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# Arbuscular Mycorrhizal Fungi Efficiency on Plant Growth and Nutrient Acquisition: A Comprehensive Review

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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Review Article

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## ABSTRACT

Arbuscular Mycorrhizal Fungi (AMF) play a crucial role in enhancing plant growth and nutrient acquisition. The impacts of pressures on crop yield have been made worse by climate change and agricultural practices such as overuse of pesticides and fertilizers, which have also damaged the environment. AMF are one environmentally friendly management strategy that is desperately needed to increase agricultural output. More importantly, it's widely acknowledged that the AMF inoculation confers resistance in host plants to a range of stressful environments, such as heat, salt, drought, metals, and abnormally high or low temperatures. This review paper provides a comprehensive analysis of the current understanding of AMF efficiency on various aspects of plant physiology, including nutrient uptake and overall plant development. The paper synthesizes information from recent studies to present a nuanced perspective on the multifaceted interactions between AMF and plants. Furthermore, challenges and future directions in AMF research are discussed, highlighting the need for a more integrated and holistic approach to harness the full potential of these fungi for enhancing plant productivity and nutrient acquisition.

*Keywords: Arbuscular Mycorrhizal Fungi (AMF); plant growth; nutrient acquisition; plant tolerance.*

## 1. INTRODUCTION

The growing concern about food security has brought plant science to light as a developing field, which has driven researchers to come up with fresh ideas for raising crop yields. Food shortage is caused by both biotic and abiotic factors that restrict global agricultural yield, such as salt, drought, floods, plant diseases, nutritional deficiencies, and toxicity. It's critical to appropriately regulate and make use of good microbial activities in order to reduce adverse environmental consequences and accomplish sustainable goals [1]. Arbuscular Mycorrhizal Fungi (AMF) form symbiotic relationships with the majority of plant species, influencing plant growth and nutrient uptake. These beneficial fungi form mutualistic symbiotic associations with the roots of most plant species, creating a vast network of interconnected hyphae that extends the root system and greatly increases the surface area available for nutrient absorption [2]. This symbiotic relationship benefits both the fungi and the plants [3].The fungi receive carbohydrates from the plants, while the plants receive increased access to nutrients such as phosphorus and nitrogen [4]. Furthermore, arbuscular mycorrhizal fungi have been shown to improve plant tolerance to various abiotic stresses, including drought, salinity, and heavy metal toxicity [5, 6].

Many studies have focused on the efficiency of arbuscular mycorrhizal fungi in enhancing plant growth and nutrient uptake [7]. These studies have consistently demonstrated the positive effects of arbuscular mycorrhizal fungi on plant growth and nutrient acquisition [8]. In addition to promoting plant growth and nutrient uptake, arbuscular mycorrhizal fungi also play a role in protecting plants against pathogens and toxic stresses [9]. Research has demonstrated that arbuscular mycorrhizal fungi can act as bioprotectants, helping plants defend against pathogens and tolerate toxic stresses. For example, [10] found that arbuscular mycorrhizal fungi enhanced the growth and essential oil production in *Ocimum basilicum* plants. These findings highlight the potential of harnessing the symbiotic relationship between arbuscular mycorrhizal fungi and plants for sustainable agriculture and plant health management practices. The research on arbuscular mycorrhizal fungi efficiency on plant growth and nutrient uptake has demonstrated consistent positive effects. Arbuscular mycorrhizal fungi have been shown to improve plant tolerance to various abiotic stresses, including drought, salinity, and heavy metal toxicity [11]. In the case of metal toxicity, several studies have indicated that arbuscular mycorrhizal fungi can improve plant tolerance and reduce the detrimental effects of heavy metals on plant growth. Furthermore, arbuscular mycorrhizal fungi have

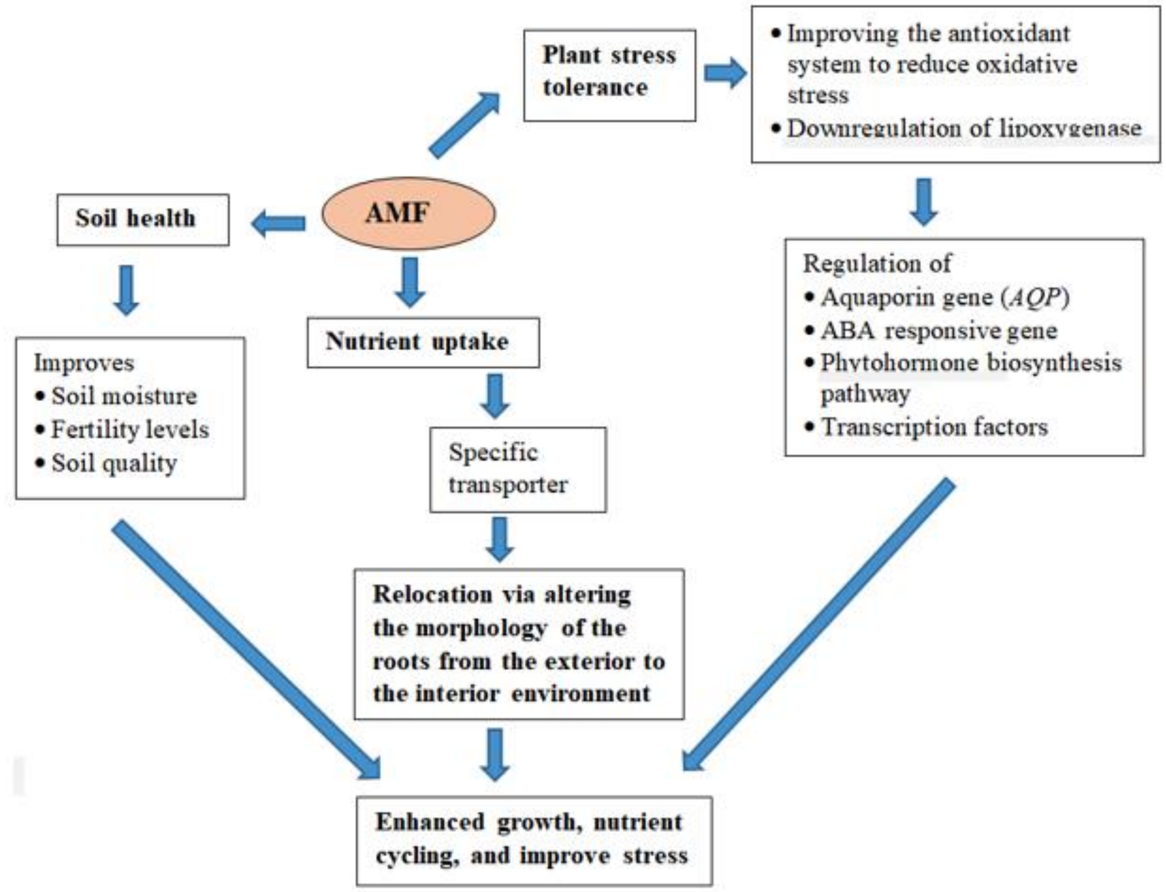


**Fig. 1. A schematic depiction of how mycorrhizal fungi control several ecological processes and stimulate plant growth and nutrient uptake in stress conditions**

been found to enhance nutrient acquisition by plants [12]. They are particularly effective at increasing the availability of phosphorus to plants, which is often a limiting nutrient in many soils.

In the scientific literature, arbuscular mycorrhizal fungi are generally acknowledged for their effectiveness in promoting plant growth and nutrient absorption. Arbuscular mycorrhizal fungi have been demonstrated to improve soil structure and stability, increase organic matter decomposition, and enhance nutrient uptake in addition to their direct effects on plant growth and nutrient uptake (Fig. 1). Arbuscular mycorrhizal fungi also have indirect effects on ecosystem functioning and soil fertility. In light of the significance of AMF and the developments in research about its applications in agriculture, this review centers on the function of AMF in the control of plant growth and development with enhanced nutrient absorption in demanding conditions.

## 2. MYCORRHIZA EVOLUTION AND TYPES

Mycorrhizae are ancient, maybe even older than the terrestrialization of plants, according to fossil and genetic data. Research reveals that proto-mycorrhizal fungi were a critical feature enabling plant terrestrialization. Genetic evidence implies that all land plants share a single common ancestor [13] who appears to have swiftly acquired mycorrhizal symbiosis [14]. An assemblage of fossil plants from the 400 million-year-old Rhynie chert have been sufficiently preserved to allow for the observation of arbuscular mycorrhizae in the stems of Aglaophyton major, providing a lower constraint on the possible development time of late mycorrhizal symbiosis [15] While the majority of contemporary mycorrhizal groups, such as orchid and erchoid mycorrhizae, date to the Cretaceous era's angiosperm radiation, ectomycorrhizae evolved far later, during the Jurassic period [16]. Genetic research suggests that legume-fixing bacterium symbiosis is a genetic outgrowth of mycorrhizal symbiosis [17]. The distribution of mycorrhizal fungi now seems to be a reflection of the rivalry and complexity in root architecture that arose during the Cenozoic Era, when angiosperm dominance was the norm and complex ecological interactions existed between species [18].

An ectomycorrhiza and an endomycorrhiza are two categories for mycorrhizas. Hyphae of endomycorrhizal fungus infiltrate the cell wall and invade the cell membrane, but ectomycorrhizal fungi do not penetrate individual cells inside the root. This distinguishes the two types of fungi [19, 20]. While, arbutoid mycorrhizas fall under the category of ectoendomycorrhizas, endomycorrhizas comprise arbuscular, ericoid, and orchid mycorrhizas. One distinct class of mycorrhizas is monotropoid.

## 3. MYCORRHIZAL MUTUALIST MECHANISMS

Most plant species have a mutualistic interaction with mycorrhizal fungi in their roots. Both the plants and the portions of the roots that house the fungus are referred to be mycorrhizal in such a connection. While only a small percentage of mycorrhizal relationships between plant species and fungi have been studied thus far, 95% of plant families that have been studied are primarily mycorrhizal, either because the majority of their species have a beneficial association with mycorrhizae or because they are completely dependent on mycorrhizae. It is well known that in the Orchidaceae family, seeds will not even germinate if the proper mycorrhizae are not present [21]. Mycorrhizal fungi and plants may have a more complicated interaction than only mutualism, according to recent studies on ectomycorrhizal plants in boreal forests. When it was surprisingly discovered that mycorrhizal fungi were storing nitrogen from plant roots during periods of nitrogen shortage, this link was recognized. According to research, certain mycorrhizae disperse nutrients in response to the surrounding plants and other mycorrhizae. They go on to describe how this revised model may account for the fact that mycorrhizae do not mitigate plant nitrogen restriction and that as soil nitrogen supply decreases, plants may suddenly transition from a mixed strategy including both mycorrhizal and nonmycorrhizal roots to a solely mycorrhizal approach [22]. Furthermore, a greater degree of variation in the intensity of mycorrhizal mutualisms may be explained by evolutionary and phylogenetic links than by ecological variables [23].

## 4. IMPACT OF AMF ON PLANT NUTRIENT ACQUISITION

### 4.1 Plant Growth Enhancement

Beneficial rhizosphere bacteria have the ability to increase crops' quality as well as their nutritional condition. Over the past 20 years, several studies on AMF have demonstrated its numerous advantages for crop yield and soil health. As a result, it is generally accepted that AMF may eventually be used in place of inorganic fertilizers due to the fact that mycorrhizal treatment may significantly lower the amount of chemical fertilizer input, particularly phosphorus [24]. As naturally occurring root symbionts, AMF help host plants by supplying vital inorganic nutrients, which enhances growth and production in both stressed and unstressed environments. AMF's ability to function as a biofertilizer may improve plants' capacity to adapt to shifting environmental conditions. Arbuscular mycorrhizal fungi (AMF) may form symbiotic associations with the majority of terrestrial plants [25]. Plant growth and yield, nutrient acquisition [26,27] especially P and other poorly mobile nutrients [28], enhanced resistance to biotic stresses [29] and abiotic stresses (salinity, drought, etc.) [30] and enhanced soil aggregation and carbon sequestration are all impacted by this type of symbiosis. AMF can also change the microbial community's structure and promote the growth of other microorganisms in the rhizosphere [31, 32], which can affect a number of biological processes, including biological N fixation [33].

The strawberry that was colonized by AMF, for instance, showed higher levels of secondary metabolites, which enhanced its antioxidant properties [34]. According to [35], AMF can improve the nutritional value of crops by influencing the synthesis of carotenoids and other volatile chemicals. AMF has positive benefits on tomato quality, as noted by [36]. Citrus fruit quality was improved in another study by [37] which found that *Glomus versiforme* boosted the amounts of sugars, organic acids, vitamin C, flavonoids, and minerals. Stronger anthocyanin, chlorophyll, carotenoids, tocopherols, total soluble phenolics, and different mineral elements accumulate when mycorrhizal symbiosis is present [38]. AMF have proven to have a significant potential for increasing crop productivity since they have been used in large-scale field production of potatoes [39], yam [40],, and maize [41]. According to [42] and [43], AMF can also improve the manufacture of beneficial phytochemicals in edible plants, enabling them to function properly in the food production chain. Maintaining the pH of the soil can help AMF mitigate abiotic stress and preserve its horticultural value. As explained below, AMF may also be quite helpful in enhancing plants' ability to withstand harsh conditions.

## 4.2 Nutrient Cycling and Uptake

Many studies have demonstrated that excessive land use may have a significant influence on biodiversity overall, which can then have an impact on how well an ecosystem functions. Transferring resources, such as organic carbon (C), in the form of lipids and sugars, is one important function of such symbiotic relationships [44]. It is well accepted that AMF colonization increases plants' absorption of nutrients. It is clear that inoculating with AMF may greatly raise the concentration of different macro- and micronutrients, which increases the synthesis of photosynthate and, in turn, the accumulation of biomass. AMF can increase nearly all plants' absorption of inorganic nutrients, particularly phosphate. Additionally, AMF are highly successful in facilitating plants' uptake of nutrients from nutrient-deficient soils. AMF interaction has been shown to enhance the phyto-availability of micronutrients such as copper and zinc in addition to macronutrients. AMF increases the host roots' capacity to absorb surface energy. Increased leaf area and higher levels of nitrogen, potassium, calcium, and phosphorus have been seen in experimental experiments conducted on tomato plants infected with AMF, indicating greater plant development [45]. AMF have a symbiotic relationship with roots in order to get vital nutrients from the host plant and then give back mineral nutrients including N, P, K, Ca, Zn, and S. As a result, AMF give the plants nutritional assistance even in unsuitable root cell environments [46].

AMF create fungal structures called arbuscules that aid in the interchange of inorganic minerals and carbon and phosphorus molecules, giving host plants a significant boost in vitality. As a result, they can greatly increase the concentration of phosphorus in both the root and shoot systems. Mycorrhizal association enhances phosphorus delivery to the infected roots of host plants in phosphorus-limited environments. For instance, the AMF-colonized maize plants showed a significant improvement in Pi absorption rate. Enhanced growth frequency of AMF inoculation is directly correlated with increased photosynthetic activity and other leaf functions. This is because enhanced growth frequency of AMF inoculation is directly correlated with the intake of N, P, and carbon, which travel towards roots and stimulate tuber development. It has been noted that under various irrigation regimes, AMF maintains P and N absorption, eventually aiding in plant growth at higher and lower P levels. For instance, in *Pelargonium graveolens* L. under drought stress, mycorrhizal symbiosis favorably raised the concentrations of N, P, and Fe [47].

AMF is thought to increase the absorption of nearly all necessary nutrients while decreasing the absorption of Na and Cl, which stimulates growth. Plant growth and development can be enhanced by the extra-radical mycelium (ERM) through efficient nutrient absorption improvement. Even in places with an adequate amount of livestock and farm-yard manure (FYM), nitrogen (N), a well-known mineral fertilizer, is a major source of soil nourishment. Numerous researchers have documented how AMF aids in the absorption of soil nutrients, particularly N and P, which can successfully stimulate the development of host plants. N is a key element restricting development in certain crops and higher plants. AMF can absorb and transport N to neighboring plants or host plants, according to a number of studies have shown that, especially under low fertilizer levels, AMF mediated enhanced shoot biomass allocation to panicles and grains through increased N and P redistribution to panicles.

According to [48], AMF inoculation enhances C and N accumulation as well as N assimilation at both ambient and increased $CO_2$ concentrations. According to [49], AMF, for instance, has been shown to enhance the development, accumulation of micro- and macronutrients, and distribution of these nutrients in plantlets cultivated in environments with elevated Mn levels in olive plants. The important dynamic characteristics that contribute to improving the advantageous effects of AMF colonization on overall plant performance are the improvement of plant nutrition and the preservation of the $Ca_2^+$ and $Na^+$ ratio. Mycorrhizal chickpea was shown to have improved growth and levels of protein, iron, and zinc. Furthermore, mycorrhizal symbiosis's contribution to different micronutrients in crops was demonstrated by two metaanalysis papers that surfaced a few years ago. According to [50], while Antirrhinum majus was experiencing a drought, the specific fungal relationship increased the amount of macronutrients such N, P, K, Ca, and Mg. AMF also demonstrated efficacy in limiting the elevated build-up of Na, Mn, Mg, and Fe in roots. According to a number of research carried out in recent years, AMF, including *Glomus mosseae* and *Rhizophagus irregularis,* demonstrated enhanced heavy metal translocation in the shoot. Mycorrhizal hyphae assist plants in absorbing micronutrients like zinc and copper, which have restricted dispersion in soil.

## 5. CHALLENGES AND FUTURE DIRECTIONS

### 5.1 Limitations of AMF Application

In modern times, pesticide usage is a crucial component of contemporary agriculture that depends on technology. Since most high-yielding crops are more prone to disease than their wild counterparts, there is a rising demand for them. High concentrations of key fertilizers, particularly nitrogen and phosphate; pesticides and fungicides; extensive tillage; and crop rotation with non-mycorrhizal crops inhibit AM activity, variety, and association. The variety, population, and root colonization of AM flora in agricultural fields are therefore changed and poorer than in nearby natural soil. Mycorrhizal symbiosis is observed to be inhibited by high P concentrations in plants brought on by high P fertilization in soil. Plants may absorb sufficient phosphorus without sacrificing carbohydrates when high P fertilizer is applied. In return for phosphate, AM fungus wants a carbon source from plants. Cooperation from both parties is necessary for AM to exist and function, and the plant itself selects the most efficient and compatible strains by sharing more resources with them. Numerous nitrogen fertilizers have been shown in pot and field trials to reduce colonization. Plant growth and root development are increased by low to medium levels of AM colonization and sporulation. Applying nitrogen fertilizer at a higher rate inhibits AM colonization in plants. Greater than ideal potassium concentration inhibits AM signaling, reduces root exudation, and accumulates soluble carbohydrates in the cortex.

Despite the fact that these agrochemicals generally have detrimental impacts on the environment, soil, and human health, crop productivity is never compromised. To control leaf, seed, and soil-borne pathogens, fungicides, both systemic and non-systemic, are employed; however, the majority of them negatively impact AM spore germination, colonization, extraradical hyphal growth, sporulation and the efficiency of P uptake by phosphatase activity. By inhibiting the processes of nutrient transfer, especially in dry soil lacking in nutrients, both fungicides hinder the growth of crops that are dependent on AM.

The hyphal network in the soil is destroyed by soil disturbances and tillage, which can physically crush AM spores, reducing root colonization. The amount of soil that AM can remove is reduced when colonized root fragments and hyphal networks are disrupted. The current favorable circumstances for AMF species are also altered by the movement of the soil layer. The physical disruption of the extra radical mycelium network during the early colonization stage is directly linked to the direct effects of conventional tillage systems on AM activity in nutrient and water uptake, glomalin-related soil aggregate formation, and bioprotection against soil pathogens. Propagule density, activity, and AMF community are all negatively impacted by extended periods of fallow land and crop rotation including non-mycorrhizal crops. The fallow time and the addition of non-host species have an impact on the density and quantity of AMF propagules, which has a negative effect on the production of subsequent crops. Waterlogged soil in paddy agriculture prevents AM activity since AM cannot develop in wet soil. Considering that conventional agrochemical-based agriculture disrupts the symbiosis and effectiveness of AM, the advantages of AM remain untapped in this context.

## 6. CONCLUSION

The main discussion surrounding AMF has been its ability to help soil organisms absorb nutrients. Nevertheless, recent research has demonstrated that plants injected with AMF can successfully fend off a variety of environmental cues, such as salinity, drought, nutrient stress, alkali stress, cold stress, and extreme temperatures, helping to increase the yield of numerous crops and vegetables per hectare. For contemporary global agricultural systems to remain consistently sustainable, it is crucial to promote the use of AMFs. Without a doubt, using AMF for agricultural enhancement may cut down on the usage of pesticides and synthetic fertilizers considerably, supporting bio-healthy farming practices. Crop plants with AMF-mediated growth and productivity increase may be able to meet the world's growing population's consumption needs. Additionally, because of their widespread use, environmentally friendly technology should be strongly supported.

## 7. FUTURE RESEARCH DIRECTIONS

Future research should primarily concentrate on identifying the genes and gene products regulating the AMF-mediated regulation of growth and development in response to stressful stimuli. Future studies in this area should focus on identifying the key cellular and metabolic pathways under varying environmental conditions, as well as the host and AMF specific protein components governing symbiotic interaction. Crop production may be increased by comprehending the crosstalk that is activated to control plant performance and the AMF-induced modifications in the tolerance mechanisms. All things considered, AMF need to be thoroughly investigated to learn more about their function in nature for sustainable agricultural output. To effectively define methods for managing the soil/plant system to enhance this significant ecological process, a greater comprehension of the significance of each route involved in AMF-mediated nutrient cycling and transfer is necessary. Novel and inventive research methodologies will be needed for this.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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