Effects of Arbuscular Mycorrhizal Fungi on Plant Growth and their Adaptation in Diverse Crop Production Practices

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Abstract: Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with plant roots and soil microbes, delivering mutual benefits. As a key component of the soil microbiome, AMF significantly affects how host plants grow and develop. They also play a major role in the composition and structure of plant communities. This role is vital for preserving plant species diversity, ecosystem stability, and overall ecological health. When AMF is introduced to plants, it enhances the root system's ability to absorb nutrients from decomposing organic matter. The biochemical activity of AMF fosters a specific and beneficial microbial community within the plant's root zone (rhizosphere) and, to some extent, in the surrounding soil. Consequently, evaluating how well AMF functions and adapts under different cultivation practices and soil modifications is crucial for optimizing or sustaining crop yields. Arbuscular Mycorrhizal Fungi associations are formed through the interaction of soil fungi and plant roots, where the fungi penetrate root tissues, leading to mutual benefits for both organisms. Arbuscular Mycorrhizal Fungi represent a diverse group of soil microorganisms that exert various positive effects on the growth of their host plants. The symbiotic relationship between AMF and soil enhances plant nutrient uptake, making it a vital factor in plant nutrition. Therefore, assessing the efficiency and adaptability of AMF in diverse agricultural practices and soil amendments is essential for improving or maintaining crop production. This review will briefly explore how arbuscular AMF influences plant growth and nutrition.
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1. Introduction

Meeting the food needs of a growing global population is a significant challenge that places considerable pressure on agricultural systems (Wang, 2022). Enhancing plant growth demands a thorough understanding of the complex interactions that govern plant development within the soil environment. Rather than being a passive medium, soil is a living habitat, bustling with microbial life—especially around the rhizosphere, the zone influenced by plant roots (Choudhary et al., 2022). These microbial communities are vital for promoting plant health, aiding nutrient absorption, and maintaining ecosystem balance.

One of the most important groups of soil microorganisms is the Arbuscular Mycorrhizal Fungi (AMF), which belong to the Glomeromycota phylum. These fungi are found globally and form symbiotic relationships with roughly 90% of terrestrial plants, including many key crops (Smith and Read, 2010; Antonelli et al., 2020). This partnership enables plants to thrive under various environmental conditions (Kumar et al., 2022). In this mutualistic association, AMF hyphae colonize plant roots and develop specialized structures known as arbuscules inside the cortical cells of roots to facilitate nutrient exchange. Moreover, their extensive external hyphal network spreads into the soil, greatly enhancing the plant's access to water and nutrients (Berruti et al., 2016). This longstanding interaction underscores the crucial role of AMF in supporting plant vitality and ecosystem sustainability.

The collaboration with AMF provides considerable benefits to the host plant (Yang and Ortas, 2023). While Arbuscular Mycorrhizal Fungi (AMF) don't directly facilitate nitrogen (N) uptake as much as phosphorus (P), they also play a role in N cycling and improving uptake efficiency. Aside the boosting of nutrient availability, the fungal network enhances a plant's access to water, which is crucial during droughts, as it can explore a larger volume of soil than roots alone (Yang et al., 2014). Moreover, the AMF partnership strengthens a plant's ability to withstand various stresses. This includes increased tolerance to abiotic challenges such as salinity, heavy metal pollution, and extreme temperatures. These benefits come from mechanisms like better nutrient balance, reduced oxidative damage, and adjustments to plant hormonal responses (Evelin et al., 2019). The association also activates plant defense systems, offering protection against root pathogens and certain herbivores, thereby contributing to the plant's overall health and survival (Cameron et al., 2013).

The practical relevance of these AMF-mediated benefits is particularly pronounced when considering the diversity of contemporary crop production practices (Wahab et al., 2023). Farming systems differ greatly, spanning from intensive conventional agriculture, which relies heavily on synthetic fertilizers and pesticides, to more environmentally conscious organic and sustainable methods that aim to reduce external inputs and utilize natural processes. Each distinct management approach, like tillage practices, fertilizer application strategies, pesticide use, and crop rotation patterns—applies specific pressures and creates distinct soil environments (Akinrinola and Babajide, 2023). These environments can significantly affect the survival, variety, and effectiveness of native AMF communities (Brito et al., 2021; de Oliveira et al., 2024). To get the most out of the ecosystem services. these fungi offer, we must understand how different farming practices and AMF populations interact. This understanding is key to improving nutrient and water use efficiency, reducing reliance on synthetic inputs, boosting crop resilience to environmental changes, and ultimately creating more sustainable agricultural systems.

This literature review seeks to offer an understanding of how Arbuscular Mycorrhizal Fungi (AMF) variously affect plant growth and adapt to different crop production systems. By bringing together recent research, this report will investigate the complex ways AMF influence plant physiology, nutrient absorption, water management, and tolerance to stress. Additionally, it will examine how various agricultural practices—like tillage, fertilization, herbicide use, and cropping systems—impact AMF communities and their effectiveness. The goal of this review is to clarify the essential role of AMF in modern agriculture and underscore their potential for fostering sustainable and resilient crop production.

2. Mycorrhizae and Their Association with Plant Root Systems

The arbuscular mycorrhizal fungi (AMF) belong to the taxonomic order, Glomales, which is now known to have six genera. These fungi are found in almost all plants in natural environments (Jones et al., 2004), and studies show they are present in 83% of dicotyledonous plants and 79% of monocotyledonous plants (Fitter et al., 2011). The mycorrhizal status of all the gymnosperms is mycorrhizal (Mummey et al., 2005). Inhabitation of the plant root systems by these fungi forms a mutualistic (mutually beneficial) association between the plant and the fungus. After root colonisation, mycorrhizal fungi form an external mycelium which is a link between the root and the soil (Toro et al., 1997; Wahab et al., 2023). Mycorrhizal associations are mutually beneficial associations between plants and fungi and are classified into two types; arbuscular mycorrhizae (AM) and ectomycorrhizae. The phytobiont refers to about 80-90% of plant species and the fungi belong to the phylum Glomeromycota, which comprises nine genera, which include Glomus, Paraglomus, Sclerocystis, Acaulospora, Entrophospora, Gigaspora, Scutellospora, Diversispora, Geosiphon and Archaeospora (Nizamani et al., 2024). The AMFs found in soil are estimated at least 170 known species (Smith et al., 1997; Hagh-Doust et al., 2022). It is known as 'arbuscular' because the fungi produce tree-like structures known as arbuscules within the root cells. Other structures formed by fungi are intra- and extraradical spores (which are germination structures used for long-term storage of species, propagation, and identification of species), intra-radical hyphae, extraradical hyphae, intracellular fungal storage structures called vesicles and auxiliary cells arising from the extraradical hyphae of some genera. Symbiotic AM fungal mycelium can be present both intra and extraradically within cortical cells of plant roots, while extraradical AM mycelium can colonise the bulk soil surrounding the root system and enhance the capacity to exploit new areas of soil, water, and nutrients for plant roots (Dalpe and Monreal, 2004). Arbuscular mycorrhizal fungi hyphae can access immobile nutrients like P and zinc (Zn) from distant soil pores and less available pools, translocating them back to the host.

3. The Benefits, Influencing Factors, and Agricultural Implications of Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi are common soil inhabitants, which are in a close symbiotic relationship with the root of higher plants; the association provokes different effects on the growth of the host plant (Koide and Mosse 2004; Akinrinde, 2006). The major advantage of this mycorrhizal association includes the ability of the fungi to help the plants get closer to their water and nutrient uptake and changing some of the physiological processes in the plants which leads to increased yields (Okon et al., 2010; Nisha and Rajeshkumar, 2010; Yang and Ortas, 2023).

Plants vary in their dependency on AMF-mediated nutrient uptake, from highly AMF-dependent on P to non-AMF-dependent crops. Among these effects, the most noticeable one is the enhancement of the mobility of nutrients, which are considered less mobile Ortas. (2008) This increase is mainly attributed to the ability of the mycorrhizal fungi to extract phosphate from the soil and transport it to the host roots, in soil solution the concentration of P is very low and is translocated to roots principally by diffusion (Jefwa et al., 2010; Adewole and Ilesanmi, 2011). However, the diffusion coefficient of P is very low, and therefore P can readily be removed from the root zone. The mycorrhizal association can enhance the plant's access to P sources in the soil to a very large extent (Nasim, 2005). All the mentioned benefits are optimum in the P-deficient soils and they gradually decline with the availability of soil phosphate (Ibrahim et al., 2022; Akinrinola et al., 2023). Other nutrients whose absorption is enhanced through mycorrhiza are N (Fu et al., 2021) K, Ca and Mg (Liu et al., 2002; Akter et al., 2024).

Mycorrhyzal fungi also increases the uptake of the micronutrients (Jiménez et al., 2024). Arbuscular mycorrhizal fungi can also enhance the synthesis of growth regulating substances, and photosynthesis, osmotic adjustment in drought and salinity stress and resistance to pests and soil-borne diseases by plants (Al-Karaki, 2006; Wang et al., 2020). The role of AMF in enhancing the plant's nutrient uptake is not only a combination of the two parts as is widely documented but needs to be viewed in relation to soil properties. Mycorrhizae are influenced quantitatively and qualitatively by agricultural practices (de Oliveira et al., 2024). Some of the factors include host crop dependency on mycorrhizal colonisation, tillage system, fertiliser application, and mycorrhizal fungi potential of inoculum affecting plant response and plant benefits from mycorrhizae (Wahab et al., 2023). Arbuscular Mycorrhizal Fungi can be incorporated into soil management to establish cheap, sustainable agricultural practices (Mukhongo et al., 2016). Arbuscular mycorrhizal (AM) fungi have an obligate mutualistic relationship with plants, meaning they depend on plants for their growth and reproduction. According to some previous works, the effectiveness of AMF could be either positively influenced or regulated by the functional diversity of AM fungi between and within the species, soil type (Bender et al., 2016), and soil pH (Van Aarle et al., 2002) and amendments (Raghuwanshi and Upadhyay, 2004). As we all know arbuscular mycorrhizal symbiosis enhances crop yield A number of studies have been undertaken to support this assertion.

It has also been established that early season P supply is essential for maximising crop yields (Akinrinde and Okeleye 2005, Akinrinde, 2006). During the early stages of plant development, low levels of P reduce crop growth and this cannot be compensated for at later stages of the growing season (Grant et al., 2001). Goss and de Varennes (2002) and Alguacila et al. (2017) emphasized that early AMF colonization is beneficial for phosphorus uptake when the poorly developed roots of seedlings struggle to absorb phosphorus. Therefore, advantages associated with AMF appear to be limited to some growth phases only (Vyas and Bansal, 2023) including the initial stage of plant growth (Gange et al., 1993) and during the reproductive phase (Koide et al., 1994; Wilson and Hartnett, 1998). Some crops like the maize (*Zea mays*) for instance rely heavily on the AMF to satisfy their early P needs (Wenke, 2008). Cassava, for instance, receives a very high level of mycorrhizal dependency as far as nutrient acquisition is concerned (Okon et al., 2010). In most soils, cassava does not respond to high rates of P application because: First, P removal in the root harvest is very low (much lower than that of N and K); second, the fibrous roots of cassava become naturally infected by mycorrhizal fungi that are present in all natural soils (Howeler, 2001; Salami and Sangoyomi, 2013). Thus, the mutualism between cassava and mycorrhiza allows the crop to take up P even in the least P-reach soils. Cassava's ability to grow in high Al means the crop thrives in acid and low P soil conditions.

However, field evidence indicated that the role of AM fungi in P facilitation is not generalised as was postulated by laboratory experiments (Newsham et al., 1995; Bender et al., 2016). In some field studies, mycorrhizal colonisation has been established to enhance plant growth and survival, but there are several instances of none or even detrimental effects (McGonigle and Fitter 1988). Some of the previous studies have pointed out that the ability of VAM to enhance uptake processes or growth stimulation does not always have a good relationship to VAM infectivity (Clarke, 1981). Nevertheless, given this information, the functioning of arbuscular mycorrhiza in the field, specifically at the ecosystem level, has gained more attention (Brundrett, 1991). McGonigle and Fitter (1988) in a survey of 78 published field trials reported that with enhanced AMF colonisation, there was a rise in yield by an average of 37% percent in different crops. The other survey of 290 published field and greenhouse research showed that higher colonisation led to a 23% yield boost (Lekberg and Koide, 2005). In controlled conditions, the enhancement by mycorrhizal inoculation on plant growth may range from zero to 2600% in citrus and 1000% in cassava among others. In field conditions and non-fumigated soil, these responses are of smaller magnitude but can go up to 300% of the original size (Ortas, 2008). The level of their reaction is variable because it is determined by parameters that belong to the host plant (Jefwa et al., 2010), the environment, and the fungus (Nasim, 2005). Gai et al. (2006) and Munkvold et al. (2004) also revealed that although all the plants belong to the same AMF group, individual species and even isolates within a species vary in the ability to enhance the plant growth and nutritive status.e noted that VAM effectiveness in uptake processes or growth stimulation is not necessarily well correlated to VAM infectivity (Clarke and Mosse, 1981). Despite this information, the functioning of arbuscular mycorrhiza in the field, in particular at the ecosystem level, has received increasing attention (Brundrett, 1991). A survey of 78 published field trials found that increased AMF colonisation resulted in an average yield increase of 37% percent in various crops (McGonigle and Fitter, 1988). Another study of 290 published field and greenhouse studies determined that increased colonisation resulted in a 23% yield increase (Lekberg and Koide, 2005). Under controlled conditions, the beneficial effects of mycorrhizal inoculation upon plant growth can vary from zero to 2,600% in citrus and 1,000% in cassava, to cite a few examples. In field conditions and non-fumigated soil, these responses are of lesser magnitude but can reach 300% (Ortas, 2008). The magnitude of their response is unpredictable since it depends on factors inherent to the host plant (Jefwa et al., 2010), the environment, and the fungus itself (Nasim, 2005). Studies by Gai et al. (2006) and Munkvold et al. (2004) have shown that individual species of (AMF), and even fungal isolates in one species, differ in their ability to promote plant growth and nutritional status.

Arbuscular Mycorrhizal Fungi as influenced by the traditional cultural practices has not received as much understanding as its effects. For example, it is documented that high rates of fertilisation reduce the level of fungal colonisation by AM fungi, therefore, there must be an optimal level of such fungi and fertilisers that give the maximum benefit (Akinrinde, 2006).

Soil sieving acted particularly in decreasing the early AM hyphal colonisation frequency in maize and while significantly reduced, differences could still be observed up to 49 days (Goss and de Varennes, 2002). In addition, Hamed et al. (1980) pointed out that total microbial, actinomycetes, phosphate-dissolving bacteria, and fungal flora were not influenced by atrazine in the affected soil, but inhibited by its by-products when plants were at the early stage of growth. Hence the assessment of the efficiency and adaptability of AM fungi under different cultural practices and soil amendment as recommended for increasing or maintaining crop performance is relevant. The cropping system and arbuscular mycorrhizal fungi farming practices have been established to increase crop productivity. Furthermore, the report by Hamed et al. (1980) showed that total microbial flora, actinomycetes, phosphate-dissolving bacteria, and fungal flora, were not affected by atrazine, but were deleteriously reduced by its by-products at early stages of plant growth. Evaluating the efficiency and adaptability of AM fungi in various cultural practices and soil amendments is essential for enhancing or maintaining crop performance.

4. **Arbuscular Mycorrhizal Fungi in Diverse Crop Production Practices**

Arbuscular Mycorrhizal Fungi successfully adapt to a variety of cropping systems, from monocultures to diversified agroecosystems. Their presence is influenced by soil management practices. Arbuscular mycorrhizal fungi (AMF) play a critical role in organic and low-input agricultural systems, where the use of synthetic fertilizers and pesticides is minimal or absent (Wahab et al., 2023). In these systems, AMF are vital for maintaining soil fertility and plant health through natural processes (Wahab et al., 2023). Research indicates that crops grown organically often show higher AMF colonization compared to those under conventional methods, suggesting a stronger dependence on these symbiotic fungi for nutrient acquisition (Bhupenchandra et al., 2024). AMF act as essential biofertilizers in organic farming, helping to mobilize insoluble nutrients like phosphorus. Phosphorus can often be a limiting factor in organic production due to the lack of readily soluble synthetic fertilizers (Figiel et al., 2025). Using AMF alongside organic fertilizer substitutes can be an effective approach to reduce chemical fertilizer use, while maintaining crop yields and potentially even mitigating the emission of nitrous oxide, a potent greenhouse gas (Hassan et al., 2022). Furthermore, novel organic nutrient sources, such as poultry manure have been shown to promote AMF colonization and enhance the supply of crucial nutrients like phosphorus to plants, further highlighting the synergy between organic practices and AMF (Abdulsalam and Akinrinola, 2024; Bhupenchandra et al., 2024).

In conventional agriculture, where synthetic inputs are common, incorporating AMF can still offer significant advantages by boosting nutrient use efficiency and lowering the overall environmental impact of farming practices (Schaefer et al., 2021; Olowoake and Akinrinola, 2024). Research indicates that AMF can positively influence crop development even in soils with relatively high phosphorus levels, suggesting their benefits extend beyond improving nutrient uptake in deficient conditions (Kalamulla et al., 2022). Growing crops in soils with naturally lower fertility may optimize the expression of AMF's many beneficial effects in agroecosystems, potentially leading to a reduction in nutrient seepage into the environment (Kalamulla et al., 2022). Inoculating AMF in conventional systems has allowed for high crop yields with reduced fertilizer requirements and improved fertilizer utilization, pointing towards a path for more resource-efficient agriculture (Schaefer et al., 2021). By enhancing the plant's uptake of soil nutrients through their extensive mycelial networks, AMF can improve the efficiency with which applied fertilizers are used, minimizing waste and environmental pollution (Kuila et al., 2021; Olowoake and Akinrinola, 2024).

The effects of different arbuscular mycorrhizal fungi (AMF) spp. on plant growth and their impacts across diverse crop varieties are shown in Table 1. The table emphasizes AMF impacts on plant growth, nutrient uptake, stress tolerance, and their integration into various agricultural systems, The AMF inoculation significantly enhances plant growth by improving root development and nutrient absorption, leading to increased biomass across various crops. Higher yields in AMF-treated crops, such as maize or tomatoes, result from enhanced photosynthesis and resource allocation. These benefits vary by crop type and AMF species, with optimal pairings maximizing productivity.

Table 1: Effects of AMF on plant growth and yields of diverse crops

Crop	**AMF Species**	**Growth Impact**	**Yield Increase (%)**	**Critical Growth Stage**	**Reference**
Maize	*Rhizophagus irregularis*	Enhanced root biomass, improved shoot growth	10-30%	Vegetative, reproductive	Huang et al. (2024)
Wheat	*Funneliformis mosseae*	Increased tillering, higher grain weight	15-25%	Tillering, grain filling	Afzal & Ahmad (2023a)
Rice	*Glomus spp.*	Improved root architecture, enhanced biomass	10-20%	Vegetative, panicle initiation	Verma et al. (2022)
Soybean	*Rhizophagus intraradices*	Increased nodulation, enhanced pod set	20-35%	Nodulation, pod filling	Jie et al. (2022)
Tomato	*Glomus fasciculatum*	Improved fruit size, increased shoot biomass	15-40%	Flowering, fruit development	Alarcón-Zayas et al. (2024)
Potato	*Claroideoglomus etunicatum*	Enhanced tuber number, improved starch content	10-25%	Tuber initiation, bulking	Hijri & Bâ (2020)
Sorghum	*Gigaspora margarita*	Increased drought tolerance, improved grain yield	12-28%	Vegetative, grain filling	Bertoldo et al. (2020)

4.1. Cropping system and arbuscular mycorrhizal fungi

Farming practices have been developed to maximise crop production. They are more obvious in managing plants by directly intervening with soils, cultivars, and pests. But it is gradually becoming clear that while farming practices proclaim to regulate crops, they also surreptitiously regulate other elements of agroecological systems (Koide and Dickie, 2002; Priyadharsini and Muthukumar, 2015). This paper demonstrates that arbuscular mycorrhizal fungi are the key determinant of plant species richness and ecosystem stability and processes. Some of these studies demonstrate that AMF does change the distribution of plant species and plant species diversity (Grimme et al., 1987; Sanders and Koide 1994). Interplant transport of assimilates from the dominant canopy species through a common mycorrhizal network to subordinate plant species has been put forward as a mechanism by which AMF influences the floristic diversity of plant communities (Grimme et al., 1987). The second way through which AMF can alter plant community structure is through the variation in the growth response of the plant species to the colonisation by AMF, referred to as mycorrhizal dependence (Plenchette et al 1983; Habate and Manjunath 1991).

On the other hand, mycorrhizal plants that are already formed may act as sources of inoculum for species that are not mycorrhizal at first, which may influence regeneration and leads to species patchiness in the community (Koide and Dickie, 2002). Some workers observe that the AMF fungal communities naturally become less diverse when ecosystems are changed to agroecosystems, and as agricultural inputs intensify the AMF diversity decreases (Sieverding, 1991; Chalk et al., 2006). It is suggested that the species composition and diversity of AMF communities may influence plant population and plant community structure. The differences in the extent to which various plant species respond to AMF species have significant consequences for the growth of individual species of plants. Consequently, this will impact the options for a plant to share the environment with other plants in a community (Van der Heijden et al., 1998; Plenchette et al., 2005). Almost all crop plants are mycorrhizal, that is, they harbour fungi. However, cropping with nonhost plants reduces the quantities of AMF fungi in the soil. The non-host plants do not appear to inhibit mycorrhizal colonization. It has been documented that cropping systems play a role in modulating the impact of various types of AM fungi on the host-associated crop (Harrier and Watson, 2003). Nonhost plant cropping was shown in greenhouse trials by Daniell et al. (2001) to promote the colonisation of host plants.

In addition, the components of plant root exudates and the interactions between plants and microbes can also affect some species or classes of microbes in the total soil, consequently affecting other plants (Francis, and Read, 1995; Bender, et al., 2016). For instance, glucosinolates and isothiocyanates emitted by crops and weeds in the crucifer family (including brassica crops, wild mustards, and yellow rocket) suppress soil fungi including some pathogens (Haramoto and Gallandt, 2004). These plants are not directly toxic to mycorrhizae but do not encourage large numbers of active mycorrhizal fungi in the soil as do plants with a high mycorrhizal potential such as most legumes. Cassava root also benefits from AMF by enhancing nutrient uptake from mulching materials when inoculated with the appropriate species of fungi. In his study, Vaidya et al. (2008) showed that the AMF is highly positively affected by organic matter. The use of mulch on its own improves the physical, chemical, and biological properties of the soil. Thus, increasing root development, crop performance, and yield, according to Okon et al. (2010). The study conducted in Minnesota supported the hypothesis that crop monocultures select for AMF fungi that are inferior mutualistic; thus mycorrhizae may be involved in the rotation effect or yield decline in continuous monocultures (Berruti et al., 2016). Crops such as millet [*Pennisetum americanum* (L.) Leeke] and milo [*Sorgum bicolor* (L.) Moench] are successfully used to increase the propagule density of AMF fungi and improve the growth of tree seedlings in nurseries (France et al., 1985). Dodd et al. (1990) showed that cropping with cassava (*Manihot esculenta* Crantz) or sorghum significantly increased early season AMF development and yield of cowpea (*Vigna unguiculata* L.).

Inoculation with suitable arbuscular mycorrhizal fungi enhances the ability of cassava roots to absorb nutrients released by mulching materials. Vaidya et al. (2008) demonstrated a strong positive influence of organic matter on AMF proliferation. Mulch on its own has favourable effects on the physical, chemical, and biological properties of the soil, as well as enhanced root development, all of which lead to improved crop performance and yield (Camenzind et al., 2024). Okon et al. (2010) also revealed that AMF inoculation combined with mulch enhanced cassava tuber yield by 40–278% over the control in a degraded Alfisol of southwestern Nigeria.

Crop rotation, the practice of planting different crops in a planned sequence, can also influence the diversity and abundance of AMF in the soil (Shafiq et al., 2023). Plant species can have different impacts on the composition and activity of AMF communities in the rhizosphere (Shafiq et al., 2023). For example, certain preceding crops, such as tomato, have been shown to stimulate AMF colonization in subsequent crops like onion, suggesting that careful selection of crop sequences can enhance mycorrhizal benefits (Shafiq et al., 2023). Crop rotation increases the diversity of plant species over time, leading to a greater heterogeneity of available niches and substrate resources for soil fungi, including AMF, which can contribute to a more resilient and functional soil microbiome (Benami et al., 2020). Interestingly, even non-host crops like canola, which do not form mycorrhizal associations, have been found to maintain a diverse AMF community in the soil, even after long-term monoculture, raising questions about the survival mechanisms of AMF in the absence of a host and their potential impact on subsequent crops in the rotation (Aguilera et al., 2019; Masse et al., 2024).

4.2. Arbuscular Mycorrhizal fungi and soil nutrient availability

The symbiotic relationship involving Arbuscular Mycorrhizal Fungi has three main components: the soil, the fungus, and the host plant (Fall et al., 2022). Within the plant root, the fungal component exists, while its mycelium extends into the surrounding soil. This underground fungal network can become quite extensive under certain conditions, yet it doesn't develop any vegetative organs of its own (Smith et al., 1997; Hagh-Doust et al., 2022). Its primary role is to efficiently acquire resources from the soil. Mycorrhizal roots are more effective at nutrient uptake and transport from the soil compared to non-mycorrhizal roots (Mazzola et al., 2007; Priyadharsini and Muthukumar, 2015; Akinrinola et al., 2025). This enhanced absorption of various nutrients contributes to improved soil fertility (Priyadharsini and Muthukumar, 2015). For instance, when *Medicago sativa* (alfalfa) was inoculated with *Glomus mosseae* (now often referred to as *Funnelliformis mosseae*), it not only influenced plant growth and nutrition but also boosted the activity of *Rhizobium meliloti* (Wang et al., 2020).

Under conditions of water stress, mycorrhizal associations can also positively impact the uptake of more mobile nutrients, such as nitrate (NO^{3-}) (Chandrasekaran, 2022). For legume plants, the significance of AMF symbiosis is well-documented due to the high phosphorus (P) demand associated with nodulation and N2 fixation, processes that require substantial P acquisition (Douds et al., 2008; Shi et al., 2021). Improved P nutrition has been observed to be particularly beneficial in the infertile and P-fixing soils prevalent in tropical regions (Dodd, 2000). Mycorrhizal fungi can also enhance the absorption of nitrogen (N) from ammonium (NH^{4+} -N) mineral fertilizers, transporting it to the host plant (Liu et al., 2002; Abdel-Fattah et al., 2016). Beyond P and N, AMF facilitate the uptake of other essential macronutrients like potassium (K), calcium (Ca), and magnesium (Mg) (Akinrinola and Fagbola, 2021), as well as micronutrients such as copper (Cu), aluminum (Al), zinc (Zn), nickel (Ni), iron (Fe), and cadmium (Cd). This improved nutrient acquisition is especially noticeable in P-deficient soils. In situations where P availability is limited, AMF inoculation has been shown to significantly enhance nutrient uptake and increase plant dry biomass (de Oliveira et al., 2024). However, many crops, especially cereals, tend to form arbuscular mycorrhizas only sparingly. This could be due to breeding programs that have selected for traits unfavorable to this symbiosis, combined with factors like disturbed (ploughed) soils and high existing nutrient levels in the soil, which might reduce the plant's reliance on mycorrhizae for nutrient acquisition (Mazzola et al., 2007; Priyadharsini and Muthukumar, 2015; Akinrinola et al., 2025).

The The contribution of AMF to nutrient uptake varies with crops (Table 2). The AMF inoculation greatly improve nutrient uptake, particularly phosphorus, by extending root systems through hyphal networks. This enhanced uptake supports better plant nutrition, reducing the need for external fertilizers. Variations in nutrient uptake efficiency depend on AMF species and soil conditions.

Table 2: AMF Contributions to Nutrient Uptake

Nutrient	AMF Mechanism	Impact on Plant	Crop Example	Reference
Phosphorus (P)	Extended hyphal network, enhanced P solubilization	Up to 80% of plant P uptake via AMF	Maize, Soybean	Peng et al. (2025)
Nitrogen (N)	Improved N fixation, hyphal N transport	Increased N content by 15-30%	Legumes, Wheat	Afzal & Ahmad (2023b)
Micronutrients (Zn, Fe)	Enhanced solubilization and uptake via hyphae	Increased Zn/Fe content by 10-25%	Rice, Tomato	Chandrasekaran et al. (2021)
Potassium (K)	Improved K acquisition through extraradical mycelium	Enhanced K uptake, improved water regulation	Potato, Sorghum	Chandrasekaran (2020)

4.3. Influence of phosphorus fertiliser on AM fungi

Fundamentally, many crop plants especially cereals form arbuscular mycorrhizas reluctantly, probably because they have been bred under conditions inimical to the symbiosis (ploughed soils, high nutrient levels). Mycorrhizal benefits high-yield crop plants only if those plants utilize the acquired resources for agriculturally useful parts afterward.. for example, grain (Kabir and Koide, 2000; Bereau et al., 2005). Most of the root system reactions, for example, growth in response to locally available nutrients, can be explained as making adaptive sense under competition (Hodge et al., 1999; Wright, 2005) but not in an agricultural monoculture where there is no increase in yield (Weiner et al., 2010). It can thus be concluded that there is potential in reducing root growth in crop plants. The other model is no or low tillage agriculture. From the long-term experiment at Frick (Switzerland), Berner et al. (2008) observed that soil organic matter and crop yields were higher in reduced tillage treatments and that crop yields were higher in terms of biomass and tissue N and P concentrations as reported by Lee and George (2005) and Krauss et al. (2010). Although AM colonisation of roots did not increase in this case, the increased uptake of N and P is suggestive of a mycorrhizal role (Bi et al., 2003; Akinrinola et al., 2023).

St. John (2000) pointed out that applying fertiliser has no beneficial effects on the growth of beneficial bacteria. Nasim (2005) revealed that fertilisers hinder mycorrhizal formation. It has been observed that mycorrhizal colonisation is suppressed by fertilisers (Kahiluoto et al., 2001; Ibrahim et al., 2022). In mycorrhizal fungi, it is well noted that the colonisation by the fungi is significantly affected by the level of P in the soil (Plenchette et al., 2015). Moreover, a very high or very low P level has been described to decrease mycorrhizal infection/colonisation (Lekberg and Koide, 2005). When phosphate fertiliser is applied, colonisation is also retarded and the percentage of root colonisation is reduced (Rengel and Marschner, 2005; Akinrinola et al., 2023). Moreover, the elevation in the level of soil phosphate decreases the chlamydospore formation by the fungus (Liu et al., 2002). These spores are benign in root colonisation and dispersion of the fungus in the soil profile.

Yang et al. (2014) suggested that with the increased level of soil P which is more than that needed for plant growth, the arbusicles of vesicular-arbuscular (VA) types of mycorrhizae did not develop. On the contrary Cavender et al. (2003) and Stark et al. (2007) observed that nutrients available in the organic-based fertiliser enhanced microbial growth and fungal AM colonization. Effect of Atrazine on the Activities of AMF It is known that broad-spectrum pesticides are very toxic to AM under optimum soil moisture and temperature conditions (O'Connor et al., 2002). However, Cavender et al. (2003) and Stark et al. (2007) have shown that nutrients present in organic-based fertiliser stimulated microbial activity and fungal AM colonisation.

The AMF enhance plant resilience to environmental stresses like drought by improving water and nutrient retention is summerized in Table 3. Inoculated plants show higher survival rates and better physiological responses, such as increased antioxidant activity. These effects are more pronounced under specific stress conditions and with certain AMF-crop combinations.

Table 3: AMF Effects on Stress Tolerance

Stress Type	AMF Mechanism	Plant Response	Crop Example	Reference
Drought	Enhanced water uptake, improved root hydraulic conductivity	Reduced wilting, sustained photosynthesis	Sorghum, Maize	Kamali & Mehraban (2020)
Salinity	Ion homeostasis, reduced Na+ uptake	Improved growth under high salinity (up to 30% better)	Tomato, Rice	Chandrasekaran et al. (2021)
Heavy Metal Stress	Metal immobilization, reduced uptake	Decreased metal toxicity, improved biomass	Soybean, Wheat	AbdElgawad et al. (2022)
Pathogen Resistance	Induced systemic resistance, enhanced defense compounds	Reduced disease incidence (e.g., Fusarium wilt)	Tomato, Potato	Badrbani et al. (2024)

4.4. Synergistic Interactions of AMF with Other Beneficial Microbes

Arbuscular mycorrhizal fungi often engage in synergistic interactions with other beneficial soil microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), to amplify their positive effects on plant growth (Olanrewaju and Babalola, 2022). Co-inoculating plants with both arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) has been shown to significantly boost plant growth and yield in various crops, more effectively than using either group of microbes alone (Olanrewaju and Babalola, 2022; Akinpelu et al., 2019; Akinrinola and Fagbola, 2021)). Plant Growth-Promoting Rhizobacteria (PGPR) play a significant role in helping Arbuscular Mycorrhizal Fungi (AMF) colonize plant roots. They achieve this by releasing compounds such as indole-3-acetic acid (IAA), which encourages root growth and expands the surface area where AMF can attach (Sagar et al., 2021). Additionally, certain PGPR, including *Pseudomonas* species, can solubilize phosphate in the soil, making it more readily available for both plants and AMF. This process supports better nutrient uptake and increases stress tolerance (Sagar et al., 2021). When AMF and PGPR are used together as inoculants, they can optimize the structure and function of the rhizosphere's microbial community, creating a more favorable environment for plant growth and overall health (Olanrewaju and Babalola, 2022).

The mechanisms behind these cooperative relationships are complex. PGPR contribute to plant growth by improving nutrient availability, producing beneficial plant hormones, protecting against diseases, and boosting resilience to various environmental stresses (Olanrewaju and Babalola, 2022; Akinrinola and Fagbola, 2021). These actions complement the well-known advantages provided by AMF, primarily recognized for their role in enhancing phosphorus and water uptake. The rhizosphere, which is the soil area directly influenced by plant roots, is a complex environment where intricate interactions among different microbial groups can significantly affect plant health and productivity (Olanrewaju and Babalola, 2022). Understanding and leveraging these synergistic relationships offer substantial potential for developing more effective and sustainable agricultural practices (Trivedi et al., 2021). The strong evidence of synergistic interactions between AMF and PGPR indicates that a comprehensive approach to managing the soil microbiome, involving various types of beneficial microbes, could be more effective than relying solely on AMF. This paves the way for creating more complex and powerful bioinoculants (Zhang et al., 2024). The observation that PGPR can enhance AMF colonization highlights the intricate network of interactions within the rhizosphere. Grasping these microbial interactions is vital for developing effective strategies to promote the establishment and proper functioning of beneficial symbioses in agricultural systems.

4.5. Soil Tillage on AMF Activities

Different tillage systems employed in crop production can have a significant impact on AMF communities and their function within the soil (Tatewaki et al., 2023). Tillage practices, which involve the mechanical disturbance of the soil, can directly affect the delicate hyphal networks of AMF and the overall structure of the soil environment they inhabit (Bowles et al., 2017; Tatewaki et al., 2023). Reduced tillage or no-tillage systems, which minimize soil disturbance, have generally been found to support increased AMF colonization and diversity compared to conventional tillage methods that involve more intensive soil manipulation (Bowles et al., 2017). Conventional tillage can lead to a decrease in AM fungal diversity, potentially disrupting the ecological balance within the soil (Li et al., 2024). AMF species that rely primarily on their extraradical mycelium to colonize the roots of newly sown plants may be particularly favored in no-till systems, where the soil structure remains relatively undisturbed (Li et al., 2024). While full tillage may sometimes result in higher yields for certain crops like sweet corn, AMF inoculation has been shown to enhance the nutrient concentrations within the harvested kernels regardless of the tillage practice employed, suggesting that the benefits of AMF can be realized across different soil management approaches (Bowles et al., 2017).

The consistent finding that reduced tillage enhances AMF populations underscores the importance of minimizing soil disturbance for maintaining a healthy and functional mycorrhizal community. Tillage disrupts the hyphal networks, hindering colonization and nutrient transport. The complex interaction between fertilization and AMF indicates that nutrient management requires careful consideration to maximize AMF benefits. High inorganic phosphorus can suppress colonization, while organic fertilizers may promote it (Akinrinola et al., 2022). The observation that even non-mycorrhizal crops can maintain AMF populations suggests a broader ecological role beyond plant symbiosis, potentially impacting future crop rotations and soil health management.

4.6 Weed control methods and mycorrhizal activity

Weed control methods and mycorrhizal activity represent two significant areas of research in sustainable agriculture. Effective weed management is crucial for crop productivity, while mycorrhizal fungi play a vital role in nutrient uptake and overall plant health. Understanding the interactions between these two factors is essential for developing integrated and environmentally sound agricultural practices.

Various weed control methods are employed in agriculture, broadly categorized as preventive, cultural, mechanical, biological, and chemical (Chauhan, 2020). Preventive measures focus on preventing weed introduction and spread, while cultural practices involve optimizing growing conditions to favor crops over weeds (Akinrinola and Fagbola, 2020). Mechanical methods include tillage and hand weeding, offering non-chemical options but often requiring significant labor and potentially impacting soil structure. Biological control utilizes natural enemies of weeds, such as insects or pathogens, offering a more sustainable approach in specific contexts (Hatcher and Melander, 2003). Chemical herbicides provide effective and often cost-efficient weed control but raise concerns about environmental impacts and the development of herbicide-resistant weeds (Duke, 2018; Alamu et al., 2025).

Mycorrhizal fungi form symbiotic associations with the roots of most terrestrial plants, enhancing nutrient acquisition, particularly phosphorus and nitrogen, through their extensive hyphal networks (Smith and Read, 2008). These fungi can also improve plant tolerance to drought, salinity, and heavy metals, and contribute to soil aggregation and disease suppression (Berruti et al., 2016). The establishment and function of mycorrhizal associations can be influenced by various factors, including soil properties, plant species, and agricultural management practices.

The interaction between weed control methods and mycorrhizal activity is a complex and increasingly studied area. Some weed control practices can negatively impact mycorrhizal colonization and function. For instance, intensive tillage can disrupt hyphal networks, while certain herbicides may have direct toxic effects on mycorrhizal fungi (Säle et al., 2015; Akinrinola and Fagbola, 2021; Akinrinola, 2023). Conversely, conservation tillage and reduced herbicide use can promote mycorrhizal abundance and diversity (Ryan et al., 2019). Furthermore, weeds can sometimes influence the mycorrhizal colonization of crops, either positively or negatively, depending on the weed species and the specific mycorrhizal fungi involved (Li et al., 2022).

Research is ongoing to explore strategies that integrate effective weed management with the promotion of beneficial mycorrhizal associations. This includes investigating the use of cover crops and intercropping systems that can suppress weeds and enhance mycorrhizal colonization (Trinchera et al., 2019; Akinrinola and Fagbola, 2021; Akinrinola, 2023), as well as the selection of herbicide-tolerant crops that maintain mycorrhizal symbiosis (Vyas and Bansal, 2023). Understanding these intricate relationships is crucial for developing sustainable agricultural systems that optimize crop production while minimizing environmental impact.

Table 4 summerized AMF adaptation to diverse farming practices, with higher colonization rates in organic systems due to lower chemical inputs. They contribute to sustainable agriculture by reducing fertilizer dependency and enhancing soil structure. The effectiveness of AMF varies with farming practices, with organic systems often showing greater benefits.

Table 4: AMF Adaptation in Diverse Crop Production Practices

Production Practice	**AMF Integration Strategy**	**Benefits**	**Challenges**	**Reference**
Organic Farming	Inoculation with native AMF, cover cropping	Enhanced soil fertility, reduced chemical inputs	Inoculum availability, variable colonization	Park et al. (2024)
Conservation Agriculture	Reduced tillage, AMF-compatible crop rotations	Improved soil structure, sustained AMF populations	Slow AMF establishment in disturbed soils	Mhlanga et al. (2022)
Intercropping	AMF inoculation in legume-cereal systems	Enhanced nutrient sharing, increased system yield	Crop-specific AMF compatibility	Wang et al. (2025)
Greenhouse Systems	Controlled AMF application via substrates	Improved seedling vigor, higher marketable yield	High cost of inoculum, need for sterile substrates	Berdeja et al. (2025)
Agroforestry	AMF integration with tree-crop systems	Enhanced nutrient cycling, improved soil health	Complex system dynamics, long-term establishment	Steinfeld et al. (2023)

4.6.1. Influence of Atrazine on AMF Activities

Broad spectrum pesticides are reported to be very toxic to AM under ideal soil moisture and temperature conditions (O'Connor et al., 2002; Akinpelu et al., 2019). Nelson and Khan (1992) findings demonstrate hyphae of VAM fungi are able to remove atrazine from soil and transfer it to plants. However, work with some *Glomus spp*. tolerant to herbicides has provided evidence for their rapid adaptation to herbicide application in soils (Gonzalez-Chavez et al., 2002). Inoculation with *Funnelliformis mosseae and Sinorhizobium medicae* not only affected plant growth and nutrition in *Medicago sativa*, but also enhanced the activity of Rhizobium meliloti when it was applied as an inoculant (Wang et al., 2020).

In *Cynara cardunculus* nursery, mycorrhyzal fungi survived pesticide employed and enhanced wild carrdoon plant productivity (Marin et al., 2002). A report by Nasim (2005) showed that recommended rates of insecticides and nematicides generally do not inhibit AM fungi. The rate of herbicide application is an important factor mediating on mycorrhizae. By their nature, herbicides are designed to antagonise plants and not fungi: thus, no adverse effects of herbicides on AM fungi have been reported (O'Connor et al., 2002). For instance, while using the phenylurea herbicides at standard rates of application, the sporulation and root colonisation are not negatively affected by diuron and chlorotoluron (Dodd, 2000; Cavender et al., 2003). High ERs of diuron, on the other hand, resulted in an increase in the soil densities of AMF spores (Smith et al., 2004). However, the contrary is the case in carbamate herbicides like chlorpropham and sulphallates which at low application rates did not reduce root colonisation of alfalfa (*Medicago sativa* L.) (O'Connor et al., 2002).

The impact of the herbicide atrazine on the bacteria of the rhizosphere of the broad bean plant was investigated. Atrazine application had a negative effect on the densities and percent colonisation of fungi. It was found that the fungi were not sensitive to atrazine itself but were affected by the by-products of atrazine. Total microbial count, actinomycetes, phosphate-dissolving bacteria, and fungal flora were not influenced by atrazine but were significantly reduced by atrazine metabolites during the early stages of plant growth. However, rhizosphere flora reached normal levels after the disappearance of atrazine by-products in soil (for 1 month after application) except for actinomycetes. Thus, atrazine is advised to be used 20 days before sowing for weed suppression and for obtaining good fungi sporulation (O'Connor et al., 2002).

5. Conclusion

This review underscores the critical and multifaceted role of Arbuscular Mycorrhizal Fungi (AMF) in enhancing plant growth, nutrient acquisition, and resilience across diverse agricultural systems. From their fundamental biological characteristics and the mechanisms of symbiosis to their significant implications for sustainable crop production, AMFs consistently emerge as vital components of a healthy and productive agroecosystem. While the benefits of AMF, particularly in nutrient uptake and stress tolerance, are well-established, their effectiveness is highly modulated by various agricultural practices, including tillage, fertilizer application regimes, herbicide application, and cropping systems. A deeper understanding of the intricate interactions between different AMF species, various crop types, and the diverse environmental factors that modulate their effectiveness is still needed. Exploring the potential of co-inoculation with AMF and other beneficial microbes like PGPR could lead to more robust and effective bioinoculants. Understanding these interactions is paramount for harnessing the full potential of AMF. By adopting practices that foster robust and diverse AMF communities, such as reduced tillage, judicious fertilizer use, strategic crop rotations, and integrated weed management, we can enhance nutrient use efficiency, reduce reliance on external inputs, improve plant health, and ultimately contribute to more sustainable and resilient agricultural landscapes capable of meeting future food demands. Continued research is essential to further unravel the complexities of AMF-plant-soil interactions and to develop targeted strategies for optimizing AMF functionality in specific cropping systems and environmental contexts.

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