Chapter

Advantages of Arbuscular Mycorrhizal Fungi (AMF) Production for the Profitability of Agriculture and Biofertilizer Industry

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Abstract

Decades of ill-agricultural practices associated with emerging risks of climatic changes have been degrading the ecosystem with immense stress on the soil health, crop productivity. Arbuscular mycorrhiza (AM) form advantageous symbiosis between plant roots and specialized soil fungi that is rampant in natural habitats. Studies show that the elevated AMF indicated good soil health, high crop turnouts benefiting the Agriculture and other industries. AMF dependent on plants for sugars, while offering benefits like intact binding of soil particles, biomass increase, improvement of water-holding capacity, replacement of harmful chemicals, increased intake of phosphorous, zinc and other nutrients, drought and salinity tolerance, carbon sequestering in soil and protection from nematodes and other predatory insects. AMF are best candidates as bio-fertilizers and this review will explore their beneficial interconnections.

Keywords: arbuscular mycorrhizal fungi (AMF), bio-fertilizers, phosphorous, drought and salinity tolerance, nematodes

1. Introduction

In past decades, there are escalating events of abiotic stress like drought, low or high-salinity, soils contaminated with heavy metals, extremely high or low temperatures and other extreme calamities of climate such as hurricanes, tornadoes have always been detrimental to agriculture and industries. Added to the list, increasing effects of the unseasonal climatic changes such as earthquakes, tsunamis have immensely damaged our lands. On top of everything else, agricultural malpractices like poorly managed animal feeding operations, overgrazing, plowing, tilling, excessive fertilizer usage, genetically modified crops, deforestation, excessive irrigation, pesticides, phosphorous mining, poor agricultural waste management, increasing soil pathogens have severely crippled the agricultural yields [1]. The world populace is projected to be 9.7 billion in 2050 and approximately 11 billion around 2100 according to UN population division and thus the global need for increased food sources by agricultural production must be definitely promoted to keep up with the population. Many improvements must come up for better agricultural quality and productivity shortcomings with insightful management.

Figure 1.
Mycorrhizal fungal association in roots of legumes (photo courtesy: Corsi and Muminjanov [2]).

The Food and Agriculture Organization (FAO) United Nations reveals major challenges to sustainable intensification of land and agricultural practices such as land degradation due to tillage erosion, soil compaction, overgrazing, nutrient mining, overuse of mineral fertilizers and herbicides, inefficient irrigation practices, ignorant crop management practices and other malpractices [2] that needs immediate attention. The FAO Agricultural Development Economics Division voice out for crucial remedial measures on agricultural practices as the population growth and global food demand towards 2030/50 seems worrisome [3].

Studies show that AMF associated agricultural practices can offer major relief by sustainable and beneficial consequences for both agricultural and natural ecosystems through its association with the plants and soil. This chapter presents the symbiotic interconnections of AMF for the advantageousness in agriculture and industry are highlighted (**Figure 1**).

2. AMF background and evolvement

The fungus is a eukaryotic organism that belonged to the plant kingdom at the beginning; nonetheless, as the studies unfolded its unique features, scientists realized that fungi were much alike animals than plants by exhibiting features like cell membrane-bound organelles, distinct nuclei, and lack of chlorophyll in their cells. Fungi have an exclusive life cycle of having principal modes of vegetative growth, nutrient intake unlike animals that enabled it to have a distinguished identity. The kingdom of fungi has about 1.5 million known species covering the yeasts, rusts, smuts, mildews, molds, and mushrooms. Some organisms like slime molds and oomycetes (water molds) show many fungi-like features and are included in the kingdom of Chromista. Fungi are widely distributed on earth and are mostly free-living, some form parasitic or symbiotic relationships with plants or animals. Many fungi are of great environmental and medical importance and its study is termed as Mycology [4].

A typical fungus has minute filamentous cytoplasmic morphologies bounded by a plasma membrane and cell wall known as hyphae. Their cell walls are made up of flexible polysaccharides called chitin, resembling the exoskeleton of insects. The hyphae have many auxiliary cell walls, known as cross-walls or septa, typically perforated with pores that are large enough for ribosomes, mitochondria, and nuclei to flow. The hyphae branch extensively as they mature, forming complex multicellular structures known as mycelium. A mycelium gives heterotrophic nourishment as they feed on organic food sources, digest them externally before absorption by secreting valuable enzymes into its surroundings. These mycelia can spread to vast areas that

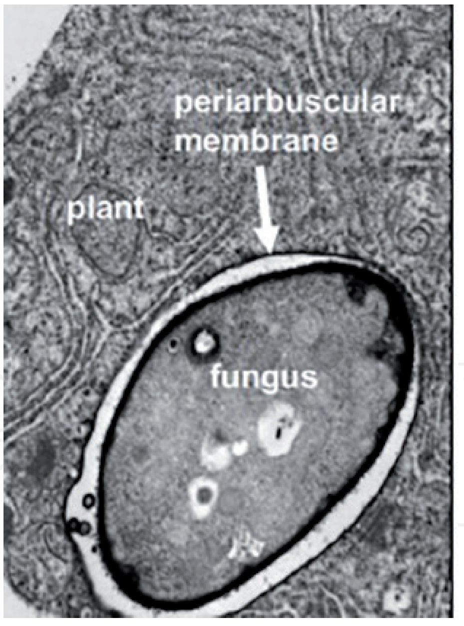

Figure 2.
Transmission Electron micrographic view of a colonized host cell with an arbuscular branch (fungus), surrounded by the peri arbuscular membrane (photo courtesy: Chen et al. [8]).

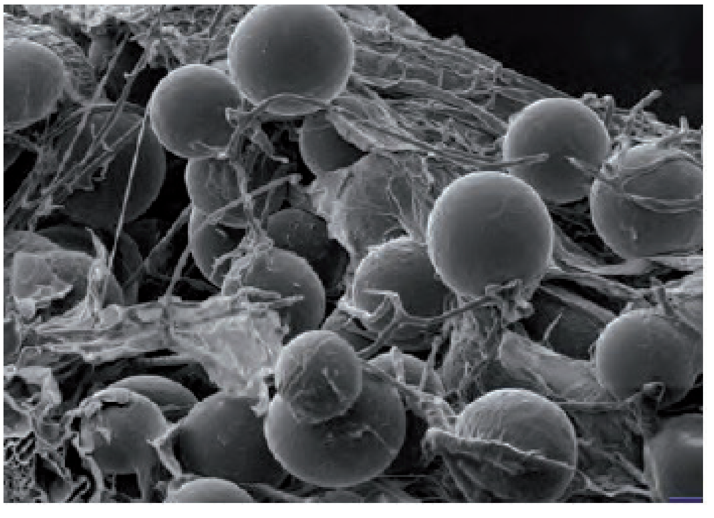

Figure 3.
Scanning electron micrograph of mycorrhizal hyphae and spores (photo curtesy: Mycorrhizal applications @ GPNMAG.COM 2018).

serve as a phenomenal symbiotic benefit to the plant root system, giving it a unique chance to obtain phosphate and other minerals far off the nutriment depleted zones, while the fungal takes sugars from the plant. Symbiotic association between a fungus and the roots of a vascular plant is often termed as Mycorrhiza or root fungi [5].

The mycorrhization of a plant root that develops as a cover surrounding the roots is termed mantle, from which the hyphae grow, and this is Ectomycorrhiza. On the other hand, Endomycorrhiza is when the mycelium is implanted within the root tissue and these are also termed as the arbuscular mycorrhizae (AM) or arbuscular mycorrhizal fungi (AMF).

More than 80% of the terrestrial plants show symbiosis with AMF and they belong to Phylum Glomeromycota. AMFs are obligate biotrophs, absorb photosynthetic byproducts and lipids in the plant symbiotic connections [6]. AM are expected to have originated approximately 480 million years ago, the fossilized fungal hyphae and spores from the Ordovician of Wisconsin (USA) bear a strong resemblance with the current AMF (Glomales, Zygomycetes). These fossils suggested that Glomales-like fungi existed in the bryophytic vegetation. Later many reports supported that AMF was essential constituents in predominant land plants in most taxa in all the ecological niches for ages. The Glomeromycota are a distinctive obligate biotrophic fungi that majorly comprises AMF related in symbiosis with many Embryophytes [7]. Nevertheless, certain mycoheterotroph plant species on AMF symbiosis turned in to obligate parasites having completely lost plastid genetic apparatus, photosynthesis genes with secondary functions, NADH dehydrogenase-like genes and photosynthesis genes. As another diversity was seen in plant taxa such as Brassicacea (or Cruciferae) and Chenopodiaceae, where they have shown asymbiotic interaction with AMF and these plants developed other strategies for their nutritional requirements (**Figures 2** and **3**) [9].

3. AMF as biofertilizers

Many active or dormant strains of bacteria or fungi or in combinations are used diametrically or collaterally to activate the rhizo-microbiome and trigger the nutrient supply from soil to plants that would ultimately result in enhancement of crop yields. These microbial strains are broadly termed as biofertilizers, bio-inoculants, agricultural inoculants, soil inoculants, or microbial inoculants. These bio-inoculants with unique merits are highly encouraged globally and are earning prominence in modern agricultural customs, practices and maneuvers contrasting to other conventional or synthetic pesticides and fertilizers. These biofertilizers are safe to handle, are required only in small quantities as they capable of fast replication, their action can be leveraged or optimized based on their incumbencies, decompose quickly with negligible ill effects to the environment and show lower resistance to host plant and infective organisms [10].

Plant growth promoting and disease suppressing microbial inoculants such as *Azospirillum, Bacillus, Pseudomonas, Rhizobium, Serratia, Stenotrophomonas,* and *Streptomyces, Ampelomyces, Coniothyrium, Glomus,* and *Trichoderma are* extensively examined and analyzed for their mechanism of action and regulatory gear. Even though multiple categories of biofertilizers are at hand, the AMF is reported of manifold advantages and graded high for soil health and crop productivity [11]. Studies have shown comparative progress where plants get better nourishment with greater AMF colonization than that of the non-mycorrhizal plants even with conditions like mineral deficiency and abiotic stress. AMF establishes symbiotic interconnection with many different types of Plants or the other way round, that leads to the formation of common mycorrhizal networks (CMNs) and such mycorrhizal interactions are exceptionally valuable for healthier plant growth and yield in most of the scenarios [12].

Certain AMF show specific combinatorial benefits with specific types of plant species from all types of geographical locations that can result in positive mycorrhizal growth response (MGR) and this is a progressive mutual adaptation that did not correlate with phylogenetic lineage patterns relevant to variant species [13]. Contrarily, some studies though agree with the functional specialization of AMF, proved that such incidence is a flexible phenomenon where plant species are required to show compatibility with at least a few AMF. This scenario with minimal host specificity and broad functional specialization encourages vast biodiversity and productivity in plant communities [14].

Rampant use of inorganic fertilizers, herbicides, and fungicides are causing multiple injurious health risks to every living organism by hazardous impacts on the quality of food, soil, air, and water systems [15]. Over the years, many investigations have proven the efficacy of AMF for best agricultural production compared to other synthetic or chemical fertilizers under the prevalent stressful conditions, as addressed below.

4. Drought tolerance

Drought is the scarcity of water in soil for prolonged durations affects plant growth. It has severe implications on the entire plant biorhythm and growth at every notch. Deficit water supply to roots causes oxidative stress due to anomalies in transpiration [16], affects enzyme activity, ion uptake, and nutrient assimilation [17]. Many investigations have evidenced that AMF can allay drought stress in varied crop like wheat, barley, maize, soybean, strawberry, and onion [18]. This remarkable tolerance is reasoned essentially due to the extra-radical hyphae of AMF that has the capability of vast area spread [19]. Further, the osmotic adjustment, stomatal regulation, enhanced proline, and glutathione level are exhibited to have augmented root efficiency, leaf area index, and biomass under the instant drought conditions and against severe environmental conditions. Reports have demonstrated that the enhancement in growth and photosynthesis in C3 (*Leymus chinensis*) and C4 (*Hemarthria altissima*) plant species through up-regulation of antioxidant system by AMF symbiosis (**Figure 4**) [20].

Figure 4.
2017 California spring trials. Coreopsis plants (image 1) inoculated with AMF (left) showed better tolerance than plants without AMF under same drought stress. Coreopsis plants (image 2) treated with AMF showed improved top growth and root system development (left) than that without AMF inoculation (right) (photo courtesy: Mycorrhizal applications @ GPNMAG.COM 2018).

5. Salinity stress alleviation

Soil salinization is an aggravating issue threatening global food safety as it suppresses the plant development leading to reduced crop harvest (due to enormous formation of reactive oxygen species (ROS)) [21]. Many research reports showed the efficiency of AMF to enhance growth and crop yield under salinity stress. AMF association triggered the synthesis of plant hormones such as jasmonic acid and salicylic acid, and inorganic nutrients (P, Ca^{2+}, N, Mg^{2+}, and K^{+}) under salt stress conditions [22]. Some mycorrhizal associated plants showed increased amount of biomass, proline, N_2, and remarkable alteration in ionic uptake. AMF inoculation showed better levels of key growth regulators such as cytokinin, polyamine and strigolactone concentrations, suppressing lipid membrane peroxidation and regulation of the osmoregulation [23].

6. Resilience to extreme temperatures

Extreme temperatures such as Heat stress and Cold stress are prevalent challenges faced by plants globally. Heat stresses reduce seed germination, growth rate and biomass, and cause wilting or burning of leaves and reproductive organs, and which leads to senescence of leaves, damage and discoloration of fruit, reduction in yield, cell death, and enhanced oxidative stress [16]. Mycorrhizal plants showed encouraging growth under the conditions of high temperature [24]. AMF supports plants in cold stress and helps plant development [25] as they can retain moisture in the plant [26], increase plant secondary metabolites boosting immune system, and improve protein content to ameliorate cold stress [27].

7. Minimization of heavy metal toxicity

Accumulation of heavy metals in food crops, fruits, vegetables, and soils are very hazardous [28]. Plants grown on soils with excessive Cd and Zn exhibit considerable suppression in shoot, root growth, leaf chlorosis, and even death [29]. AMF associations have shown fortified growth and crop yield under aluminum stress and other metals [30]. Heavy metals are immobilized in the internal or external surface of fungal hyphae and will be stored in their vacuoles or may chelate with some other substances in the cytoplasm, minimizing the toxicity effects [31]. Mycelia of various AMF have a high cation-exchange capacity and absorption of metals [32] and they enhance the plant biomass, that uptake important immovable nutrients like Cu, Zn, and P further nullifies the metal toxicity [33].

8. Oxidative stress

Exposure of plants to drought, salinity, heat and cold stress, other harmful conditions causes oxidative stress, an enhanced production of reactive oxygen species (ROS), which can be highly injurious to plants [34]. Some of the enzymes including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and glutathione reductase (GR) prevent the production of ROS [35]. Mycorrhizal plants have proven to successfully overcome oxidative stress by improved biomass production, leaf water relations and stomatal conductance [36], other amplifying operations include improved photosynthetic rate, uptake and accumulation of minerals, assemblage of osmo-protectants, up-regulation of antioxidant enzyme activity, and change in the rhizosphere ecosystem [37]. Studies have shown the improved nutritional status of AMF plants under osmotic stress conditions resulting from deficit irrigation or salinity. Some of the substantial variations were observed in the charectorstics of phytohormones, absorption of minerals, compilation of osmolytes and secondary metabolites, and in the antioxidant execution systems. These impacts are presumed to have enhanced the nutraceutical value of yield in crops mounting to immense agronomic accomplishments [38].

9. Biotic stress

Plants encounter biotic stresses caused by pathogenic fungi, viruses, bacteria, nematodes, insects, etc. that cause diseases, infections and affect crop productivity. AMF association is known for potential biocontrol mechanisms such as antibiotic production, competitive interaction strategies among the rhizo-microbiome and pathogens, mycoparasitism, and inducing genetic expression changes able to induce systemic resistance inside the host plant [39]. AMF is reported to have biocontrol capacity over powdery mildews [40] and the nonpathogenic and saprotrophic species of Rhizoctonia, Fusarium, and Trichoderma have been utilized to reduce damage caused by genetically and phenotypically similar pathogenic fungi. They are known to control soil-borne and plant diseases and studies reported that increased plant growth was seen in associated with strains of *Trichoderma, Glomus intraradices, Glomus mosseae*, and other plant growth-promoting microorganisms due to systemic resistance against plant pathogens by upregulating specific genes in the host plant [41]. There is a growing body of evidence on multifunctional prospects of AMF as efficient biocontrol agents for augmented plant productivity by enhancing crop nutrition. Many AMF act as broad biopesticides or selective agents such as mycoinsecticides, mycoacaricides, myconematicides and others [42].

10. Minerals and phosphorous transport

AMF improves plant nutrition and helps them to cope with changing environments. Plants use inorganic phosphate (Pi) and it is the most important limiting factor for its growth. Since soluble Pi levels are low in the soil, the symbiotic interconnection with AMF will efficiently supply the needful Pi and other mineral nutrients in exchange for carbohydrates [43]. AMF expresses proteins to transfer inorganic phosphate (Pi) from the soil to colonized roots through symbiotic interfaces [44]. AMF compatible plants have two Pi uptake pathways that have different sets of phosphate transporters: a direct up take pathway through the epidermis and root hairs, and a symbiotic uptake pathway for the Pi provided by the fungus [45]. In Addition, AMF shows extraordinary symbiotic Pi uptake, by boosting the plant mineral nutrient acquisition even with low-nutrient supply [46].

11. Crop yield enhancement

AMF can improve the nutrient status, quality, and yield of the crops, AMF-colonized crops show increased levels of secondary metabolites with antioxidant [47] and enhancement of dietary quality of crops with carotenoids and volatile compounds were observed [48]. Mycorrhizal symbiosis enhances the accumulation

Figure 5.
Effect of mycorrhizal treatment on corn (on the left) with their control (on the right). Ohio, USA, 2019 (photo courtesy: Groundwork BioAg).

of anthocyanins, chlorophyll, carotenoids, total soluble phenolics, tocopherols, sugars, organic acids, vitamin C, flavonoids, and mineral nutrients [49] and enhanced the biosynthesis of phytochemicals in edible plants (**Figure 5**) [50].

12. Soil erosion and nutrient leaching

AMF helps to successfully overcome soil erosion and nutrient leaching in natural as well as in agricultural lands [51]. AMF mycelium is highly ramified and creates a three-dimensional matrix that enmeshes and crosslinks soil particles without compacting the soil with soil glycoprotein, glomalin for stabilization of soil aggregates [52]. Glomalin and glomalin-related soil proteins (GRSPs) account for a vital fraction of total organic soil carbon (2–5%), and for sequestration of carbon in the soil [53]. The hyphal network of AMF, and their promoting effects on plant growth and root system development, protect the soil from erosion by wind and water, promotes water retention capacity and nutrient supply [54].

Nutrient leaching is a serious risk as it results in soil infertility and pollution of groundwater and surface water (rivers, lakes). Agricultural lands are disturbed by malpractices like extensive plowing and tilling, and receive large amounts of fertilizer with N, P and K. These can get washed out from the soil due to the lack of retention systems leading to undesirable consequences [55]. AMF reduces nutrient leaching from the soil [56] by operating at different levels, such as improving soil structure, nutrient sequestration to the micro and macro-soil aggregates, uptake of nutrients from the soil solution and reviving its retention capacity [57].

13. Crop care and horticulture

Cultivation of a garden, orchard, or nursery of flowers, fruits, vegetables, or ornamental plants with AMF associations has received notable appreciation. Other extended aspects of horticulture include plant conservation, landscape restoration, soil management, landscape and garden design, construction, maintenance, and arboriculture [58]. The AMF attributes such as upregulation of Pi, nutrients, survival rate, plantlet micropropagation, crop uniformity, enhanced fruit production with high nutrient values, resistance to biotic and abiotic stress are attracting botanists, horticulturists, and other scientists (**Figures 6** and 7) [60].

Figure 6.
Outcome of AMF inoculation on enhanced root structure and size of Banana saplings; control compared with the test saplings T_{1-4} (photo courtesy: Emara [59]).

Figure 7.
Geranium plants grown on commercial nutrient regime (left) and that grown with the same nutrient supply with additional mycorrhizal fungi (right) which shows better nutrient and water uptake and use efficiency (photo curtesy: Mycorrhizal applications @ GPNMAG.COM 2018).

14. Potential use in reforestation, landscaping, bioremediation and revegetation

Mycorrhizal associations are extensively utilized for reforestation programs, the ectomycorrhizal fungi are employed to produce containerized seedlings and AMF are raised with plantlets to survive transplantation shock [61]. Such seedlings may have better survival after planting in tropical settings or another natural environment with varied climate conditions [62].

Landscaping is an evolving industry financed by enthusiastic customers from private corporations, businesses, private homes and government agencies for esthetic highway and road maintenance, seeking low-cost and natural solutions. AMF association has encouraged the best native planting and reclamation practices with appealing sports fields, road medians, golf courses, public and private parks, and gardens [60].

Bioremediation and revegetation are a scenario that promotes plant growth in contaminated soils and AMF has acclaimed its potential in this regard also [63]. Decades of agricultural and industrial malpractices, volcanic ash, mine spoils, waste deposits and other anthropogenically polluted sites are filled with organic compounds or heavy metals. AMF has mineral-scavenging capacities with two kinds of strategies, they accumulate and sequester toxic metal ions, or they deliver to plants in the form of essential mineral nutrients such as Cu and Zn [64].

Figure 8.
Improved land scaping with AMF (photo courtesy: AMF lawns @ AMFLawns. Landscape Company).

Bioremediation and phytoremediation by mycorrhizal inoculants are an emerging frontier and needs attention (**Figure 8**).

15. Conclusion

AMF association with plants amplifies its growth and harvest with fortified nutrients, parallelly resists environmental stress and defends from infections. Furthermore, revamps soil quality, texture, and water retention capabilities in both the agricultural and industrial sectors. With all the fundamental features, they are proving to be significant in both academic and commercial arenas. Novel cost-effective techniques are required to check AMF quality control, social media, computer-based technologies can help to promote mycorrhizae application on agricultural field. The awareness presentations through social media will be a best method to reach the importance of AMF to organic farmers. Antimicrobial resistance is an evolved hazard in the modern world and replacing chemical fertilizers, synthetic pesticides, fertilizers, and other microbicides with biofertilizers is predominantly essential.

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