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Review Article

Associations of Arbuscular Mycorrhizal Fungi (AMF) for Enhancements in Soil Fertility and Promotion of Plant Growth: A Review

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Abstract

Arbuscular Mycorrhizal Fungi are used for soil fertility enhancements and stimulating plant growth in which they association with other organisms like terrestrial plants. Mycorrhizas create an association between fungi and the roots of plants. Therefore, the review was made to point out important fungal species involved in fungal plant interaction and their major roles in agriculture as well as ecosystem. 80% of plants form associations with mycorrhizal fungi. The fungal are used to use their different organs like chain, arbuscular, vesicle, supportive cells and spore to interact with the other plant/ plat's organ. The mycorrhizal fungi can be categorized into two principal classifications based on their anatomical interactions with the roots of host plants. Arbuscular Mycorrhizal and Ectomycorrhizal fungi utilize two distinct strategies for nutrient acquisition. The main categories of vesicular arbuscular mycorrhizal associations are linear or coiling and of ectomycorrhizal associations are epidermal or cortical. The rhizospheric and endophytic microbes promote plant growth as inoculated with crop. AM fungi as an obligate symbiont share a distinct feature called arbuscules as a site of nutrient exchanges between host and fungi. Arbuscules developed between cell wall and plasma membrane of root cortical cells and differentiated from plant plasma membrane by periarbuscular membrane. Arbuscular mycorrhizal fungi (AMF) play an indispensable role in augmenting plant nutrient acquisition, enhancing plant resilience and tolerance to various environmental stresses, improving soil fertility and structure, and providing numerous beneficial effects. AMF engage in interactions with other soil microorganisms, such as plant growth-promoting rhizobacteria, resulting in a synergistic effect that promotes plant growth and offers protection against pathogens associated with Rhizobia. Both AMF and Rhizobia utilize the same signaling pathways, which facilitate their association with host plants and enable nitrogen fixation within the soil ecosystem. A positive relationship has been established between AMF colonization and the diversity of soil microbial communities. Nitrogen-fixing rhizobia, mycorrhizal fungi, and root nodule symbioses typically exhibit synergistic interactions concerning infection rates and their effects on mineral nutrition and plant growth, thereby significantly enhancing the status of soil fertility, particularly with respect to soil quality characteristics.

Keywords

Arbuscular, Arbuscules, Mycorrhizal, Fungi, Plant-nutrients, Plant Growth, Soil-Fertility

1. Introduction

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Arbuscular Mycorrhizal Fungi (AMF) belong to *phylum Mucoromycota* and *subphylum Glomeromycotina* [1]. AMF are obligate symbiotic soil fungi that form friendly associations with nearly 80% of terrestrial plant species, including the agricultural crops [2]. AMF are soil microorganisms that, providing a direct physical link between soil and plant roots to facilitate the plant nutrient availability [3]. The term mycorrhizal is derived from the Greek words for '*fungus*' and '*root*' [4]. Arbuscular mycorrhiza (AM) (*Plural mycorrhizae*) is a type of mycorrhiza in which the symbiont fungus (AM fungi, or AMF) penetrates the cortical cells of the roots of a vascular plant forming arbuscules. Arbuscular mycorrhiza is a type of endomycorrhiza along with ericoid mycorrhiza and orchid mycorrhiza are characterized by the formation of unique tree-like structures, the arbuscules [72].

The colonization of arbuscular mycorrhizal fungi (AMF) encompasses a diverse array of woody plant species, including both gymnosperms and angiosperms, which comprise various flowering families as well as certain non-flowering families [5]. Mostly, these fungi exhibit saprotrophic characteristics, deriving their nutritional needs from decayed organic matter, while a limited subset of fungi is characterized by dependence on living organisms for nutrient acquisition, which may occur through mutualistic or parasitic interactions [6]. Additionally, some fungi possess the capability to alter their feeding strategies to either saprotrophic, mutualistic, or parasitic modes, contingent upon the prevailing environmental conditions [7]. Mycorrhizal fungi necessitate a symbiotic association with plant roots to fulfill their life cycle requirements; conversely, certain fungi are capable of existing as free-living entities within natural ecosystems [8].

One significant category of soil microorganisms that perform an essential function in facilitating plant growth by enhancing the absorption of nutrients and water, as well as contributing to soil ecosystem processes such as aggregation and carbon sequestration, is arbuscular mycorrhizal fungi [9, 10]. AMF establish symbiotic associations with the roots of cultivated plants and primarily exchange mineral nutrients that limit plant growth for photosynthates [11], thereby optimizing plant access to nutrient-dense soil regions [12] and exploiting pore spaces that are otherwise unreachable by roots. AMF significantly improve the efficiency of nutrient and water utilization in agricultural crops [13]. Mycorrhizal fungi create a mutually advantageous relationship between plants and microorganisms [5, 13], wherein the fungus acquires essential nutrients (organic carbon) from the host plant to facilitate its growth and development [14]. Concurrently, it aids the plant in the absorption of water and nutrients (nitrate and phosphate), thereby enhancing stress resilience [7]. The plant provides the fungus with carbon derived from its fixed photosynthates, while the fungus supports the plant in acquiring phosphate and other mineral nutrients from the soil matrix [15, 11]. This reciprocal exchange of nutrients occurs through highly branched structures known as arbuscules. Beyond nutritional benefits, mycorrhizal plants also exhibit heightened resistance to root pathogens and increased tolerance to drought conditions [15, 16].

2. Classification of Arbuscular Mycorrhizal Fungi

The mycorrhizal fungi can be categorized into two principal classifications based on their anatomical interactions with the roots of host plants [45]. The initial category consists of septate fungi, which are classified under Basidiomycota and Ascomycota are associated with ectomycorrhizas (the hyphae of these fungi do not penetrate the cell lumen; rather, they proliferate in the epidermal cells and envelop the root tips of the host plants) [46, 51]. The subsequent classification encompasses arbuscular mycorrhizas, ericoid, and orchid mycorrhizas, which are classified as endomycorrhizas (the hyphae infiltrate and proliferate within the cells of plant roots) [6]. Arbuscular Mycorrhizal (AM) and Ectomycorrhizal (ECM) fungi utilize two distinct strategies for nutrient acquisition: The main categories of vesicular-arbuscular mycorrhizal associations (VAM) are 'linear' or 'coiling', and of ectomycorrhizal associations (ECM) are 'epidermal' or 'cortical' [73]. AMF absorb nutrients released by saprotrophic microorganisms, while ECM fungi mineralize nutrients from organic substrates, allowing them to directly access certain forms of organic nitrogen [17]. AM symbionts have been shown to enhance plant growth more significantly, whereas ECM symbionts tend to promote the growth of mycorrhizal fungi more effectively [18]. Mycorrhizas ('fungus-roots') are symbiotic associations between specialised soil fungi and plants [72], in which seven types of mycorrhizas are recognised, but several are very similar. Vesicular–arbuscular mycorrhizas (VAM, also called arbuscular mycorrhizas), are the most widespread type. Ectomycorrhizas (ECM) occur in certain families of gymnosperms and, dicotyledons and in one monocotyledon genus. The remaining types of mycorrhizas are restricted to specific plant families [72]. ECM fungi include at least 6000 species, primarily of basidiomycetes with some ascomycetes and zygomycetes, but their diversity is poorly known in tropical and southern regions [77, 78].

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Table of Structural definitions, roles, host plants and Associations of Micorrhizal fungi with host plants

Category	Definition	Role	Host plants
Arbuscular mycorrhizas (AM)	Associations formed within roots that usually have arbuscules and often have vesicles	Nutrient acquisition for plant (P, K, N, etc.)	Most families of vascular plants and some bryophytes
Ectomycorrhizas (EM)	Associations with a hyphal mantle enclosing short lateral roots and a Hartig net of labyrinthine hyphae that penetrate between root cells	Nutrient acquisition for plant (N, P, etc.)	Certain families or genera of flowering plants and some gymnosperms (some host AM also)
Orchid mycorrhizas	Associations where coils of hyphae (pelotons) penetrate within cells in a root or stem in the plant family Orchidaceae	Nutrient acquisition for plant (N, P, etc.)	Orchidaceae
Ericoid mycorrhizas	Coils of hyphae within very thin roots (hair roots) of the Ericaceae	Nutrient acquisition for plant (N, P, etc.)	Ericaceae
Subepidermal mycorrhizas	Hyphae in cavities under epidermal cells, only known from one Australian monocot genus	Expected to be plant nutrient uptake	*Thysanotus* spp. (Laxmaniaceae)

Figure 1. *Types of mycorrhizal association. Desert truffles: phylogeny, physiology, distribution and domestication. Source: - Roth-Bejerano, et al., 2014.*

3. Arbuscular Mycorrhizal Fungi Interaction Mechanisms with Plant Roots

Plant and soil associated microbiomes with plant growth-promoting traits could be utilized as biofertilizers and biopesticides from crops growing under the abiotic stress condition and natural conditions for agricultural sustainability [19, 20]. These plant growth-promoting microbes have three domains, like archaea, bacteria and eukarya [21]. The rhizospheric and endophytic microbes promote plant growth as inoculated with crop [21]. AM fungi as an obligate symbiont share a distinct feature called arbuscules as a site of nutrient exchanges between host and fungi [19]. Arbuscules developed between cell wall and plasma membrane of root cortical cells and differentiated from plant plasma membrane by periarbuscular membrane [22]. Mycorrhizal fungi typically have more consistent growth patterns in plants than do parasitic or endophytic fungi, due to regulation by root features resulting from plant-fungus coevolution [72].

The main morphological structure of AMF is Arbuscules, vesicles, auxiliary cells, hyphae and spores which perform diverse function [19]. Extraradical hyphae as a root extension provide large surface area for the absorption of water and nutrients from soil solution. These nutrients and water transported to the intraradical hyphae and plants in exchange with photosynthetic fixed carbon. Another important characteristic of AMF is their spore production ability with single or multiple layers and size ranges from 22 to 1050 µm in diameter [23]. AMF spores contain very unique characteristics and structures such as subtending hypha, sporiferous saccule, sporogenous cell, pregermination structures, peridium, cicatrix or pedicel, and these structures are important or good morphological identification study at species level [24, 25]. AMF have a great genomic distinction size of 16.54mb in rhizophagus intraradices to 1058.4mb in racocetra gregaria [26]. Host plants actively accommodate AMF by creating a tube-like intracellular infection structure called pre-penetration apparatus which requires cellular symbiosis-specific gene expression [27].

4. Arbuscular Mycorrhizal Fungi for Plant Nutrient and Water Enhancements

AMF play a crucial role in enhancing plant nutrition acquisition, increasing plant tolerance and resistance against stresses, improving soil fertility and structure, and having numerous beneficial advantages [5]. Large quantities of Glomus geosporum spores were observed in saline soils, indicating that AMF can thrive in saline soils. AMF interact with other microbes in the soil, e.g., plant growth-promoting rhizobacteria (PGPR) with the synergistic effect of AMF and PGPR in enhancing plant growth and protection against pathogens [28]. Nitrogen (N) fixation in the soil is carried by Rhizobia [29]. Different conducted studies documented that; AMF and Rhizobia share the same signalling pathway, which triggers their association with plants [29]. A positive correlation exists between AMF colonization and soil microbial diversity [30]. N_2 fixing rhizobia, the mycorrhizal fungi and root nodule symbioses are typically synergistic both with regard to infection rate and their impact on mineral nutrition and growth of the plant [31]. AMF contribute to an increased nutrient status in the mycorrhizosphere; by decomposing organic N compounds, plants may have a greater benefit through additional nitrogen provided through N_2 fixation [31]. Mycorrhizal fungi always associate with the roots of higher plants [32], certainly over 90% of plant species, including forest trees, wild grasses and many crops, in which they improve the nutrient status of their host plants, influencing mineral nutrition, water absorption, growth and disease resistance [32, 33]. In a co-existing situation, the plant provides carbon to the fungi by transferring carbohydrates [34]. Arbuscular mycorrhiza Fungi can be beneficial to plants depends on climatic situations. A plant with AMF has an advantage over those that lack this association [35] and has more resistance to diseases [36, 37]. AMF are easily adapted to various habitats and a range of hosts. Their role in protecting plants during various stresses such as drought and heat is instrumental [38].

Colonized plants by AMF displays enhanced phosphorus (P) absorption, with nearly 80% of the plant's P uptake occurring at lower concentrations within the soil solution compared to non-mycorrhizal inoculated plants [39, 40]. The AMF establishes an extraradical mycelium (ERM) network that efficiently explores the soil environment to acquire nutrients [41, 42], facilitating access to more soluble phosphate forms [43, 44] and enhancing plant nitrogen (N) uptake [45]. Furthermore, the symbiosis leads to improved acquisition of various other soil nutrients like copper (Cu), iron (Fe), potassium (K), zinc (Zn), calcium (Ca), and sulfur (S), particularly beneficial in nutrient-deficient soils [45-47]. Growth and nutrient absorption of maize indicated that the presence of two AMF, namely Funneliformis mosseae and F. versiforme, resulted in enhanced plant growth in comparison to plants without fungal inoculation [47]. Among the two fungi, F. mosseae exhibited the highest effectiveness. Furthermore, the application of a commercial AMF inoculant on maize plants led to enhancements in plant growth, yield, and phosphorus uptake in both plots with no fertilization and plots with phosphorus fertilization [46]. Plant productivity is low when soil factors inhibit mycorrhizal fungi populations (fungicides, disturbance, pH, salinity, waterlogging, temperature, etc.) [74, 75]. Fungus productivity is decreased by factors that harm plants (herbicides, pollution, disturbance, etc.) [76].

5. AMF for Plant Nutrient and Water Absorption Mechanisms

There are two approaches of absorption for nutrients and water by AMF. After germination in asymbiotic phase, hyphal morphogenesis occurs in the availability of root exudates released by host plants [47, 48]. The germling hyphae, while elongate and grow in branching pattern, come in direct contact with the host roots, grow inter-cellularly through appressoria by penetrating in root cells starts and produces arbuscules within the root cortex [49, 50]. Then the extracellular hyphal network gains a high absorbing volume and surface-volume, increase uptake and translocation of water and essential nutrients mainly phosphorus and nitrogen [51], with nutrient transporter genes present in the hyphae [52]. Hyphal diameter is less than 100 times than finest roots and 10-20times lesser than root hairs [47]. In conditions of drought, when the soil hydraulic potential is significantly low for absorption by root hairs, it can be readily transported with the assistance of AMF hyphae [53]. Additionally, these hyphae located outside the roots have the ability to penetrate and acquire nutrients and water from tiny soil gaps that are inaccessible to the roots [54]. The extensive network of mycelia further enhances the absorptive area far beyond that of the root system, and these mycelia mats also contribute to the retention of soil moisture [53]. The primary function of the root system is to deplete nutrients from the zone surrounding the roots [47]. Quick absorption from beyond root depletion zone by extensive mycelia network is the major mechanism of this symbiosis [55, 56]. The AM extraradical hyphae can extend upto 50m in rhizosphere and translocation of phosphate as polyphpsphate granules through the hyphae [57, 58]. Physiologically, monophosphates of AM enhances and alters the functions of plant growth regulators to stimulate increased formation of tertiary roots, and promoting the expansion of cortical cells in the root as they establish colonization specifically within the cortex [59]. A potential species of AMF enhances the plant growth and also used to mitigate abiotic stresses such as drought, through different mechanisms. Gigaspora decipiens, Glomus mosseae fungal species enhanced the plant growth, chlorophyll content [60], Arbuscular mycorrhizal fungal species increased the uptake of minerals [61], Rhizophagus intraradices species Enhanced K, N, and P uptake [62], and also Funneliformis geosporus species enhanced water usage efficiency [63] to mitigate the drought stress during a drought season.

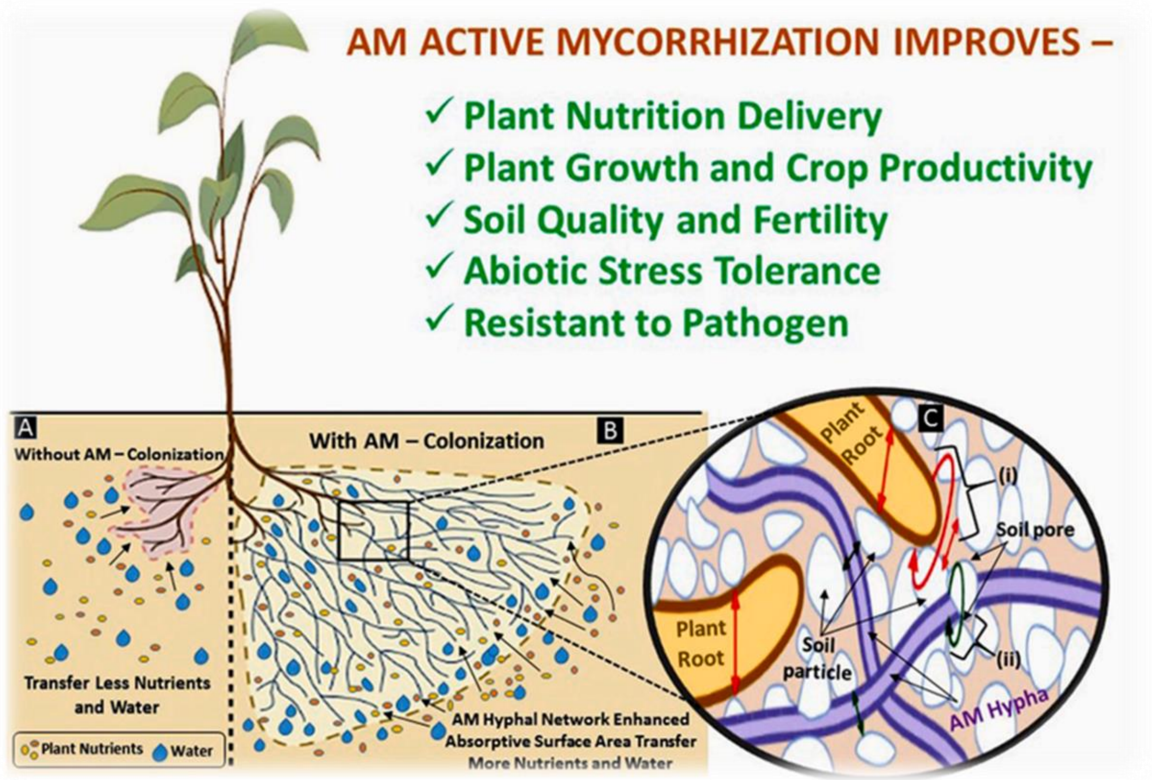

Figure 2. *Function of AMF: Function of AMF: At the left portion (A), the zone around the plant root without AM colonization represents the limited absorptive surface area for nutrient and water; B:- zone around the plant root with extensive AM network (mycorrhizosphere) represents the extended absorptive; C:- The comparative exploration pattern of plant root and the fungal hyphae into the soil. Plant root with larger diameter unable to access through fine pores into the soil particles, AMF hyphae being finer able to explore through finer soil pores (i) and absorb water from lower water potential (ii).*

6. Arbuscular Mycorrhizal Fungi (AMF) for Stress Tolerance

Arbuscular mycorrhizal fungi (AMF), can mitigate the effects of biotic and abiotic stresses, offering an important complementary measure to protect crop yields [64]. Studies have shown that AMF help in alleviating the negative effects of heat stress in many plants, although relevant information on AMF legume interaction is limited. Under heat stress, the ability of plant roots to absorb water and nutrients reduces [65]. AMF improve plant tolerance to heat mainly through enhancement of water and nutrient uptake, which in turn improves plant growth and yield under heat stress [66]. This is evident from higher water use efficiency, water holding capacity, and relative water content in AMF-inoculated maize (Zea mays) grown at 40℃ [66, 67]. Meanwhile, AMF-inoculated asparagus (*Asparagus officinalis*) accumulated more of the macronutrients nitrogen (N), phosphorous (P), and potassium (K), and micronutrients such as calcium (Ca), magnesium (Mg), and iron (Fe) than non-AMF plants under heat stress [68]. In the model legume plant M. truncatula, a night temperature elevated by 1.53℃ negatively affected growth. Inoculation with the AMF Rhizophagus irregularis mitigated the effects of heat stress and enhanced M. truncatula growth in terms of biomass, flower and seed number, leaf sugar, shoot zinc, and root phosphorus contents. While the mechanisms have not been reported for any legume species, AMF have been associated with improved photosynthetic capacity, stomatal conductance, and transpiration rate in heat-stressed maize inoculated with a mixed AMF culture of R. irregularis, Funneliformis mosseae, and F. geosporum [68]. The improved photosynthesis in AMF-inoculated plants could be attributed to protective effects from the symbiotic fungi against oxidative damage caused by high temperature. Under heat stress, mycorrhizal plants often exhibit enhanced activities of various antioxidant enzymes [69]. AMF Septoglomus deserticola and S. constrictum ameliorated heat stress-associated oxidative damage in tomato (Solanaceae lycopersicum) by reducing the levels of lipid peroxidation and H_2O_2, while elevating the antioxidant enzyme activities in root and leaves [70]. This dynamic symbiosis plays a critical role in successful plant performance, that AMF help to ameliorate plant responses to abiotic and biotic stressors [71]. It has been reported that mycorrhizal associations help plants increase nutrient uptake during water-stressed conditions by increasing hydraulic conductivity in roots [79].

Abbreviations

AMF Arbuscular Mycorrhizal Fungi
AM Arbuscular Mycorrhizal
ECMF Ectomycorrhizal
VAM Vesicular-arbuscular Mycorrhizal

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Author Contributions

Leta Ajema Gebisa is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Zou, Y. N., Wu, Q. S. and Kuča, K., 2021. Unravelling the role of arbuscular mycorrhizal fungi in mitigating the oxidative burst of plants under drought stress. Plant Biology, 23, pp. 50-57.

[2] Hui, L. I., XinNan, Z. O. N. G., Zhang, J. and ZongHan, Z. H. U., 2011. Physical growth of children in urban, suburban and rural mainland China: a study of 20 years' change. Biomedical and Environmental Sciences, 24(1), pp. 1-11.

[3] Barea, J. M. and Jeffries, P., 1995. Arbuscular mycorrhizas in sustainable soil-plant systems. Mycorrhiza: structure, function, molecular biology and biotechnology, pp. 521-560.

[4] Bonfante, P. and Genre, A., 2010. Mechanisms underlying beneficial plant–fungus interactions in mycorrhizal symbiosis. Nature communications, 1(1), p. 48.

[5] Chen, E. C., Morin, E., Beaudet, D., Noel, J., Yildirir, G., Ndikumana, S., Charron, P., St‐Onge, C., Giorgi, J., Krüger, M. and Marton, T., 2018. High intraspecific genome diversity in the model arbuscular mycorrhizal symbiont Rhizophagus irregularis. New Phytologist, 220(4), pp. 1161-1171.

[6] Mbodj, D., Effa-Effa, B., Kane, A., Manneh, B., Gantet, P., Laplaze, L., Diedhiou, A. G. and Grondin, A., 2018. Arbuscular mycorrhizal symbiosis in rice: establishment, environmental control and impact on plant growth and resistance to abiotic stresses. Rhizosphere, 8, pp. 12-26.

[7] Selosse, M. A., Strullu-Derrien, C., Martin, F. M., Kamoun, S. and Kenrick, P., 2015. Plants, fungi and oomycetes: a 400-million-year affair that shapes the biosphere. New Phytologist, 206(2), pp. 501-506.

[8] Khaliq, A., Perveen, S., Alamer, K. H., Zia Ul Haq, M., Rafique, Z., Alsudays, I. M., Althobaiti, A. T., Saleh, M. A., Hussain, S. and Attia, H., 2022. Arbuscular mycorrhizal fungi symbiosis to enhance plant–soil interaction. Sustainability, 14(13), p. 7840.

[9] Powell, J. R. and Rillig, M. C., 2018. Biodiversity of arbuscular mycorrhizal fungi and ecosystem function. New phytologist, 220(4), pp. 1059-1075.

[10] Tedersoo, L., Sánchez-Ramírez, S., Koljalg, U., Bahram, M., Döring, M., Schigel, D., May, T., Ryberg, M. and Abarenkov, K., 2018. High-level classification of the Fungi and a tool for evolutionary ecological analyses. Fungal diversity, 90, pp. 135-159.

[11] Smith, S. E. and Read, D. J., 2010. Mycorrhizal symbiosis. Academic press.

[12] Manoharan, L., Rosenstock, N. P., Williams, A. and Hedlund, K., 2017. Agricultural management practices influence AMF diversity and community composition with cascading effects on plant productivity. Applied Soil Ecology, 115, pp. 53-59.

[13] Mai, W., Xue, X., Feng, G., Yang, R. and Tian, C., 2019. Arbuscular mycorrhizal fungi–15-fold enlargement of the soil volume of cotton roots for phosphorus uptake in intensive planting conditions. European journal of soil biology, 90, pp. 31-35.

[14] Mbodj, D., Effa-Effa, B., Kane, A., Manneh, B., Gantet, P., Laplaze, L., Diedhiou, A. G. and Grondin, A., 2018. Arbuscular mycorrhizal symbiosis in rice: establishment, environmental control and impact on plant growth and resistance to abiotic stresses. *Rhizosphere*, *8*, pp.12-26.

[15] Smith, S. E. and Gianinazzi-Pearson, V., 1988. Physiological interactions between symbionts in vesicular-arbuscular mycorrhizal plants. Annual review of plant physiology and plant molecular biology, 39(1), pp. 221-244.

[16] Nursery, T. and Chakravarty, P., 1992. Effects of vesicular-arbuscular mycorrhizal fungi on the development of Verticillium and Fusarium wilts of alfalfa. Plant Disease, 76(3), pp. 239-243.

[17] Phillips, R. P., Brzostek, E. and Midgley, M. G., 2013. The mycorrhizal-associated nutrient economy: a new framework for predicting carbon–nutrient couplings in temperate forests. New Phytologist, 199(1), pp. 41-51.

[18] Dong, Y., Wang, Z., Sun, H., Yang, W. and Xu, H., 2018. The response patterns of arbuscular mycorrhizal and ectomycorrhizal symbionts under elevated CO_2: A meta-analysis. Frontiers in microbiology, 9, p. 1248.

[19] Parihar, M., Chitara, M., Khati, P., Kumari, A., Mishra, P. K., Rakshit, A., Rana, K., Meena, V. S., Singh, A. K., Choudhary, M. and Bisht, J. K., 2020. Arbuscular mycorrhizal fungi: Abundance, interaction with plants and potential biological applications. Advances in Plant Microbiome and Sustainable Agriculture: Diversity and Biotechnological Applications, pp. 105-143.

[20] Kumar, V., Joshi, S., Pant, N. C., Sangwan, P., Yadav, A. N., Saxena, A. and Singh, D., 2019. Molecular approaches for combating multiple abiotic stresses in crops of arid and semi-arid region. In Molecular approaches in plant biology and environmental challenges (pp. 149-170). Singapore: Springer Singapore.

[21] Kour, D., Rana, K. L., Kaur, T., Sheikh, I., Yadav, A. N., Kumar, V., Dhaliwal, H. S. and Saxena, A. K., 2020. Microbe-mediated alleviation of drought stress and acquisition of phosphorus in great millet (Sorghum bicolour L.) by drought-adaptive and phosphorus-solubilizing microbes. Biocatalysis and agricultural Biotechnology, 23, p. 101501.

[22] Lambais, M. R. and Ramos, A. C., 2010. Biochemical signals and their transduction in arbuscular mycorrhizas. Mycorrhizas, 30.

[23] Walker, C., 1983. Taxonomic concepts in the Endogonaceae: spore wall characteristics in species descriptions.

[24] Goto, B. T. and Maia, L. C., 2006. Glomerospores: a new denomination for the spores of Glomeromycota, a group molecularly distinct from the Zygomycota. Mycotaxon, 96(4), pp. 129-132.

[25] Souza, T., 2015. Handbook of arbuscular mycorrhizal fungi (p. 153). Cham: Springer.

[26] Hijri, M. and Sanders, I. R., 2004. The arbuscular mycorrhizal fungus Glomus intraradices is haploid and has a small genome size in the lower limit of eukaryotes. Fungal Genetics and Biology, 41(2), pp. 253-261.

[27] Genre A, Chabaud M, Faccio A, Barker DG, Bonfante P. 2008. Prepenetration apparatus assembly precedes and predicts the colonization patterns of arbuscular mycorrhizal fungi within the root cortex of both Medicago truncatula and Daucus carota. Plant Cell 20: 1407–20.

[28] Nanjundappa, A., Bagyaraj, D. J., Saxena, A. K., Kumar, M. and Chakdar, H., 2019. Interaction between arbuscular mycorrhizal fungi and Bacillus spp. in soil enhancing growth of crop plants. Fungal biology and biotechnology, 6(1), p. 23.

[29] Primieri, S., Santos, J. C. P. and Antunes, P. M., 2021. Nodule-associated bacteria alter the mutualism between arbuscular mycorrhizal fungi and N2 fixing bacteria. Soil Biology and Biochemistry, 154, p. 108149.

[30] Ferreira, D. A., da Silva, T. F., Pylro, V. S., Salles, J. F., Andreote, F. D. and Dini-Andreote, F., 2021. Soil microbial diversity affects the plant-root colonization by arbuscular mycorrhizal fungi. Microbial Ecology, 82, pp. 100-103.

[31] Artursson, V., Finlay, R. D. and Jansson, J. K., 2006. Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. Environmental microbiology, 8(1), pp. 1-10.

[32] Hijikata, N., Murase, M., Tani, C., Ohtomo, R., Osaki, M. and Ezawa, T., 2010. Polyphosphate has a central role in the rapid and massive accumulation of phosphorus in extraradical mycelium of an arbuscular mycorrhizal fungus. *The New Phytologist*, *186*(2), pp. 285-289.

[33] Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., Ahmed, N. and Zhang, L., 2019. Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. *Frontiers in plant science*, *10*, p. 1068.

[34] Roth, R. and Paszkowski, U., 2017. Plant carbon nourishment of arbuscular mycorrhizal fungi. Current opinion in plant biology, 39, pp. 50-56.

[35] Jakobsen, I. and Hammer, E. C., 2015. Nutrient dynamics in arbuscular mycorrhizal networks. Mycorrhizal networks, pp. 91-131.

[36] Jung, S. C., Martinez-Medina, A., Lopez-Raez, J. A. and Pozo, M. J., 2012. Mycorrhiza-induced resistance and priming of plant defenses. Journal of chemical ecology, 38, pp. 651-664.

[37] Cameron, D. D., Neal, A. L., van Wees, S. C. and Ton, J., 2013. Mycorrhiza-induced resistance: more than the sum of its parts?. Trends in plant science, 18(10), pp. 539-545.

[38] Chitarra, W., Pagliarani, C., Maserti, B., Lumini, E., Siciliano, I., Cascone, P., Schubert, A., Gambino, G., Balestrini, R. and Guerrieri, E., 2016. Insights on the impact of arbuscular mycorrhizal symbiosis on tomato tolerance to water stress. Plant Physiology, 171(2), pp. 1009-1023.

[39] Lynch, J. P. and Brown, K. M., 2001. Topsoil foraging–an architectural adaptation of plants to low phosphorus availability. Plant and Soil, 237, pp. 225-237.

[40] Douds Jr, D. D., Nagahashi, G., Reider, C. and Hepperly, P. R., 2007. Inoculation with arbuscular mycorrhizal fungi increases the yield of potatoes in a high P soil. Biological agriculture & horticulture, 25(1), pp. 67-78.

[41] Rakshit, A. and Bhadoria, P. S., 2010. Role of VAM on growth and phosphorus nutrition of maize with low soluble phosphate fertilization. Acta Agronómica, 59(1), pp. 111-118.

[42] Plenchette, C., Clermont-Dauphin, C., Meynard, J. M. and Fortin, J. A., 2005. Managing arbuscular mycorrhizal fungi in cropping systems. Canadian Journal of Plant Science, 85(1), pp. 31-40.

[43] De Sousa, R. N. ed., 2023. Arbuscular Mycorrhizal Fungi in Agriculture: New Insights. BoD–Books on Demand.

[44] Barea Navarro, J. M., 2002. Mycorrhizosphere interactions to improve plant fitness and soil quality.

[45] Lecomte, J., St-Arnaud, M. and Hijri, M., 2011. Isolation and identification of soil bacteria growing at the expense of arbuscular mycorrhizal fungi. FEMS microbiology letters, 317(1), pp. 43-51.

[46] Corkidi, L., Rowland, D. L., Johnson, N. C. and Allen, E. B., 2002. Nitrogen fertilization alters the functioning of arbuscular mycorrhizas at two semiarid grasslands. Plant and soil, 240, pp. 299-310.

[47] Kuila, D. and Ghosh, S., 2022. Aspects, problems and utilization of Arbuscular Mycorrhizal (AM) application as biofertilizer in sustainable agriculture. Current Research in Microbial Sciences, 3, p. 100107.

[48] Coelho, L. C. S., Mignoni, D. S. B., Silva, F. S. B., Braga, M. R., 2019. Seed exudates of Sesbania virgata (Cav.) Pers. stimulate the asymbiotic phase of the arbuscular mycorrhizal fungus Gigaspora albida Becker & Hall. Hoehnea 46, e272018.

[49] Berruti, A., Lumini, E., Balestrini, R. and Bianciotto, V., 2016. Arbuscular mycorrhizal fungi as natural biofertilizers: let's benefit from past successes. Frontiers in microbiology, 6, p. 1559.

[50] Giovannini, L., Palla, M., Agnolucci, M., Avio, L., Sbrana, C., Turrini, A. and Giovannetti, M., 2020. Arbuscular mycorrhizal fungi and associated microbiota as plant biostimulants: research strategies for the selection of the best performing inocula. Agronomy, 10(1), p.106.

[51] Baum, C., El-Tohamy, W. and Gruda, N., 2015. Increasing the productivity and product quality of vegetable crops using arbuscular mycorrhizal fungi: a review. Scientia horticulturae, 187, pp. 131-141.

[52] Casieri, L., Ait Lahmidi, N., Doidy, J., Veneault-Fourrey, C., Migeon, A., Bonneau, L., Courty, P. E., Garcia, K., Charbonnier, M., Delteil, A. and Brun, A., 2013. Biotrophic transportome in mutualistic plant–fungal interactions. Mycorrhiza, 23, pp. 597-625.

[53] Aguilera, P., Cumming, J., Oehl, F., Cornejo, P. and Borie, F., 2015. Diversity of arbuscular mycorrhizal fungi in acidic soils and their contribution to aluminum phytotoxicity alleviation. Aluminum stress adaptation in plants, pp. 203-228.

[54] Püschel, D., Bitterlich, M., Rydlová, J. and Jansa, J., 2020. Facilitation of plant water uptake by an arbuscular mycorrhizal fungus: a Gordian knot of roots and hyphae. Mycorrhiza, 30(2), pp. 299-313.

[55] Kobae, Y., 2019. Dynamic phosphate uptake in arbuscular mycorrhizal roots under field conditions. Frontiers in environmental Science, 6, p.159.

[56] Johri, A. K., Oelmüller, R., Dua, M., Yadav, V., Kumar, M., Tuteja, N., Varma, A., Bonfante, P., Persson, B. L. and Stroud, R. M., 2015. Fungal association and utilization of phosphate by plants: success, limitations, and future prospects. Frontiers in microbiology, 6, p.984.

[57] Chiu, C. H. and Paszkowski, U., 2019. Mechanisms and impact of symbiotic phosphate acquisition. Cold Spring Harbor Perspectives in Biology, 11(6), p. a034603.

[58] Sato, T., Hachiya, S., Inamura, N., Ezawa, T., Cheng, W. and Tawaraya, K., 2019. Secretion of acid phosphatase from extraradical hyphae of the arbuscular mycorrhizal fungus Rhizophagus clarus is regulated in response to phosphate availability. Mycorrhiza, 29, pp. 599-605.

[59] Gutjahr, C. and Paszkowski, U., 2013. Multiple control levels of root system remodeling in arbuscular mycorrhizal symbiosis. Frontiers in plant science, 4, p.204.

[60] Pal, A. and Pandey, S., 2016. Role of arbuscular mycorrhizal fungi on plant growth and reclamation of barren soil with wheat (Triticum aestivum L.) crop. Int J Soil Sci, 12(1), pp. 25-31.

[61] Ouledali, S., Ennajeh, M., Zrig, A., Gianinazzi, S. and Khemira, H., 2018. Estimating the contribution of arbuscular mycorrhizal fungi to drought tolerance of potted olive trees (Olea europaea). Acta Physiologiae Plantarum, 40, pp. 1-13.

[62] Zhao, R., Guo, W., Bi, N., Guo, J., Wang, L., Zhao, J. and Zhang, J., 2015. Arbuscular mycorrhizal fungi affect the growth, nutrient uptake and water status of maize (Zea mays L.) grown in two types of coal mine spoils under drought stress. Applied Soil Ecology, 88, pp. 41-49.

[63] Boyer, L. R., Brain, P., Xu, X. M. and Jeffries, P., 2015. Inoculation of drought-stressed strawberry with a mixed inoculum of two arbuscular mycorrhizal fungi: effects on population dynamics of fungal species in roots and consequential plant tolerance to water deficiency. Mycorrhiza, 25, pp. 215-227.

[64] W. T., Chua, K. O., Mazumdar, P., Cheng, A., Osman, N. and Harikrishna, J. A., 2022. Arbuscular mycorrhizal symbiosis: A strategy for mitigating the impacts of climate change on tropical legume crops. Plants, 11(21), p.2875.

[65] Zhu, X., Song, F. and Liu, F., 2017. Arbuscular mycorrhizal fungi and tolerance of temperature stress in plants. Arbuscular mycorrhizas and stress tolerance of plants, pp. 163-194.

[66] Zhu, X. C., Song, F. B., Liu, S. Q. and Liu, T. D., 2011. Effects of arbuscular mycorrhizal fungus on photosynthesis and water status of maize under high temperature stress. Plant and soil, 346, pp. 189-199.

[67] Yeasmin, R., Bonser, S. P., Motoki, S. and Nishihara, E., 2019. Arbuscular mycorrhiza influences growth and nutrient uptake of asparagus (Asparagus officinalis L.) under heat stress. HortScience, 54(5), pp. 846-850.

[68] Mathur, S., Sharma, M. P. and Jajoo, A., 2018. Improved photosynthetic efficacy of maize (Zea mays) plants with arbuscular mycorrhizal fungi (AMF) under high temperature stress. Journal of Photochemistry and Photobiology B: Biology, 180, pp. 149-154.

[69] Maya, M. A. and Matsubara, Y. I., 2013. Influence of arbuscular mycorrhiza on the growth and antioxidative activity in cyclamen under heat stress. Mycorrhiza, 23, pp. 381-390.

[70] Duc, N. H., Csintalan, Z. and Posta, K., 2018. Arbuscular mycorrhizal fungi mitigate negative effects of combined drought and heat stress on tomato plants. Plant Physiology and Biochemistry, 132, pp. 297-307.

[71] McPherson, M. R., Zak, D. R., Ibáñez, I., Upchurch, R. A. and Argiroff, W. A., 2024. Arbuscular mycorrhizal diversity increases across a plant productivity gradient driven by soil nitrogen availability. Plant‐Environment Interactions, 5(4), p. e70002.

[72] Brundrett, M. C., 2002. Coevolution of roots and mycorrhizas of land plants. *New phytologist*, *154*(2), pp. 275-304.

[73] Brundrett, M., 2004. Diversity and classification of mycorrhizal associations. *Biological reviews*, *79*(3), pp. 473-495.

[74] Mehrotra, V. S. ed., 2005. *Mycorrhiza: role and applications*. Allied Publishers.

[75] Sidhu, S. S. and Chakravarty, P., 1990. Effect of selected forestry herbicides on ectomycorrhizal development and seedling growth of lodgepole pine and white spruce under controlled and field environment. *European Journal of Forest Pathology*, *20*(2), pp. 77-94.

[76] Termorshuizen, A. J. and Schaffers, A. P., 1987. Occurrence of carpophores of ectomycorrhizal fungi in selected stands of Pinus sylvestris in the Netherlands in relation to stand vitality and air pollution. *Plant and soil*, *104*, pp. 209-217.

[77] Molina, T. J., Kishihara, K., Siderovskid, D. P., Van Ewijk, W., Narendran, A., Timms, E., Wakeham, A., Paige, C. J., Hartmann, K. U., Veillette, A. and Davidson, D., 1992. Profound block in thymocyte development in mice lacking p56lck. *Nature*, *357*(6374), pp. 161-164.

[78] Castellano, M. A. and Bougher, N. L., 1994. Consideration of the taxonomy and biodiversity of Australian ectomycorrhizal fungi. *Plant and soil*, *159*, pp. 37-46.

[79] Roth-Bejerano, N., Navarro-Ródenas, A. and Gutiérrez, A., 2014. Types of mycorrhizal association. *Desert truffles: phylogeny, physiology, distribution and domestication*, pp. 69-80.