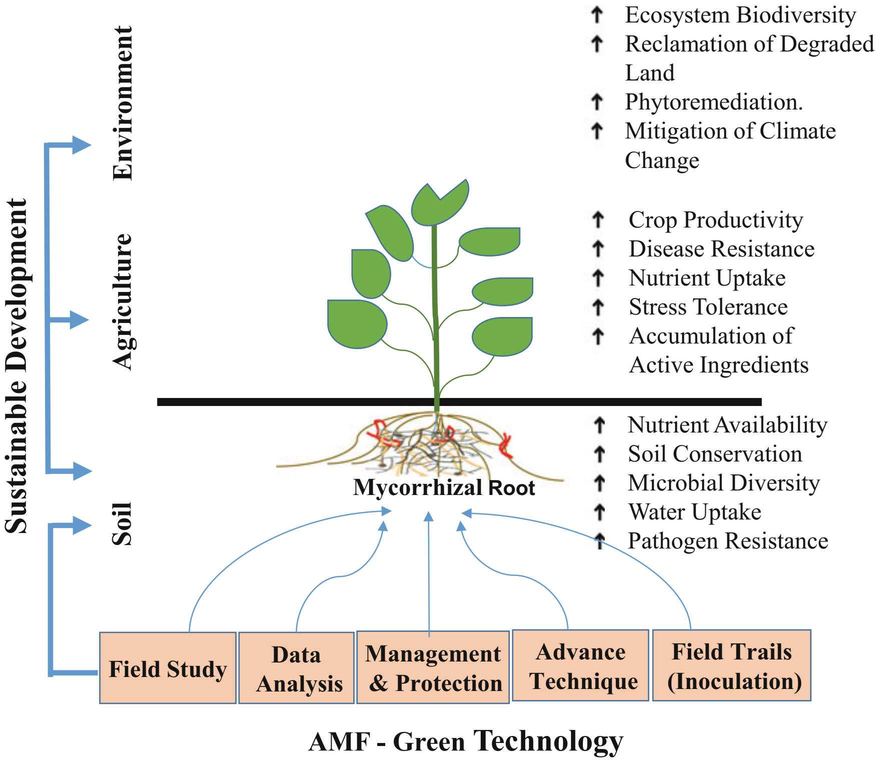

Fig. 20.2 An overview of various approaches associated with AMF-colonized plant roots, and their possible influencing role in sustainable agriculture and environment

2017). Data from field assessment records show the status of soil of the studied field and about the existing mycorrhizal and other microbial community which further provide site-specific information requirement about management and protection of AMF abundance and functioning (Rillig et al. 2016). Various crop management practices have shown improved yield in relation to mycorrhizal abundance (Monreal et al. 2015). Strategies with zero or less tillage and cover cropping have also shown enhanced root colonization and density of AMF in agriculture fields (Brito et al. 2013; Bowles et al. 2016). Moreover, advanced technologies of microbial community engineering and techniques like plant breeding are required to maintain the abundance and diversity of beneficial mycorrhiza and for manipulation and improvement of AMF with desirable traits respectively (Mueller and Sachs 2015; Hohmann and Messmer 2017). Production and field applications of AMF inoculum is the direct way to enhance the AMF propagules density in the agricultural field (Solaiman et al. 2014; Hijri 2016); however, constrain is the functioning of AMF in collaboration with many other microbes.

20.8 Conclusion and Future Perspectives

To enhance the ecosystem functioning and agricultural productivity without disturbing the balance of ecosystems and environment, utilization of arbuscular mycorrhizal fungi as a biofertilizer could be a potential solution; however, to achieve increased production, a major constraint is the development of AMF culture, abundance and density in the crop fields. Although AMF play a positive role in maintaining soil and plant health, the re-establishment of natural level of AMF richness is a major task, which could substitute the harmful chemical fertilizers and recompense a way to sustainable agriculture and environment. AMF could be utilized as a sustainable tool to improve the concentration of both macro- and micronutrients; hence could be an alternative to agronomic bio-fortification. Since AMF facilitate plants with macro- and micronutrients, it could positively influence the herbage, yield and quality of the crop, which is probably difficult to achieve using agro-chemicals. Therefore, we can recommend that field inoculation with AMF, depending upon the types of plant species and their environmental conditions, could be an effective alternative to agrochemicals. As the population is increasing day-by-day, there is a need of increased food production too, which could be only possible with the help of sustainable techniques or green techniques, like AMF-based bio-fertilizations along with PGPRs. To begin with, field trials with AMF inoculants and farmer’s awareness towards cost-effective techniques are important to reducing input of agrochemicals in the agriculture. Once agricultural fields are enriched with microbial inoculants, this approach can be of great significant for managing sustainable agriculture and environment at the large scale.

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