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THE IMPACT OF ARBUSCULAR MYCORRHIZAL FUNGAL INOCULANTS ON GROWTH, NUTRIENTS, AND YIELD OF VEGETABLE PLANTS: A REVIEW

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ABSTRACT
Arbuscular mycorrhizal fungi (AMF), belonging to the phylum *Glomeromycota*, establish symbiotic associations with plant roots, enhancing nutrient uptake through extensive hyphal networks. These networks facilitate the acquisition of essential nutrients, particularly phosphorus, while the host plants supply the fungi with photosynthates. This review examines the impact of AMF inoculation on onion, tomato, cucumber, and pepper. The findings highlight the numerous benefits conferred by AMF symbiosis, which includes significant enhancements in plant growth and development. AMF inoculation has been shown to improve photosynthetic efficiency, increase plant height, leaf area, root length, and both fresh and dry biomass, as well as boost fruit yield in terms of number, size, and weight. Furthermore, AMF contribute to improved nutrient and water absorption by extending their hyphae into deeper soil layers, thereby enhancing resource availability for plants. Additionally, AMF inoculation plays a crucial role in mitigating biotic and abiotic stresses in vegetable crops while also improving soil stability by reducing leaching and erosion.

Keywords: Arbuscular mycorrhizal fungi (AMF), Photosynthates, Inoculants, Mycelium, Symbiosis

INTRODUCTION

Arbuscular mycorrhizal fungi (AMF), classified within the phylum *Glomeromycota,* are soil borne fungi that establish symbiotic relations with plant roots, thereby enhancing nutrient uptake, which is facilitated through extensive hyphal networks that enable host plants to access nutrients, particularly phosphorus (Smith and Read, 2008; Nzanza *et al.*, 2012; Ilyas *et al.,* 2024), while the host plants reciprocally provide the arbuscular mycorrhizal fungi with photosynthates, predominantly comprising of sugars and lipids (Gutjahr *et al.,* 2015; Martin and and van der Heijden 2024). The roles attributed to arbuscular mycorrhizal fungi encompass enhanced growth and nutrient acquisition of host plants (Barber *et al.,* 2013; Chen *et al.,* 2021; Wang *et al.,* 2022), increased tolerance of host plants to salinity (Soussa *et al.,* 2024; Evelin *et al.,* 2019), improved drought resilience (Daei *et al.,* 2009; Bagheri *et al.,* 2019; Alhinani *et al.*, 2024), protection of hosts against pathogens (Sery *et al.,* 2016; Chen *et al.,* 2017; Tchabi *et al.,* 2022), increased disease resistance (Jung *et al.,* 2012; Song *et al.,* 2015; Chosaly *et al.,* 2019), and enhanced competitiveness over non-mycorrhizal flora (Cameron, 2010; Moreb *et al.,* 2020; Urbano *et al.,* 2023). Another critical ecological service rendered by arbuscular mycorrhizal fungi involves the beneficial modification of soil structure (Ahammed and Hajiboland, 2024; Bender *et al.,* 2015). The intricate hyphal network of arbuscular mycorrhizal fungi mycelium establishes a three-dimensional matrix that interlocks and intertwines soil particles without leading to soil compaction, thus fostering positive impacts on plant development and root system architecture (Gutjahr and Paszkowski, 2013). Although arbuscular mycorrhizal fungi are obligate symbionts, they are not host-specific; a single species may associate with multiple plant species within the same ecological niche (Rao *et al.,* 2000; Masebo *et al.,* 2023), and conversely, one host plant can nurture diverse populations of arbuscular mycorrhizal fungal species (Khade and Rodrigues, 2009; Yakasai and Rabiu, 2023). Arbuscular mycorrhizal fungi are capable of forming symbiotic relationships with more than 80% of all vascular terrestrial plants including majority of field crops (Belay *et al.,* 2015; Begum *et al.,* 2019).

It has already been documented that excessive application of chemical fertilizers and pesticides adversely impacts the physical and chemical characteristics of soils, which in turn affects the productivity and appropriateness of soil for various crops (Wang *et al.,* 2022; Raj *et al.,* 2023). A good approach to augment vegetable production while, concurrently enhancing and preserving soil quality is the employment of soil microorganisms such as AMF that can serve as bio-fertilizers to elevate both crops quality and environmental health. The symbiotic interaction between these fungi and plant roots is of paramount importance and has the potential to diminish crop reliance on synthetic fertilizers (Begum *et al.,* 2019). Arbuscular mycorrhizal fungi can establish symbiosis with the majority of vegetable crops, including prominent species from various families such as *Amaryllidaceae* (onion), *Apiaceae* (carrot), *Asteraceae* (lettuce), *Cucurbitaceae* (cucumber), *Fabaceae* (bean), and *Solanaceae* (tomato) (Baum *et al.,* 2015). The benefits of artificially inoculating a diverse range of vegetable plant species with arbuscular mycorrhizal fungi have been substantiated in numerous scholarly investigations (Chen *et al.,* 2018; Golubkina *et al.,* 2020; Felfoldi *et al.,* 2022; Ilyas *et al* 2024). Arbuscular mycorrhizal fungal inoculants have become a topic of significant interest due to their potential to enhance plant growth and development. The utilization of AMF as a biofertilizer in agricultural practice is advocated with the objective of enhancing productivity and minimizing reliance on chemical fertilizers. Most plants growing naturally under field conditions are colonized to some extent by AMF, however, it is unclear whether the natural levels of AMF colonization are sufficient to optimize plant survival and growth. Thus inoculation of seedlings before or at the time of transplanting with AMF inoculants can be beneficial for plants growth as well as sustainability of the environment (Chen *et al.,* 2020; Shafiq *et al.,* 2023; Ahammed and Hajiboland 2024). The responses of host plants to mycorrhizal inoculation vary greatly with the species of AMF used, the source and viability of the fungal inoculum, the host plants, and environmental conditions (Jamiolkwaska *et al.,* 2020; Chafai *et al.,* 2023). The aim of the present study is to review literature on the positive impact of AMF inoculation on vegetable plants specifically onion, tomato, cucumber and pepper, as they are the most widely used vegetable crops worldwide.

Impact of AMF Inoculation on Onion Plants

Onion (*Allium cepa*) is recognized as one of the most ancient and extensively cultivated vegetables globally (Kavitha and Reddy, 2018). This vegetable possesses numerous nutritional and medicinal properties, serving as a significant source of phosphorus, calcium, vitamin C, protein, and carbohydrates (Barakade *et al*., 2011). Onion plants exhibit a pronounced mycorrhizal association due to their relatively sparse root system, which lacks root hairs, thereby rendering the crop reliant on arbuscular mycorrhizal fungi for effective water and nutrient acquisition (Mollavali *et al.,* 2017; Iliyas *et al.,* 2024). The symbiotic relationship with AMF enhances the uptake of essential nutrients such as phosphorus, nitrogen, and copper, while also potentially ameliorating plant tolerance to various environmental stresses (Baum *et al.,* 2015). Aliasgharzad *et al*. (2009) demonstrated that AMF inoculation significantly augmented the absorption of phosphorus and potassium in onions subjected to drought stress when contrasted with uninoculated controls. Furthermore, Tawaraya *et al.* (2012) recognized the critical role of AMF inoculation in improving phosphorus assimilation in Welsh onions by solubilizing inorganic phosphorus present in the soil, leading to increased phosphorus uptake and concentration within plant tissues. Additional research indicated that the inoculation of onion plants with native AMF inoculants positively influenced early growth and nutrient assimilation (Albrechtova *et al.,* 2012; Abdullahi and Sheriff, 2013). In another investigations, the application of *Glomus intraradices* to onion plants markedly enhanced bulb weight and overall biomass (Reininger & Sieber, 2013).

In a related context, Bettoni *et al.* (2014) found that the application of AMF to onion seedlings resulted in heightened levels of proteins, proline, and soluble sugars within onion leaves, thereby improving the resilience of the plants to environmental stressors and aiding in their growth. In another study, AMF inoculation led to an 11% increase in the total carbohydrate content of onions compared to controls, while a 6% enhancement in total sugar content was observed due to the combined application of sodium selenate and AMF (Golubkina *et al.,* 2020). Other studies have illustrated that the conjunction of AMF inoculation with phosphorus fertilization can significantly augment both fresh and dry weights of onion plants, as well as enhance chlorophyll content and phosphorus concentrations in the roots, shoots, and bulbs (El-Sherbeny *et al.,* 2021). The underlying mechanism for these enhancements is primarily ascribed to the fungi's capability to extend the root system through their hyphal networks, thereby broadening the soil volume available for nutrient and water exploration (Begum *et al.,* 2019; Golubkina *et al.,* 2020). Shafiq *et al.* (2023) also documented a significant promotion of plant growth (15–30%) and root parameters (50%) in onion plants inoculated with AMF relative to controls. Besides fostering growth and nutrient uptake, AMF inoculation has been associated with improved biochemical characteristics in onion plants. Specifically, AMF can stimulate the biosynthesis of flavonoids and other antioxidants, which are crucial for plant health and may provide additional health benefits upon consumption (Mollavali *et al.,* 2017; Golubkina *et al.,* 2020). The increase in nutrient content of the inoculated plants may also be attributed by the ability of the Mycorrhizal hyphae to increased water uptake, which hastens the flow of these nutrients through the plant roots colonized by AMF (Wang *et al.,* 2022).

The role of AMF in disease suppression is another critical aspect of their application in onion cultivation. In terms of disease resistance, AMF inoculation has been shown to improve onion plants' resilience against *Sclerotium cepivorum*, the causative agent of white rot (Leta & Selvaraj, 2012). Another research indicated that AMF can help mitigate the effects of soil-borne pathogens *Fusarium oxysporum*, which is known to cause wilt disease in onions (Salamiah *et al.,* 2019). By enhancing the plant's immune response and competing with pathogens for resources, AMF can significantly reduce disease incidence, leading to healthier crops and higher yields (Wag *et al.,* 2022). In another research AMF inoculation has been well documented to increased onion plants tolerance to salinity and water stress (Bolandnazar, 2009). Ercoli *et al.,* (2017) also reported the importance of AMF inoculation in enhancing onion plants resistance to drought and salinity. AMF also interact synergistically with other soil microorganisms, as research indicates that co-inoculation of AMF with other plant growth-promoting rhizobacteria (PGPR), further enhances the establishment of AMF and improve plant growth responses (Pokluda *et al.,* 2023; Nanjundappa *et al.,* 2019). Thus AMF inoculation is a promising strategy for improving onion cultivation, particularly in low-input and sustainable agricultural systems.

Impact of AMF Inoculation on Tomato Plants

Tomato (*Solanum lycopersicum*) represents a crucial role for human dietary requirements and holds significant economic importance, ranking among the foremost vegetables globally, with an annual production of approximately 182.3 million tons cultivated over an area of 4.85 million hectares (FAO, 2019). Tomato consumption delivers an outstanding fusion of beneficial nutrients, encompassing essential minerals, vitamins, flavonoids, and antioxidants like lycopene,beta-carotene, and lutein. In the cultivation of tomatoes, arbuscular mycorrhizal fungi (AMF) are extensively employed to augment plant growth, enhance overall health, and increase yield (Oseni *et al.,* 2010). Poulton *et al.* (2002) documented that the inoculation of tomato plants with *Rhizophagus intraradices* AMF resulted in elevated phosphorus levels, surpassing those of non-inoculated plants. In a separate investigation, AMF inoculation conducted under field conditions was found to induce a higher relative water content (RWC) in leaves, regardless of varying drought stress scenarios in mycorrhizal-inoculated tomato plants (Subramanian *et al.,* 2006). The inoculation of *Rhizophagus etunicatum* AMF in phosphorus-enriched environments led to an expansion of leaf surface area prior to flowering and an increase in total flower production per plant (Conversa *et al.,* 2013), while Douds *et al.* (2016) reported a notable enhancement in shoot growth and yield as a result of AMF inoculation in tomato plants. Furthermore, Bowles *et al.* (2016) indicated a significant increase in yield (+25%) and leaf nitrogen and phosphorus uptake (+22% and +26%, respectively) in tomato plants that received inoculation. Similarly, tomato plants inoculated at the nursery stage with *Rhizophagus intraradices* AMF exhibited improved growth and yield, along with increased nitrogen and phosphorus uptake in both shoots and roots. Additionally, AMF inoculation enhanced the nutritional quality of the fruits by elevating the levels of citric acid, carotenoids, and antioxidant capacity (Bona *et al.,* 2017). In a distinct study conducted by

Chafai *et al.* (2023), AMF inoculation resulted in significantly increased concentrations of Calcium (Ca), Potassium (K), Iron (Fe), Zinc (Zn), and Phosphorus (P) in tomato plants, when compared to control specimens, which was attributed to the increased mycorrhizal colonization of the roots. The increase in nutrients concentration may be attributed to AMF's ability to enhance plants to expand their roots and eventually reach poorly available nutrients like phosphate, nitrogen, potassium and microelements, as well as water (Bolandnazar 2009, Begum *et al.,* 2019; Samri *et al.,* 2021). Phosphorus is relatively immobile in the soil because the element forms insoluble complexes with abundant cations such iron (Fe), aluminum (Al), and calcium (Ca) (Fitter *et al.,* 2011; Rhouphael *et al.,* 2015), and because of slow diffusion of P in the soil, a zone of depletion develops rapidly around plant roots and AMF form an extensive hyphal network that substantially increases the surface area to absorb and transport P into the roots (Knerr *et al.,* 2019). The phosphorus in the soil is taken up via a phosphate transporter located in the extra-radical hyphae of the fungus (Harrison and Van Buuren, 1995).

Arcidiacono *et al.* (2023) also reported a substantial increase in biomass, growth, yield, photosynthetic pigments, antioxidant enzyme activity, and mineral content of tomato plants when compared with un-inoculated controls under drought stress conditions. The symbiotic relationship between the host plant and AMF significantly bolstered resistance to drought stress by enhancing water uptake, improving water use efficiency, and modifying root morphology (Felfoldi *et al.,* 2022). Moreover, AMF symbiosis modulates hormone levels and diminishes the generation of reactive oxygen species, thereby reducing the adverse effects of drought stress (Begum *et al.,* 2019). Additionally, research conducted by Soussa *et al.* (2024) indicated that the combination of AMF and biochar inoculation resulted in improved growth and yield of tomato plants under conditions of heat and salinity stress, further enhancing the plant's defense mechanisms, as evidenced by the accumulation of proline, ascorbate, and glutathione.

In addition to improving nutrient and water uptake, AMF inoculation has been shown to enhance the resistance of tomato plants to various biotic stresses, including pathogens and pests. Research indicates that mycorrhizal colonization can prime the defense mechanisms of tomato plants, leading to increased expression of defense-related genes upon pathogen attack (Nzanza *et al.,* 2012; Song *et al.,* 2015). Study by Jamiołkowska *et a*l. (2020) showed no significant effect of AMF (*Claroideoglomus etunicatum and Rhizophagus intraradices*) on the total and marketable yield of tomato, but rather observed the effect of the AMF on reducing the number of diseased fruits, thus the ability of AMF to improve plant health and resilience against diseases can lead to higher yields and better-quality fruits.

Impact of AMF Inoculation on Cucumber plants

Cucumber (*Cucumus sativus*) is an annual vegetable crop that also forms the arbuscular mycorrhizal symbiosis (Chen *et al.,* 2017) Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with the root systems of cucumber plants, significantly augmenting their capacity for nutrient absorption, particularly with respect to phosphorus, which is frequently in short supply in agricultural soils. This symbiotic relationship not only facilitates enhanced plant growth but also leads to improved yields and superior fruit quality. Wang *et al.* (2003) reported that cucumber seedlings treated with AMF inoculation showed increased growth potential in contrast to non-inoculated seedlings, with the inoculated variety indicating a marked improvement in cucumber yield. In a subsequent study, Wang *et al.* (2008) corroborated the beneficial effects of *G. mosseae* AMF on the growth of cucumber seedlings, while noting that *G. versiforme* exhibited an adverse impact; these findings suggest that the response of a particular plant species to AMF is highly contingent upon the specific species of AMF involved. Ortas (2010) also documented significant enhancements in cucumber seedling survival rates, fruit yields, and the concentrations of phosphorus and zinc in shoots following inoculation with *Glomus* species. Prior investigations similarly indicated that AMF inoculation improves stress resistance and fortifies the nutrient uptake capabilities of cucumber plants (Han *et al.,* 2012). In a separate analysis conducted by Barber *et al.* (2013), increase in yield, nutrient levels, and the visitation of pollinating insects were noted in cucumber plants that were inoculated with AMF when compared to their uninoculated counterparts. Chen *et al.* (2017) recorded a notable enhancement in growth, photosynthetic efficiency, and nutrient assimilation in cucumber seedlings subjected to three distinct AMF treatments. Xiuxiu *et al.* (2019) reported significant improvements in root activity, chlorophyll content, and photosynthetic rates in cucumber seedlings as a consequence of AMF inoculation. Tian *et al.* (2023) reported the efficacy of *Diversifora versiforme* in substantially increasing cucumber biomass and leaf gas exchange under conditions of heat stress. Another considerable benefit of AMF inoculation in cucumber plants pertains to its capacity to bolster resistance against both biotic and abiotic stressors. Research has illustrated that AMF can mitigate the adverse effects of root-knot nematodes (*Meloidogyne incognita*), a prevalent pest that negatively impacts cucumber crops (Zhang *et al.,* 2008). In further investigations, AMF was shown to enhance drought tolerance by improving the root system's ability to procure water and nutrients, thereby resulting in increased biomass and enhance physiological performance, including improved photosystem II efficiency. Studies have established that the inoculation of cucumber plants with *Glomus mosseae* elevates root biomass and overall plant vitality by strengthening their defense mechanisms against pathogens such as *Alternaria alternata*, as evidenced by heightened enzymatic activity within the plants (Khrieba *et al.,* 2023). Moreover, Alhinani *et al.* (2024) reported that drought-stressed cucumber plants inoculated with AMF exhibited significant enhancements in plant height and glycine betaine concentrations, both of which are essential for maintaining osmotic balance under stress conditions. Additionally, AMF inoculation has been demonstrated to improve tolerance to waterlogging in cucumber plants, thereby augmenting their resilience to unfavorable environmental circumstances (Xiang, 2024). These findings underscore the potential of AMF bio-inoculants as a promising approach for augmenting cucumber plant yield while preserving environmental sustainability.

Impact of AMF Inoculation on Pepper Plants

Pepper plants *(Capsicum annuum L.)* is a herbaceous plant of great economic importance as it is a food source rich in plant chemical compounds and vitamins (A and C), and has multiple medicinal properties (Boyhan *et al.,* 2019). In addition, pepper contains many nutrients that include; fibers, fats, proteins and carbohydrates and micro elements such as Zn, Cu and Fe (Moreb *et al.,* 2020). Pepper plant exhibits a superficial root architecture that inhibits its capacity to mitigate water loss resulting from transpiration and nutrient absorption, thereby rendering it heavily reliant on mycorrhizal symbiosis for these essential functions (AbdelRahim *et al.,* 2023). The inoculation of pepper plants with AMF has been empirically demonstrated to significantly enhance a multitude of growth metrics, fruit yield, and the overall health of the plant, positioning this practice as a critical component of sustainable agricultural methodologies. Claudia *et al.* (2009) identified that the inoculation of pepper plants with AMF mitigated transplant stress, thereby expediting the maturation phase of the plants, which consequently resulted in both higher yields and superior quality. Furthermore, Ortas *et al.* (2011) documented a substantial enhancement in both growth and yield of pepper plants following AMF inoculation when compared with control specimens. The research by Soylu *et al*. (2013) revealed that the mycorrhizal inoculation involving *Claroideoglomus etunicatum* greatly enhanced the fresh and dry biomass of pepper plant roots and shoots, in addition to plant height, leaf diameter, and root length when compared with the control plants. Moreover, inoculation of AMF in pepper plants has been reported to be more efficacious in inhibiting the progression of pathogenic diseases than the sterilization of infected soil through a three-hour exposure to hot water vapor (Fauziyah *et al.,* 2017). Hegazi *et al.* (2017) documented that mycorrhizal inoculation substantially enhanced the dry matter content of pepper plants when compared to control groups; in addition, Balog *et al*. (2017) affirmed that AMF inoculation improved yield in pepper plants within their investigation. Similarly, Duc *et al.* (2017) demonstrated that the concurrent inoculation of AMF with *Pseudomonas fluorescens* and *Trichoderma spp.* Significantly bolstered defense enzymes and yield across various pepper cultivars, suggesting a synergistic effect that can be harnessed for enhanced agricultural productivity. This multifaceted approach does not promotes plant growth but also strengthens the plants' defensive mechanisms against pathogens. The observed improvements in the growth of pepper plants can be ascribed to the augmented surface area of root systems resulting from the symbiotic association, which facilitates increased water and nutrient acquisition from the soil in exchange for carbohydrates supplied by the plant (Yilma, 2019). Additionally, the influence of AMF mycelium in inducing biological, physical, and chemical alterations through the secretion of glomalin, a protein compound that adheres soil particles together, may also contribute to enhanced soil water retention capabilities (AbdelRahim *et al.,* 2023). Further investigations have revealed that effective colonization of pepper roots by AMF not only stimulates growth but also bolsters the plants' immune systems, thereby offering protection against nematode stressors (Tchabi *et al.,* 2022). This dual advantage of growth promotion and pest resistance highlights the ecological significance of AMF within agricultural frameworks. In a separate study conducted by Franczuk *et al.* (2023), the application of AMF in conjunction with varying levels of mineral fertilizers yielded enhanced growth, yield, and nutritional quality of sweet peppers. Such improvements in nutrient uptake are critical, as they directly correlate with the overall productivity of pepper crops. In addition to growth and yield, AMF inoculation has been shown to influence the metabolic processes within pepper plants. AMF inoculation led to metabolic reprogramming of phyto-hormones and secondary metabolites, which are crucial for plant development and stress responses (Bonini *et al.,* 2020). This metabolic enhancement can lead to improved resilience against environmental stressors, further supporting the argument for AMF use in pepper cultivation.

The effectiveness of AMF inoculation can vary based on the specific strains used and their compatibility with the host plant. It was also highlighted that the interaction between AMF and pepper plants can be influenced by factors such as fungal genotype (Angúlo-Castro *et al.,* 2021). This complexity necessitates careful selection of AMF strains to maximize their beneficial effects on pepper growth and yield.

CONCLUSION

Arbuscular mycorrhizal fungi inoculation promote many aspects of vegetable plants development that includes: nutrient and water acquisition, increased growth and development, photosynthetic activity and yield of plants. It has also been clearly documented that plants inoculated with AMF can effectively combat various environmental cues, like salinity, drought, nutrient stress, pathogens and diseases. In addition, the hyphal networks of AMF improve soil characters such as soil particle aggregation thereby improving the resistance of soil toward erosion by wind and water. As agricultural practices continue to evolve towards more sustainable methods, the incorporation of AMF into vegetable plants cultivation may continue to present a viable strategy for improving crop productivity and quality.

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