



Glycoprotein Producing AM Fungi lifecycle and Potential Role in Agricultural Plant Lifespan and Global Environmental Changes for Sustainable Green Technology

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Abstract

The fungi forming arbuscular mycorrhizal fungi (AM fungi) are obligate symbionts microbe that predominates with inside the roots and soil of land flora. AM fungi are monophyletic group of phylum Glomeromycota. The AM fungi now no longer simplest arise in roots however additionally produce hung networks of extraradical mycelium (ERM) indeterminate length, spreading from host roots into the encompassing soil and establishing belowground interconnections amongst plants belonging to the identical or to unique taxa, in which they form a dense mycelial network (MNW). Reproduction in AM fungi takes place via asexual spores, which might be produced at the hyphae tips. These thick-walled spores stay with inside the soil for prolonged periods of time. AM fungi facilitate host plants to develop vigorously beneath stressful situations with the aid of using mediating a chain of complicated conversation occasions among the plant and the AM fungus leading to enhanced photosynthetic rate and other gas exchange in addition to improved water. AM fungi provide key nutrients to host plant lifespan. AM fungi transfer phosphorus (P), other macro and micro nutrients, along with water to the hosts of grassland and tropical forest plants in exchange for sugars. AM fungi form a network of filaments that associate with plant roots and draw nutrients from the soil that the root system would not be able to access otherwise. AM fungus plant alliance stimulates plant growth and accelerates root improvement in nearly all crops. The AM fungal extraradical hyphae (ERH) alongside glomalin connected soil protein (GCSP) extensively influence the soil carbon dynamics (SCD) and enhance soil and plant health. They additionally increase the resistance in plants against plant pathogens and surface area of root system for higher absorption of nutrients from soil. Therefore, they can be used as biofertilizer in addition to biocontrol agent. Present manuscript delineated the prospective of AM fungi as a biostimulants can potentially strengthen plants' adaptability to converting Agriculture system for green technology.

Keywords: AM Fungi; Reproduction; Symbiosis; Sustainable Agriculture; Green Technology

Introduction

Fungus is a microscopic microorganism of the group eukaryotes that consists of yeasts, moulds and mushrooms.

These organisms are very small requiring a microscope for thorough observation. They are globally plentiful and found in a huge variety of habitats. Numerous useful fungal species to be had in hemisphere that helped shape civilisation and

fungi have had a considerable impact on human and plant lifespan. Plants began setting up throughout terrestrial environments more than 430 million years ago; they had been observed via way of means of a symbiotic fungus, mycorrhizae. AM fungus (Endomycorrhiza), are grouped in a monophyletic group, the phylum Glomeromycota consists of all known AM fungi has coevolved with the majority of plant ever since. Considering the lengthy evolutionary records of mycorrhizae, it is not surprising that the mycorrhizal association is present in more than 95% of all vascular plant, as AM fungi apparently lacks host specificity. AM fungi are a root endosymbiosis among plants and glycoprotein producing fungi (GPPF). It is the greatest widespread terrestrial plant symbionts, enhancing water and mineral nutrients uptake to the plant. Mycorrhizae display many characteristics of primitive fungi: they produce spores, display little diversification, does now no longer have a sexual reproductive cycle, and cannot alive without living host. There are various types of mycorrhizae found in hemisphere. Ectomycorrhiza rely on fungi enveloping the roots in a sheath (mantle) and a Hartig net of hyphae that extends into the roots among cells in forest plants. The fungal partner can belong to the Ascomycota, Basidiomycota, or Zygomycota. In a second type, the Glomeromycota fungi form vesicular arbuscular interactions with AM fungi. AM fungi form arbuscules that penetrate root cells and are the site of the metabolic exchanges among the fungus and the host plant. The arbuscules (pint-sized trees like structure) have a shrub like appearance. Orchids rely on a third type of mycorrhiza. Orchids are epiphytes that form small seeds without much storage to sustain germination and growth. Their seeds are not germinated without a mycorrhizal partner (Basidiomycete). After nutrients in the seed are depleted, fungal symbionts support the growth of the orchid by providing necessary carbohydrates and minerals. A few orchids continue to be mycorrhizal association throughout their lifespan. AM fungi are obligate biotrophs feeding simplest on the products of photosynthesis of their living hosts. Generally, the fungi are not specialized to their potential hosts, although some plant species more favour the development of these fungi than others [1-6]. The fungi belong to the most commonly occurring soil microorganisms of the world and are associated with plants of the earth together with angiosperms, gymnosperms and pteridophytes having roots, in addition to the gametophytes of a few mosses, lycopods, and Psilotus, which do now no longer have real roots [2].

Various literature imply that AM fungi increase the root absorptive area and subsequently the plant nutrition's [7-11], influence succession of plant communities [12], their competitiveness [13,14] and phenology [13], equalize the level of nutrition of co-existing plants by formation of hyphal bridges transferring nutrients among them [15],

and increase soil structure through binding sand grains into aggregates by ERH [16-19]. AM fungi increased the tolerance of plants to heavy metals [20-24]; water stresses [25], in addition pathogenic fungi and nematodes [26-29]. The requirement of AM fungi for as much as 20% of host photosynthate for establishment and maintenance is nicely accepted [30-32]. Keeping in view, the importance of AM fungi and additionally the contemporary studies improvements related to their applications in agriculture and forestry, this manuscript focuses on the lifespan and potential role of AM fungi as biofertilizer within the regulation of plant growth, development, with improved nutrient uptake beneath nerve-racking environments, overall crop improvement and converting universal sustainable Agriculture for green technology.

Background of AM Fungi

AM fungi are soilborne mutual symbiotic fungi that could extensively enhance plant nutrients uptake and resistance to numerous abiotic stresses. AM fungi include of intraradical hyphae (IRH) in the roots and extraradical hyphal (ERH) structures outside the roots. The IRH structures are related to arbuscules, vesicles, and IRH. The ERH structures are spores, and auxiliary cells are formed members of the genera *Gigaspora*, *Pacispora*, and *Scutellospora*. Haustoria like arbuscules are the main sites of nutrient exchange among a host plant and a fungus [6,18,20,24,32]. They are formed inside the cells of the internal root cortex (IRC) [1,4-6,33,34] and are indicators of active lively mycorrhizae. Arbuscules vary in morphology, relying at the commonplace association of the arbuscular fungal species [35]. Fungi of the genera *Acaulospora*, *Archaeospora*, *Ambispora*, *Diversispora*, *Entrophospora*, *Glomus*, *Intrapora*, *Kuklospora*, *Pacispora*, and *Paraglomus* produce arbuscules with cylindrical or slightly flared, slender trunks, whose branches steadily taper in width towards tips. Arbuscules of members of the genera *Gigaspora* and *Scutellospora* usually have swollen trunks with branches tapering abruptly at tips. Globose or ovoid, thin-walled vesicles are storage organs filled with lipids and glycolipids [36]. AM fungal vesicles are origin an intercalary swelling in the root's tips of IRH. Vesicles can be inter or intracellular and can be found in both the internal and the outer layers of the cortical parenchyma. In *Glomus* species vesicles are mostly ellipsoid, while the ones of *Acaulospora*, *Entrophospora*, and *Kuklospora* highly vary in shape and often have knobs and concavities on their surface [35]. Vesicles are never produced by members of the genera *Gigaspora* and *Scutellospora*. Members of the genera *Archaeospora*, *Intraspora*, and *Paraglomus* not often produce vesicles. Intercellular hyphae (ICH) in roots additionally comprise storage materials and take part in transportation of the substances absorbed by ERH from the soil to arbuscules or directly to root cells of the host plant [1,4,6-7]. IRH can be straight or with H or

Y shaped branches. They might also form coils, whose frequency of incidence relies upon on their position in a root and the generic affiliation of the arbuscular fungal species [35]. Generally, coils extra abundantly arise at entry points. IRH of *Glomus* species are infrequently coiled in the other regions of an AM fungal root. In contrast, coils produced by species of the other genera of AM fungi usually are abundant and evenly distributed along mycorrhizal roots. AM fungi additionally vary in the degree of evenness of distribution along roots and the intensity of staining. The distribution of AM fungal structures of members of the genera *Ambispora*, *Archaeospora*, *Acaulospora*, *Diversispora*, *Entrophospora*, *Intraspora*, *Kuklospora*, and *Paraglomus* is patchy, while that of mycorrhizae of the genera *Gigaspora*, *Glomus*, *Pacispora*, and *Scutellospora* commonly is continuous. The strength of staining of AM fungi of the genera *Ambispora*, *Archaeospora*, *Diversispora*, *Intraspora*, and *Paraglomus* could be very faint to faint, the ones of *Acaulospora*, *Entrophospora*, and *Kuklospora* faint to moderate, those of *Glomus* dark, and those of *Gigaspora*, *Pacispora* and *Scutellospora* very dark [37-38]. A majority of the species of AM fungi belong to the sub-phylum Glomeromycotina, of the phylum Mucoromycota [39]. Four orders of AM fungi, namely, Glomerales, Archaeosporales, Paraglomerales, and Diversisporales, had been recognized on this sub-phylum that still consist of 25 genera [40]. They are obligate biotrophs and ingest plant photosynthetic products [41] and lipids to perform their life-cycle [42]. AM fungi mediated growth promotion is not only by enhancing water and mineral nutrients uptake from the adjoining soil however additionally via way of means of safeguarding the plants from fungal pathogens [27,29,43-44]. Therefore, AM fungi are critical endosymbionts playing an effective role in plant productivity and the functioning of the ecosystem for sustainable crop improvement.

Paleobiology of AM fungi

Paleobiological and molecular evidence imply that AM fungi are an ancient symbiosis that originated at more than 460 million years ago. AM fungal symbiosis is ubiquitous among terrestrial plants, which indicates that mycorrhizas were present in the early ancestors of extant global plants. This positive association with plants can also additionally have facilitated the development of terrestrial plants. The Rhynie chert of the lower Devonian has yielded fossils of the earliest land plants where in AM fungi have been observed [45]. The Early Devonian noticed the development of terrestrial flora. Plants of the Rhynie chert from the Lower Devonian have been determined to contain structures resembling vesicles and spores of present *Glomus* species. Colonized fossil roots had been observed in *Aglaophyton* foremost and *Rhynia*, which can be ancient plants possessing characteristics of vascular plants and bryophytes with primitive protostelic rhizomes [46]. IRH was observed in

root intracellular spaces, and arbuscules were observed with inside the layer thin wall cells similar to palisade parenchyma. The fossil arbuscules appear very much similar to those of existing AM fungi [46]. The cells containing arbuscules have thickened walls, which can be additionally observed in extant colonized cells. Mycorrhizas from the Miocene show a vesicular morphology closely resembling that of present Glomerales. This conserved morphology can also additionally reflect the ready availability of nutrients provided by the plant hosts in each modern and Miocene mutualism [45]. However, it could be argued that the efficacy of signalling approaches is probable to have evolved since the Miocene, and this can't be detected in the fossil record. A fine-tuning of the signalling processes could enhance coordination and nutrient exchange among symbionts at the same time as growing the fitness of each the fungi and the plant symbionts.

Molecular Evidence of AM Fungi

Increased interest in AM fungal symbiosis and the improvement of sophisticated molecular techniques has led to the rapid improvement of genetic evidence. Wang, et al. [47] investigated plant genes inclusive of DMI1, DMI3; IPD3 involved in communication with order Glomales fungal partners. These three genes can be sequenced from all major clades of modern land plants, including liverworts, the maximum basal group, and phylogeny of the three genes proved to agree with then current land plant phylogenies. This means that mycorrhizal genes ought to be present with inside the common ancestor of land plants, and they ought to be vertically inherited considering plants colonized land [47].

Distribution and Habitat of AM Fungi

AM fungi are found in all soils as fungal spores, and lack any intrinsic movement capabilities. Spores are typically present in the rhizosphere soil region which is usually the middle region of soil, in the immediate area of a plant root system and soil associated microorganisms. However, once in the vicinity of a nearby host plant's root system and under the correct conditions spore germination can initiate. This result in the growth of hyphae the ones branch out to close by host plant root systems. Whereby, a mutual symbiotic relationship establishes among the two organisms.

Reproduction and Lifecycle of AM Fungi

Reproduction in AM fungi happens via spores that are produced at the hyphal tips. These thick-walled spores stay with inside the soil for extended periods of time. AM fungal spores had been capable of germinate and bring produce hyphae with living host.

Presymbiosis of AM Fungi

The improvement of AM fungi earlier than root colonization (RC), referred to as presymbiosis, comprises three stages including as spore germination, hyphal growth and host recognition and appressorium formation.

AM Fungal Spore Germination

Generally, AM fungal spore reproduction happening with the aid of using asexual spores (Figure 1). AM fungal spores are thick-walled, multinucleate resting structures especially produced on the tip of sporogenous hyphae continuous with mycorrhizal ERH. The germination of the spore does not depend on the plant, as spores have been germinated under experimental conditions in the absence of plants both *in vitro* (modified living roots) and *in vivo* condition. However, the speed of germination may be hyperbolic with aid of using host root exudates (Figure 2). AM fungal spores germinate given suitable conditions of the soil matrix, temperature, CO₂ concentration, pH, and PC.

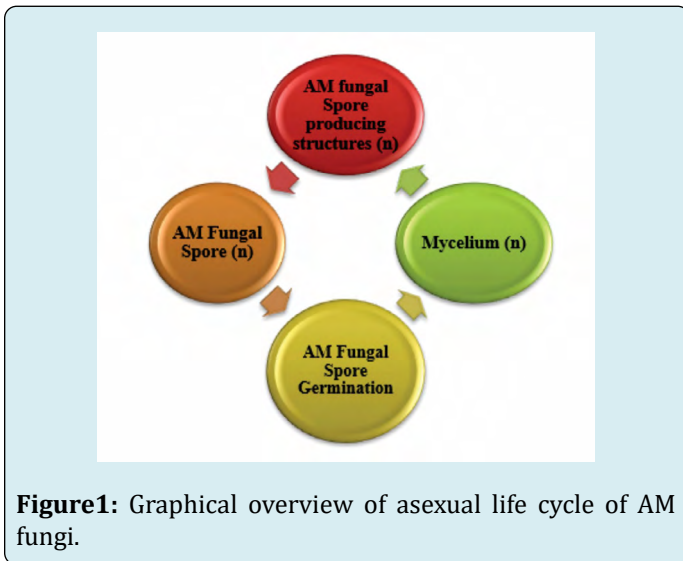


Figure1: Graphical overview of asexual life cycle of AM fungi.

Hyphal growth of AM Fungi

The growth of AM fungal hyphae through the soil is controlled by host root exudates referred to as strigolactones, and consequently the soil PC (Figure 2). Low PC within the soil increase hyphal growth (HG) and branching similarly as induce plant exudation of compounds that manipulate hyphal branching intensity [48-49]. The branching of AM fungal hyphae grown up in P media of 1 mM is extensively decreased; however, the length of the germ tube and total hyphal growth weren't affected. A level of 10 mM P pent-up each hyphal growth and branching of AM fungi. This PC occurs in natural soil conditions and might consequently make a contribution to decreased AM fungal colonization

[48].

Host Recognition of AM Fungi

Root exudates (RE) from AM fungal host plants grown all through a liquid medium with and without P are proven to have an impact on hyphal growth (Figure 2). Spores of *Gigaspora margarita* and *Glomus intraradices* had been grown in host plant exudates. Hyphae of AM fungi grown within the exudates from roots starved of P grew plenty of and created tertiary branches as compared to the ones grown in exudates from plants given adequate P. Once the expansion promoting root exudates had been superimposed in low concentration, the AM fungi created scattered long branches. Because the concentration of exudates was enlarged, the fungi created a lot of tightly clustered branches. At the highest concentration arbuscules, the AM fungal structures of P exchange had been formed [48]. Further evidence that AM fungi exhibit host-specific chemotaxis, that allow hyphal growth (HG) closer to the roots of a potential host plant: Spores of *Glomus mosseae* had been separated from the roots of a host plant, no host plants, and dead host plant through a membrane permeable most effective to hyphae. In the treatment with the host plant, the fungi crossed the membrane and continually emerged within 800 μm of the root, however now no longer within side the remedies with nonhost plants and dead plants [50].

Appressorium/Infection Structure Formation

AM fungal hyphae encounter the root foundation of a host plant, an appressorium or infection structure forms on the root cuticle (Figure 2). From this structure hyphae can penetrate into the host's parenchyma cortex (Figure 2). AM fungi would really like no chemical signals from the plant to make the appressoria. AM fungi may form appressoria on the cell walls of "ghost" cells in the course of which the protoplast have been eliminated to eliminate signaling among the fungi and additionally the plant host (Figure 2). However, the hyphae didn't similarly penetrate the cells and develop in close to the root cortex, which suggests that signalling among symbionts is needed for similarly increase growth as soon as appressoria are fashioned [49].

AM Fungal Cell Structure, Metabolism and Lifespans

AM fungi are an obligate biotroph, it requires a living photoautotrophic host to complete their lifecycle and produce the next generation of spores (Figures 1 & 2). AM fungal species are totally asexual spore (Figure 1) produced on the pointer of the hyphae. AM fungal spores are producing outside or inside the host root. AM fungal spores are capable to germinate without a host plant *in vitro* condition with contact of modified living roots. In absence of living root, spores germinate and formed a germination tube which

grows via the soil until it finds a host root. AM fungal spores penetrate the root and develop among root cells or it penetrates the cell wall and grown inside root cells (Figure 2). Once spores penetrate the root cells, arbuscules are formed (Figure 2). The arbuscules are tree shaped subcellular for nutrient exchange among AM fungi and symbiotic plant partners. Soil might also additionally include over hundred meters of hyphae per cubic centimetres [24,51]. This network of hyphae is designed to increase the plants uptake of important macro and micro nutrients which include N, P, K, Zn, Fe, S, Mn, Mg, Cu and water.

Symbiosis of AM fungi

AM fungus forms extremely branched structures in parenchyma for nutrient exchange for the plant referred arbuscules (Figure 2) [1,4,6,52]. These are the distinguishing specific structures of AM fungus. Arbuscules are the sites of exchange for P, C, water, and alternative nutrients [1,4,6,24,28,53,54]. There are two forms: Paris sort is characterised by the expansion of hyphae from one cell to the next; and Arum sort is characterised by the expansion of hyphae within the house between plant cells (55). The selection between Paris sort and Arum sort is primarily determined by the host family, though some families or species are capable of either sort [55]. The host plant exerts an effect over the ERH proliferation and arbuscule formation [1]. There's a decondensation of the body substance plant's chromatin that indicates inflated transcription of the plant's deoxyribonucleic acid (DNA) in arbuscule containing cells [52]. Major modifications are needed within the plant host cell to accommodate the arbuscules. The vacuoles shrink and different cellular organelles proliferate. The plant cell cytoskeleton structure is organized around the arbuscules. There are two different sorts of hyphae that originate from the colonised host plant root. Once colonization has occurred, transient runner hyphae grow from the plant root into the soil. These are the ERH that take up P and other nutrients that are given to the plant. AM fungal hyphae have a high surface-to-volume quantitative relation, creating their assimilative ability larger than that of plant roots [56]. AM fungal hyphae also are finer than roots and may enter into pores of the soil that are inaccessible to roots [1,57]. The fourth kind of AM fungal hyphae is morphologically distinct and grows from the roots and colonizes different host plant roots [53].

Diversity of AM Fungi

A general 336 species of AM fungi, inside which half dozen dominant genera inclusive of *Acaulospora*, *Glomus*, *Gigaspora*, *Scutellospora* and *Enterophospora* are superabundant in cultivated than in non-cultivated lands (AM fungi species listen on Gogle.com). Genus *Glomus* is

dominant genera available in worldwide in land and it's multiplied for biostimulants.

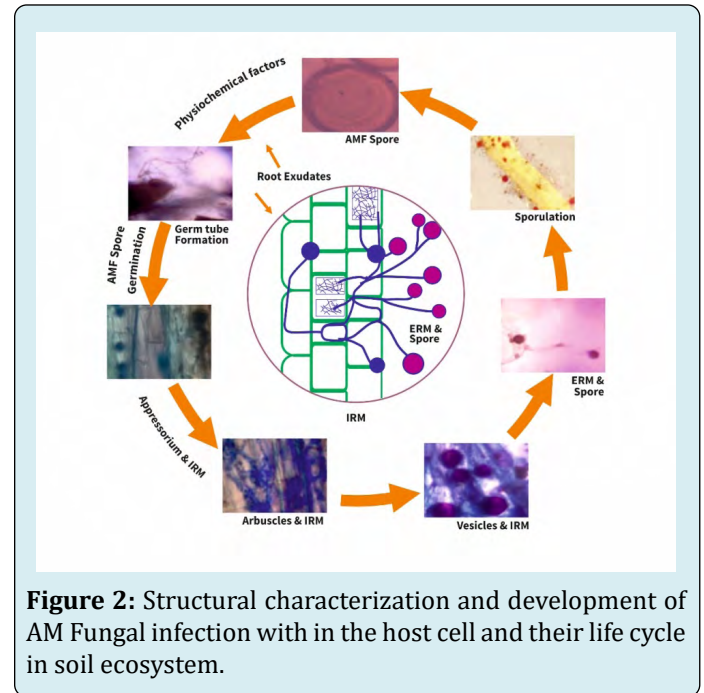


Figure 2: Structural characterization and development of AM Fungal infection within the host cell and their life cycle in soil ecosystem.

Characteristics of AM Fungi

The symbiotic association of AM fungi is a traditional instance of mutualistic relationship that could regulate the growth and improvement of plants (Figures 3,5). The mycelial network of fungi extends underneath the roots of the plant and promotes nutrient uptake (NU) that is otherwise not available. The AM fungal mycelium colonizes roots of many plants belong to different species, resulting into a common mycorrhizal network (CMN). CMN is taken in to the consideration as a primary component of the terrestrial ecosystem (TC) with its extensive consequences on distinct plant communities, specifically on invasive plants [1,24,32,58] and the fungal mediated transport of phosphorus (P) and nitrogen (N) to plants [11,17,43,59-60]. Moreover, communal nutrients additionally relocate from fungi to the plant, together with different related effects and enhance plant tolerance to biotic and abiotic factors (Figure 3- 5). They have the capacity to enhance characteristics of soil and therefore inspire plant improvement in normal in addition to in stressful circumstances [61-63]. AM fungi colonization improves tolerance of plants to stressful cues with the aid of using bringing approximately numerous modifications of their morpho-physiological traits [62-64]. AM fungi are considered as natural growth regulators of a majority of terrestrial flora. AM fungi are used as bioinoculants, and researchers inspire their use as prominent biofertilizers in sustainable crop productivity. Furthermore, AM fungi inoculated soil forms more constant masses and significantly

higher extraradical hyphal mycelium [1,6,24,32,65]. Glomalin related soil protein (GRSP) is thought to maintain water content in soils exposed to different abiotic stresses [66], which afterward regulates water frequencies among soil and plants, automatically triggering plant improvement. Glomalin contains 30–40% C and its associated compounds that safeguard soil from desiccation with the aid of using improving the soil water holding capacity [67]. Growth associated functions, which includes stomatal conductance, leaf water potential (LWP), relative water content (RWC), PSII efficiency, and CO₂ assimilation are affected by AM fungi inoculation [24,68,69]. AM fungi additionally help enhance water stress tolerance by physiological alteration of the above ground organs and tissues [70]. AM fungi enhance the accumulation of dry matter and improve water moisture uptake, therefore enhancing plant tolerance against stresses. Exploitation of AM fungi for plant growth in various biological ecosystems can make a contribution significantly to organic culturing for growth promotion and yield maximization.

Environmental Significance of AM Fungi

AM fungi are extraordinary useful to the environment, as they dramatically help in enhancing soil and plant fitness and maximise the absorption of macro and micro nutrients (Figures 3-4). This symbiotic relationship among fungus and plant spanning millions of years and feature allowed for plant to colonise areas that might had been too harsh to withstand. However, their presence in soil makes them liable to erosion, and tilling. Tilling reduces the inoculation of the soil and the efficacy of the fungi by disrupting the hyphal network (Figure 3).

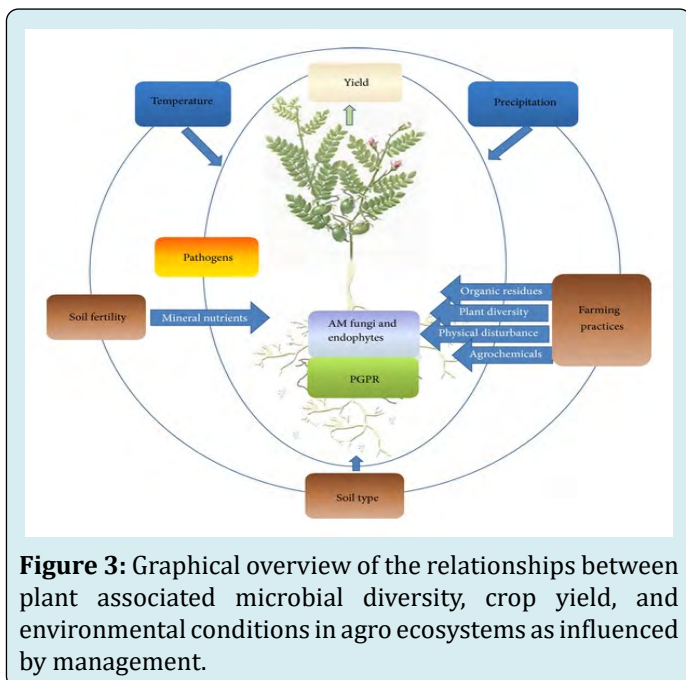


Figure 3: Graphical overview of the relationships between plant associated microbial diversity, crop yield, and environmental conditions in agro ecosystems as influenced by management.

Application of AM Fungi as a Bio-fertilizer

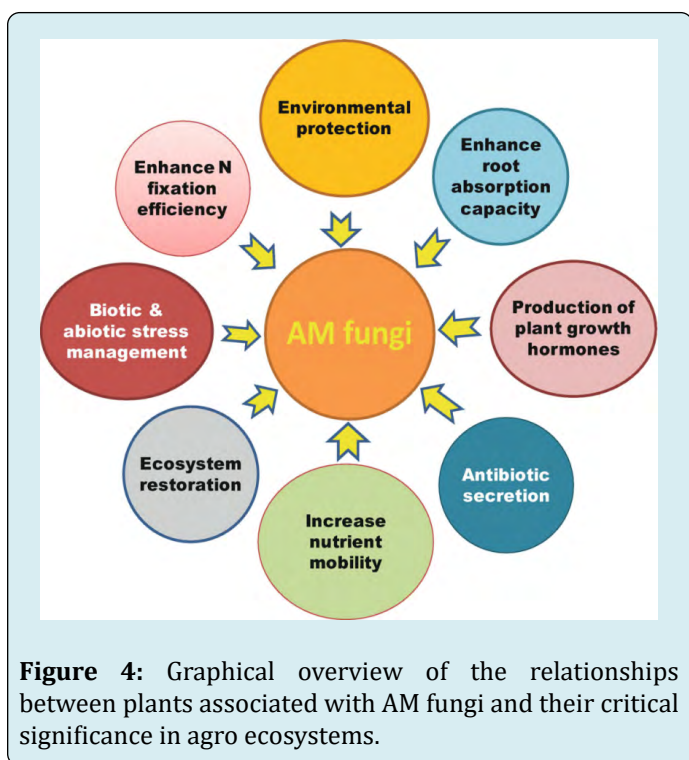
AM fungi produce glomalin protein in soil environment and will increase aggregation of soil particles. It is likewise enhancing soil oxygen and carbon content for plant and soil health (Figure 3). AM fungal mediated plant increased many folds root growth and helps quicker plant establishment. It increases absorption range through as plenty as 50 times additional and increase overall root biomass and root yield in cereals, pulses, vegetables, spices, fruits crops. Biofertilizers (as AM fungi) are a mixture of naturally occurring substances (spores, root bit, hypha, mycelium and substrate) that are used to improve soil fertility, productivity and they're their critical significance in agro ecosystems described in figure 5. AM fungi are very beneficial for soil health (SH) in addition to for PG and development. Different research studies carried out on AM fungi during the past three decades have highlighted their uncountable advantages on soil and PH and crop productiveness (CP). Therefore, it is broadly believed that AM fungi could be considered as a replacement of chemical fertilizers (CF), because of the fact AM fungi utility can effectively reduce the quantitative use of CF input [1,6,11,24]. Continuous use of lifeless CF, herbicides, and fungicides has prompted diverse troubles to soil, plants, and human health (HH), through their negative effect on the quality of food products, SH, air and water systems [11,60,71]. It is thought that AM fungi can possibly lower down the use of CF up to 50% for best agricultural production; however, this estimate relies upon at the form of plant species and the prevalent stressful regimes.

Nutrient uptake and exchange Efficiency of AM Fungi

AM fungi are favourable mutual symbiotic relationship with host. Bioactive phytochemicals involved in interactions between plants and soil microorganisms along with AM fungi. They have restrained saprobic ability and depend on the host plant for their carbon nutrition for food. AM fungi take up the products of the plant host's photosynthesis as hexoses. Carbon switch from plant to fungi might also additionally arise through the arbuscules or IRH [1,4-6,32,72]. Secondary synthesis from the hexoses via way of means of AM fungi takes place within the intraradical mycelium (IRM). Inside the mycelium, hexose is transformed to trehalose and glycogen. Trehalose and glycogen are carbon storage forms that can be rapidly synthesized and degraded and might buffer the intracellular sugar concentrations. The intraradical hexose enters the oxidative pentose phosphate pathway, which produces pentose for nucleic acids. Lipid biosynthesis additionally takes place with inside the IRM. Lipids are then stored or exported to ERH wherein they'll store or metabolized. The breakdown of lipids into hexoses, referred as gluconeogenesis, occurs in the ERM [72]. Approximately

25% of the carbon translocated from the plant to the fungi is stored in the ERH [73]. Nearly 20% of the host plant's carbon can be transferred to the AM fungi [72]. This represents the host plant's considerable carbon investment in mycorrhizal network (MNW) and contribution to the below-ground organic carbon pool (OCP).

Increasing the plant's carbon supply to the AM fungi, AM fungi are escalations uptake and transfer of P and different macro and micro nutrients from to host plant. Likewise, nutrients uptake and transfer are lowered when the photosynthate supplied to the fungi is decreased. Species of AM fungi differ in their capabilities to supply the plant with nutrients. In a few cases, AM fungi are poor symbionts, offering little P even as taking exceedingly excessive quantities of carbon [74]. The foremost gain of AM fungi to plants has been attributed to extended uptake of nutrients, mainly P. AM fungi can be much more efficient than plant roots at taking up P. P and different minerals travels to the root via diffusion and hyphae reduce the distance required for diffusion, thus increasing uptake.



The rate of P flowing into AM fungi can be up to six times that of the root hairs [75]. In few cases, the role of P and different nutrients uptake can be completely taken over by the MNW, and all of the plant's P can be of hyphal origin [74]. AM fungi are maximum frequent in plants growing on mineral soils, and are of severe significance for plants growing in nutrient-deficient substrates consisting of in volcanic soil and sand dune environments. The populations of AM

fungi are best in plant groups with excessive rang consisting of tropical rainforests and temperate grasslands in which they've many ability host plants and might take advantage of their ability to colonize a broad host range. There is a decrease incidence of mycorrhizal colonization (MC) in very arid or nutrient-rich soils. Mycorrhizas had been found in aquatic habitats; however, waterlogged soils had been proven to lower MC in a few species [76].

Mineral Nutrition Efficiency of AM Fungi

Excessive land use can also additionally have a drastic effect on the general biodiversity, which in turn can also additionally have an effect on the ecosystem function as publicised through numerous reports. AM fungi enhance water and nutrients uptake because of AM fungal ERH accomplishing out of the depletion region and extract mineral and nutrients are offer to host. AM fungi are plenty beneficial to increase bioavailability of nutrients and allowing for reduced irrigation and higher fertilizer efficiency (Figure 4). An outstanding role of such symbiotic relationship is to transfer nutrients which include organic carbon (OC), with inside the form of lipids and sugars [77]. MC is broadly believed to stimulate nutrient uptake in plants. It is obvious that inoculation of AM fungi can enhance the concentration of numerous macro and micro nutrients significantly, which results in accelerated photosynthate manufacturing and for this reason accelerated biomass accumulation [6,11,18,59,78]. AM fungi have the functionality to reinforce the uptake of inorganic nutrients in nearly all plants, specifically of P [1,11,18,59]. AM fungi also are very powerful in assisting plants to take up nutrients from the nutrient-deficient soils. Apart from the macronutrients, AM fungi affiliation has been reported to increase the phyto availability of micronutrients such as Zn, Fe and Cu [6,24]. AM fungi enhance the surface absorbing functionality of host roots. Experimental trials on tomato plants inoculated with AM fungi have proven accelerated leaf area, and N, K, calcium, and P contents, reflecting superior plant growth [79]. AM fungi develop symbiosis with roots to acquire crucial nutrients from the host plant and therefore offer mineral nutrients which include N, P, K, Ca, Zn, and S in return. Thus, AM fungi offer nutritional support to the plants even beneath irrelevant situations in the root cells. AM fungi produce arbuscules fungal structures (AFS), which help in exchange of inorganic minerals and the compounds of C and P, ultimately imparting a considerable vigor to host plants [4,8,79,80-82]. Therefore, they are able to substantially enhance the P concentration in each root and shoot systems. Under P restricted situation, AM fungal affiliation improves P supply to the infected roots of host plants. Increased photosynthetic activities and different leaf functions are directly related to improved growth frequency of AM fungi inoculation that is directly linked to the uptake of N, P, and C,

which move towards roots and promote the improvement of crops. It has been determined that AM fungi maintain P and N uptake ultimately helping in plant improvement at better and decrease P ranges.

AM fungal symbiosis undoubtedly accelerated the concentrations of N, P, and Fe in *Pelargonium graveolens* L. under drought stress [85]. Gomez-Bellot et al. [86] stated improved ranges of P, Ca, and K in *Euonymus japonica* under salinity stress because of immediate fungus attachment. It is thought that AM fungi enhance the uptake of almost all essential nutrients and contrarily decrease the uptake of Na and Cl, leading to growth stimulation [87,88]. Many scientists have stated the role of AM fungi in uptake of soil nutrients, specifically of N and P that could efficiently promote the growth of host plants. Several research studies have defined that AM fungi have the capacity to absorb and transfer N to the close by plants or host plants. AM fungi symbiosis produce tremendous underground ERM starting from the roots as much as the encircling rhizosphere, thereby assisting in enhancing the uptake of nutrients. AM fungi immunization improves C and N accumulation and N assimilation under ambient and elevated CO₂ concentrations [89]. AM fungi had been stated to enhance growth, accumulation of micro and macro-nutrients, and their allocation with inside the plantlets grown under accelerated increased ranges of Mn [11,79,90]. Enhancement of plant nutrition and upkeep of Ca²⁺ and Na⁺ ratio are the substantial dynamic attributes that assist enhance useful components of AM fungi colonization on universal plant performance. Improved growth and levels of protein, Fe, and Zn had been discovered in mycorrhizal chickpea [91]. Moreover, different reports have proven superior activity of a K⁺ transporter withinside the mycorrhizal roots of *Lotus japonicus* [92]. Moreover, meta-analysis reports confirmed the role of mycorrhizal symbiosis to numerous micro-nutrients in crops. Several researches carried out at same stage in the previous couple of years have proven that AM fungi (*Glomus mosseae* and *Rhizophagus irregularis*) exhibited improved heavy metal translocation with inside the shoot [93]. Micronutrients (Zn and Cu) being diffusion restricted in soils are absorbed through plants with the help of AM fungal hyphae.

Plant Productivity Efficacy of AM fungi

AM fungi now no longer most effective can enhance the nutrient status of crops, however can also enhance the quality and quantity of crops. AM fungi colonized strawberry exhibited increased levels of secondary metabolites resulting in improved antioxidant property [94]. AM fungi can enhance the dietary quality of crops by affecting and manufacturing of carotenoids and certain volatile compounds [95]. Prasad [79] located useful consequences of AM fungi on the quality and productiveness of solanaceous crops (tomatoes, potato,

and brinjal). Zeng et al. [96] have mentioned improved contents of sugars, organic acids, vitamin C, flavonoids, and minerals because of *Glomus versiforme* resulting in enhanced citrus fruit quality. AM fungal symbiosis induces more suitable accumulation of anthocyanins, chlorophyll, carotenoids, overall soluble phenolics, tocopherols, and numerous mineral nutrients [97-102]. AM fungi had been employed in a large-scale field production of maize, [103], yam [104], potato [105], soybean [102,106-108] Allium [11] confirming that AM fungi own a substantial ability for boosting crop yield. AM fungi also can improve the biosynthesis of valuable phytochemicals in edible plants and lead them to healthy food manufacturing chain [109].

AM Fungi Increase Production of Growth Hormones

Plants with AM fungi exhibit better content of growth regulators such as cytokinin's and auxins as comparison to non-mycorrhizal ones. AM fungi colonised roots display adjustments in root morphology through acquiring plentiful thicker and deliver fewer root hairs. Hormone's accumulation in the host tissue is affected by MC with adjustments in the levels of cytokinin's, abscisic acid, gibberellins like substances. The effect of AM fungi on photosynthesis and host morphology might also be hormonal.

Abiotic Stresses efficacy of AM Fungi

Drought tolerance Activity of AM Fungi

AM fungi inoculated plants are successful to tolerance of drought; heat and toxic level of minerals because of the fact those fungi useful for take-up toxic minerals and enhance general plant and soil health [6,11, 24]. AM fungi assist plants to uptake soil nutrients in exchange for sugars produced by the plants. In forests, ectomycorrhizas form long strands known as hyphae that run among trees, acting as connectors. This massive underground transportation network is known as the CMN. The CMN makes use of chemical communication to exchange nutrients among trees on an as need basis. Besides nutrients, the CMN additionally facilitate trees get water that their personal roots might now no longer be capable of reach. Once deep soils are wet and shallow soils are dry, trees pull water upward through their tap roots, which might be deep withinside the soil, as much as the shallow roots. Evaporation is through the leaves and from the soil surface act like a drinking straw, pulling water through the plant and soil. AM fungi can clutch that water coming up from the deep tap root of one tree, transfer it alongside the highways of the CMN, and deposit it in the roots of a distant tree. AM fungi treated plants are increased tolerance to drought and survival in excessive soil temperature, soil toxins and extreme soil pH.

Salinity tolerance Efficacy of AM Fungi

It is widely recognised that the soil salinization is an increasing environmental hassle posing an excessive risk to global food security. Salinity stress is thought to suppress growth of plants with the aid of using affecting the vegetative improvement and net assimilation rate resulting in decreased yield. It is likewise promoting the immoderate era of reactive oxygen species [110-111]. Salt affected soils, really appropriate use of AM fungi for mitigating the salinity caused detrimental results on plants [112]. Several research studies have stated the performance of AM fungi to impart growth and yield enhancement in plants under salinity stress [113]. El-Nashar [114] reported that AM fungi enhanced growth rate, leaf water potential (LWP), and water use efficiency (WUE) of the *Antirrhinum majus* plants. Ait-El-Mokhtar et al. [115] have reported the useful effects of AM fungi symbiosis on physiological parameters together with photosynthetic rate, stomatal conductance, and leaf water relations under saline regimes. AM fungi inoculated *Allium sativum* plants confirmed improved growth which including leaf area index, fresh and dry biomass under saline conditions [11,116]. Concentrations of total P, Ca²⁺, N, Mg²⁺, and K⁺ have been better withinside the AM fungal treated *Cucumis sativus* plants as compared with uninoculated plants under salt stress conditions [117]. AM fungal inoculation to *Capsicum annuum* exhibited improved chlorophyll contents, and Mg₂⁺ and N uptake coupled with decreased Na⁺ transport under saline conditions [118]. AM fungal inoculation can effectively regulate the levels of key growth regulators. AM fungi colonized plants have the capability to decrease oxidative stress by suppressing lipid membrane peroxidation under salinity stress [113,119]. AM fungi have been additionally to improve the accumulation of numerous organic acids ensuring in up regulation of the osmoregulation process in plants grown under saline stress.

Heavy Metals Tolerance Efficacy of AM Fungi

AM fungi are extensively believed to support plant establishment in soils contaminated with heavy metals, due to their potential to reinforce protection system of the AM fungal mediated plants to promote growth and expansion. Heavy metals might also additionally acquire in food crops, fruits, vegetables, and soils, inflicting numerous health hazards. AM fungi affiliation with wheat positively improved nutrient uptake under aluminium stress [120]. Heavy metals can be immobilized in the fungal hyphae of internal and external origin [121] which have the capability to fix heavy metals in the cell wall and store them in the vacuole or might also additionally chelate with a few different substances in the cytoplasm [122] and subsequently reduce metal toxicity withinside the plants. The sturdy outcomes of AM fungi on plant improvement and growth under severe stressful situations

are most customarily because of the capability of these fungi in improving morphological and physiological processes that boom plant biomass and therefore uptake of essential immovable nutrients such as Cu, Zn, and P and accordingly decreased metal toxicity in the host plants [24,32,123-124]. It is likewise believed that improved growth or chelation in the rhizospheric soil can cause metal dilution in plant tissues [125]. AM fungi reportedly bind Cd and Zn in the cell wall of mantle hyphae and cortical cells, thereby restricting their uptake and ensuing in better growth, yield, and nutrient status [32]. AM fungal mycelia have a high cation exchange potential and absorption of metals [126]. It is pertinent that low Cd mobility and toxicity also can be addressed with AM fungi through increasing soil pH [127], restoring Cd in the ERM [128], and binding Cd to glomalin, a glycoprotein. AM fungi had been very effective in decreasing the levels of Cd in each the vacuoles and cell wall, which added approximately Cd detoxification in rice [129]. Various procedures that occur through the AM fungi are immobilization/restriction of metal compounds, precipitation of polyphosphate granules in the soil, adsorption to fungal cell wall chitin, and heavy metal chelation inside the fungus (Figure 5).

High and Low Temperature Tolerance Efficacy of AM fungi

As soil temperatures increase, plant community reactions might be relying on AM fungal interactions for sustainable yield. Heat stress notably influences PG and development with the resources of the usage of imparting, loss of plant vigor and inhibition of seed germination, retarded growth rate, decreased biomass production, wilting and burning of leaves and reproductive organs, abscission and senescence of leaves, damage further to discoloration of fruit, reduction in yield and cell death and greater appropriate oxidative stress. Generally, AM fungi treated plants spectacle better growth under heat stress. Maya and Matsubara [130] have stated the association of *Glomus fasciculatum* with PG and development most important to positive changes in growth under the conditions of high temperature. AM fungi can increase plant tolerance to cold stress. Moreover, a majority of information's state that several plants inoculated with AM fungi at low temperature grow broaden better than without AM fungal inoculated plants [131,132]. AM fungi support plants in preventing cold stress and eventually improve plant development [133]. AM fungi also can maintain moisture in the host plant increase plant secondary metabolites leading to strengthen plant immune system, and increase protein content for supporting the plants to combat cold stress conditions [134]. Symbiotic AM fungal relationship improves water and plant relationships and increases gas exchange potential and osmotic adjustment [135]. AM fungi increase the synthesis of chlorophyll leading to a noteworthy perfection in the concentrations of numerous metabolites in

plants subjected to cold stress conditions [24,134,136].

Environments, Human and AM Fungi

The complete ability that AM fungi can play in agriculture, phytoremediation habitat loss and whilst complete to attain more healthier lawns are currently being investigated. The ability for restoring regions affected with industrial processes ought to enhance the effective value of the area by promoting the revegetation of the area and rebuild the soil of the disturbed area. Similarly, the ability to enhance agricultural yields; if now no longer enhance plant survival, through inoculating the soil with AM fungi ought to show to be a beneficial strategy in the future to ensure food security.

Seed Production and Offspring Fertility Efficacy of AM Fungi

AM fungi are improved vigor in offspring generations and greater fertility and survival of seeds from AM fungal mediated plants

AM Fungi Increased Tolerances to Disease and Pest

AM fungi increase tolerance pests to root and soilborne pathogens and increase tolerance to foliar pathogens via Mycorrhiza-induced resistance in addition to escalation secondary metabolite production [1,27,29].

Carbon Cycling Efficacy of AM Fungi

Significant quantity of carbon flows via AM fungal mycelia to absolutely extraordinary additives of soils. Production of glycoproteins inclusive of glomalin which might be involved inside the formation and strength of soil aggregates ought to have additionally an essential influence on extraordinary microorganisms associated with the AM fungal mycelium [23,54,137].

Phytoremediation Efficacy of AM Fungi

Disturbance of native plant groups in desertification-threatened regions is frequently accompanied through degradation of physical and biological soil properties, soil structure, nutrient availability, and organic matter. When restoring disturbed land, it is crucial to replace not only the above ground vegetation but also biological and physical soil properties [138]. A particularly new technique to restoring land is to inoculate soil with AM fungi whilst reintroducing vegetation in ecological restoration. It has enabled host plants to establish themselves on degraded soil and enhance soil quality and health [24,32,139]. Soil's quality parameters

had been considerably improved long-term when a mixture of indigenous AM fungal species was introduced compared to non-nodulated soil and soil inoculated with a single exotic species of AM fungi [138]. The benefits had been elevated PG, enhanced P uptake [140] and soil N content, higher soil organic matter, soil aggregation, attributed to higher legume nodulation in the presence of AM fungi, higher water infiltration, and soil aeration because of soil aggregation [24,138]. Native strains of AM fungi improve the extraction of heavy metal(s) from the polluted soils and make the soil healthy and appropriate for crop production [141].

Inferior World without AM Fungi

The vital and useful symbiotic relationship among plants and AM fungi cannot be taken for granted. Life absent AM fungi might be extensively different, because the beneficial relationship among AM fungi and plant are of utter significance for their survival. Their role in the ecosystem in addition to agriculture might be impossible to replace.

Extortions to AM Fungi

Climate change poses a great threat to AM fungi, because of irreparable damage to diverse ecosystems, in addition to the increasing rate of habitat loss because of human activities. Therefore, successive steps must be carried out to mitigate next screw ups which could stand up from those concerns.

Global Climate Change Efficacy of AM fungi

Global climate change is affecting AM fungal populations and interactions among AM fungi and their plant hosts. It is usually accepted that interactions among organisms can affect their response to global climate change. In latest meta-analyses, AM fungi have been discovered to improve plant biomass under drought conditions and reduce plant biomass under simulated nitrogen deposition studies [24,142,143]. AM fungi themselves had been proven to increase their biomass in response to accelerated atmospheric CO₂ [144]. Climate change is offering us with demanding situations associated with water, food, and nutrient availability. Some places might also additionally have shortages, even as others have excess. The relationship among forest trees and the AM fungi that assist them percentage sources primarily based totally on need would possibly assist us solve those problems.

Insects/pests Resistance Efficiency of AM fungi

AM fungi can usage these underground connections to produce and receive warning signals [145] specifically, once a host plant is attacked by an aphid, the plant signals close connected plants of its condition. The

host plant releases volatile organic compounds that attract the insect's predators. The plants connected by AM fungi also are prompted to provide identical volatile organic compounds that defend the uninfected plants from being targeted by the insect pest [145]. In addition, this assists the AM fungi by preventing the plant's carbon relocation that negatively affects the fungi's growth and happens once the plant is attacked by herbivores [145].

Conclusion

Various research studies have already recognized the useful role of AM fungi in enhancing PG below stressful environments. Therefore, on this manuscript, the existing evidence associated with the AM fungal lifecycle and its widespread position has been combined in a coherent manner for know-how of AM fungal symbiotic courting with a variety of plants below stress environments. Previously, the AM fungi had been particular mentioned as useful entities for nutrient uptake from soil; however, recently, it's been honestly depicted that plants inoculated with AM fungi can efficaciously fight divers environmental cues, such as salinity, drought, nutrient stress, alkali stress, cold stress, and excessive temperatures, and therefore enables boosting yield and productiveness of a massive wide variety of agricultural crops, pulses, oilseeds, fruit, fibre crops, vegetables, forest in addition to nursery development. Encouragement of AM fungi utilization is of enormous significance for modern global agricultural systems for their consistent sustainability. Undoubtedly, exploitation of AM fungi for agricultural development can substantially lessen the usage of artificial (lifeless) fertilizers and different chemicals, thereby endorsing the bio healthy agriculture. AM fungi inoculation, growth and productiveness enhancement in crop plants might be useful to triumph over the consumption requirement of increasing population throughout the globe. In addition, environment friendly technologies shall be exceptionally advocated because of their widespread use. The number one cognizance of destiny research studies must be at the identity of genes and gene products controlling the AM fungi mediated growth and improvement regulation below stressful cues. Understanding the AM fungi brought about modulations in the tolerance mechanisms and additionally the crosstalk triggered to control plant overall performance can facilitate enhance crop productivity. AM fungi must be explored in any respect ranges to extra inspect their role in nature as a biofertilizer for sustainable agricultural production for green technology.

Conflict of Interest Statements

There is no conflict of interest.

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