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# Appraisal of Arbuscular Mycorrhiza in Fruit Production and Mitigation Against Stress: Current Insights and Prospects

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## ABSTRACT

Arbuscular mycorrhizal (AM) fungi have emerged as a key biological fertilizer in sustainable fruit farming that promotes nutrient uptake, improving edaphic conditions, and increasing crop resilience to eco-physiological stressors. Through symbiotic relations with the higher plant roots, AM fungi facilitate the uptake of essential minerals and nutrients, leading to improved plant health, increased yields, and reduced reliance on synthetic fertilizers. These attributes contribute to environmentally sustainable fruit production. This review explores the current applications, achievements, and limitations of AM fungi in fruit production, with a focus on commercially available inoculants and specific case studies demonstrating their efficacy. However, factors such as variability in the colonization efficiency, soil–specific interactions, and logistics challenges in larger scale applications hinder their widespread adoption. Moreover, the compatibility with conventional crop varieties and the dynamic interaction within the soil microbiomes present additional challenges. The future perspective aims to enhance AM efficiency through breeding, genetic engineering, and elucidation of molecular signaling pathways to optimize plant-fungal interactions. The Integration of precision agriculture, advanced bioformulations, and biotechnological advancements is expected to improve AM fungi adaptability across diverse climatic conditions and cropping systems, thereby promoting their broader implementation in commercial fruit production.

## Keywords

abiotic stress, biostimulants, crop production, fungi, stress mitigation

## 1. Introduction

The recognition of phytonutrients and essential nutrients in crops for their health–promoting and protective effects has significantly increased in recent years [1]. Consequently, its role as a fundamental component of a balanced diet has gained substantial attention. Horticultural crops, including vegetables, fruits, spices and nuts, are directly consumed by humans, while other products such as flowers, ornamental plants, and medicinal and aromatic species

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contribute to various health and commercial applications [2, 3, 4, 5]. Regular consumption of edible horticultural crops has been strongly linked with reduced risks of chronic diseases, including certain cancers, heart diseases, infections, and metabolic syndromes [6]. The growing global emphasis on balanced nutrition, coupled with an increasing population, has led to a rising demand for horticultural commodities, further reinforcing their significance in human health and food security. The greatest challenge contemporary horticulture needs to overcome is the production of food for the increasingly growing world population and the minimization of the environmental impact that could lead to the destruction of the industry [7]. The horticulture industry and scientists have the largest sustainability challenge regarding attaining the first two objectives. The need for the pace to be continued is to have a part of a greener and more sustainable approach [1]. The horticultural enterprises strive to feed a growing population without deteriorating environmental circumstances. These horticulture crops can absorb 500–1000 kg of nitrogen, phosphorus, and potassium ha/year or more under ideal management, but this has major environmental and cost consequences [8]. In the recent decade, various innovations in technology have been presented to reduce the usage of chemicals and improve production system sustainability. The use of ”biostimulants” is promising and effective. The collective name ”biostimulants” refers to a class of substances that do not operate like insecticides or fertilizers but improve plant performance at lower concentrations [9]. In 2012, the European Biostimulants Industry Council (EBIC) defined plant biostimulants as substances and microorganisms that, when applied to plants or the rhizosphere, stimulate natural processes to enhance nutrient uptake, use efficiency, improve tolerance to abiotic stress, and increase crop quality, without exerting direct action on pests. Among these, arbuscular mycorrhizal fungi (AMF) are notably significant, as they improve mineral uptake and thereby influence plant nutrition and overall efficacy. Beneficial microorganisms play a crucial role in achieving these improvements [11]. As microbial inoculants, AMF function both as biofertilizers and biostimulants, enhance microbial inoculants like AMF boost soil nutrient absorption and availability, and contributing to improved plant growth and agricultural sustainability [12].

The mechanisms of beneficial microorganisms hold significant potential value for sustainable horticultural production, as highlighted by Rouphael *et al.* [11]. Mycorrhizal fungi establish symbiotic relationships with plant roots, manifesting diverse forms depending on the taxonomic classification of the fungal species and the host plant. Their distribution and effectiveness are significantly influenced by climatic conditions, soil characteristics, and host–plant compatibility. Mycorrhizae, which can be either endotrophic or ectotrophic, significantly enhance mineral absorption. The *Glomeromycotina* subphylum of Mucoromycota encompasses the principal arbuscular mycorrhizal fungus (AMF). The *Glomeromycotina* subphylum comprises 25 taxa and four orders: *Glomerales*, *Paraglomerales*, *Archaeosporales*, and *Diversisporales*. Defensive tactics encompass alterations in transcript levels of genes associated with signaling pathways or stress responses, AMF–mediated mitigation of oxidative stress, and expedited absorption of water and nutrients [13]. The efficacy of AMF is contingent upon soil and ambient variables [14]. With the meticulous selection of suitable species–genotype–fungus combinations and effective management, optimal AMF strains provide significant multiple benefits [14]. This review paper highlights the biostimulatory effects of AMF on the quality, nutritional value, and overall health of fruit trees, vegetables, and ornamental plants. It further explores the interplay between microbial communities and farm management practices, highlighting their influence on the agronomic and physiological responses of AMF-associated plants in mitigating abiotic stress. Notably, AMF play a crucial role in improving nutrient uptake, reducing the need for fertilizers and pesticides, and improving crop resilience. However, their widespread benefits remain underutilized due to host–specific interactions, inoculation methods, and environmental variability [15, 16]. Understanding these mechanisms is essential for optimizing large–scale, sustainable horticultural production [17, 18]. The review focuses on recent advancements in AMF applications, emphasizing their role in improving crop quality through enhanced nutritional content, flavor, appearance, and shelf life. Nutritional quality is closely linked to elevated levels of essential minerals, bioactive compounds, and secondary metabolites. Strategies such as micronutrient application, conventional breeding, tissue culture, and co-inoculation with plant growth–promoting bacteria (PGPB) further enhance these benefits [17, 19, 20]. The synergistic potential of AMF and PGPB in improving crop yield and secondary metabolite production is also explored. Given the increasing recognition of phytonutrients and minerals in horticultural crops, AMF–based biostimulants offer a sustainable approach to enhancing plant health, productivity, and their role in balanced human diets.

## 2. Arbuscular Mycorrhiza

Microbial inoculants are primarily classified into two categories: biopesticides and biofertilizers [11, 12]. Biofertilizers, often referred to as biostimulants or bioinoculants consist of living organisms that enhance plant development through several mechanisms, including biomass and root expansion, nutrient provision, and improved nutrient uptake capability, achieved by application to plants, seeds, or soil [20]. Microbial biostimulants play a vital role in the nutrient solubilization, uptake, metabolism, and transfer of nutrients, contributing to improved plant growth and resilience. They enhance phytochemical accumulation and encourage the formation of robust root systems that optimize nutrient acquisition and photosynthesis and improve overall nutrient use efficiency. Additionally, microbial biostimulants strengthen antioxidant defense mechanisms to mitigate oxidative stress and enhance plant adaptability to environmental challenges [1, 2]. Recently, biostimulants derived from living microorganisms have garnered significant interest from researchers and industry professionals due to their superior capacity to promote the growth of plants compared to traditional agricultural ecosystems [12]. Microorganisms are superior enzyme producers and can therefore serve as viable alternatives for creating advantageous microbial associations to be utilized with gelatin for enhanced biostimulants efficacy [20]. The microorganisms functioning as biostimulants mostly consist of helpful fungi, such as arbuscular mycorrhizal fungi and free–living bacteria. Numerous factors influence the implementation of microbial inoculants as biofertilizers, including plant species, compatibility with different kinds of soil, chemical fertilizers, and environmental circumstances [18, 19]. Root exudates play a pivotal role in influencing microbial inoculation efficacy and serve as a substrate for physiologically active compound synthesis. AMF substantially enhance plant growth through multiple mechanisms [21], includes enhancing root surface area for enhanced water uptake, and improved availability of nutrients, particularly phosphorus under nutrient–deficient conditions. In general, modifications in root architecture, and enzymatic and physiological functions. Additionally, AMF influences antioxidative responses and regulates abscisic acid–induced plant hormones, specifically 6 out of 38, involved in stress responses [19, 20, 22]. This leads numerous microbial primary degraders to preferentially utilize the carbon source polyhydroxyalkanoates [23].

AM fungi are excreted by roots and belong to a distinct taxonomic family within the phylum Glomeromycota, different from all other true fungi. The initial terrestrial plants possessed AM fungi, which likely facilitated their colonization of land, as indicated by molecular phylogenetic evidence [24, 25]. AM are perhaps the most prevalent plant symbionts, associated with 80–90 percent of terrestrial plant types. These species encompass numerous significant horticultural crops, including the Solanaceae, Alliaceae, fruit trees, and ornamental plants. All arbuscular mycorrhizal fungi can engage in mutualistic relationships with all mycorrhizal plants, barring exceptional situations [1, 11, 12]. Consequently, it is infeasible to recommend particular AM fungal strains for specific horticultural crops. Most commercially available inocula predominantly comprise organisms from the genera *Rhizophagus* and *Funneliformis*, as species from the genera *Gigaspora* and *Scutelleospora* may compromise soil structure. These organisms are ubiquitous in soils across diverse climatic situations [12]. Consequently, they can be applied in horticultural production throughout all locations worldwide. The life cycle of AMF commences during the symbiotic

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phase, initiated by the germination of asexually generated chlamydospores in the soil. Germination is solely contingent upon the physical elements of humidity and temperature. As obligatory biotrophs, AMFs pull back their cytoplasm and enter a latent state in the absence of the plant. The presymbiotic stage commences when the primary germ tube begins to branch near the plant's roots [11, 12]. This can be prompted by root exudates [1] or by certain metabolites such as strigolactones [26]. The fungus's interaction with the root surface facilitates the formation of hyphopodia on the root's surface. The epidermal cells beneath the hyphopodia of a plant engage in a mycorrhizal–specific process, forming the pre–penetration apparatus, an intracellular transitory structure utilized by the fungus for roots to penetrate [25, 26]. In certain regions, the fungus's hyphae infiltrate or intercede between the cells, exhibiting linear or coiled formations, so colonizing the roots. The method of fungal colonization varies upon entering the inner cortex. The fungus, as part of the colonizers, has produced hyphae for penetration into the soil, enabling it to gather nutrients, interact with microbes, and colonize neighboring hosts, whether of the same or other species [20]. Consequently, the networks of root and hyphae integrate plants and their arbuscular mycorrhizal fungus. AMF are formed within roots and represent a unique species of fungi that have consistently been classed as phylogenetically distinct from all other genuine fungi, belonging to the Phylum Glomeromycota [1, 11, 12, 27].

## 2.1 Role of arbuscular mycorrhiza in nutrition of fruit crops

AM fungi form symbiotic relationships with the majority of crop plants to increase nutrient uptake, especially for phosphorus (P) and nitrogen (N) [28]. AM fungi can mobilize P from insoluble sources through the alteration of soil pH & release of organic acids. These fungi also enhance N uptake, especially under drought stress [1, 11, 12]. These plants, in turn, provide carbon to the AM fungi for these nutrients, which enhance growth and promote high yield, resulting in healthier plants. This AM symbiosis shows various degrees of effectiveness between different plant species; hence, seed origin is crucial for mycorrhizal application [29]. Organic fertilizers and slow–release fertilizers may encourage AM activity. However, chemical fertilizers tend to suppress AM [11, 12]. AM fungi dwell in a critical balance in sustainable agriculture, viz., enhancing nutrient uptake, drought resilience, and crop productivity [10]. These fungi help the fruit crops to increase P uptake by the formation of pathways for P acquisition from various sources, such as soluble and organic pools, as well as rock phosphates [1]. They increase plant growth so that dependency on phosphatic fertilizers can be decreased to as much as 50% in nutrient-deprived soils [30]. A more significant dependency of host plant species on mycorrhizal infection influences benefits arising from AM inoculation in mixed cropping; it can affect such effects and competition, where those plants with a higher requirement for mycorrhiza may get greater benefits from applying AM fungi. Thus, these phenomena are warranted to be understood while managing P optimization for fruit crops and sustainable orchard practices. These fungi play a pivotal role in efficient nutrient uptake and utilization [10]. It facilitates phosphorus, nitrogen, and microelements uptake, mainly under stress conditions [1, 20, 21]. They increase seedling survival, growth, yield, and various stress tolerance in fruits [10]. In minimally disturbed conditions, viz., direct seeding and mulch-based cropping systems, prefer the use of AM fungi, as it provides sound ecological balance [31]. Improved colonization enhances the uptake and utilization efficiency of nitrogen, thus limiting the use of fertilizers, and prevents the loss of nutrients through leaching and gaseous emissions since the nutrient interception zone becomes larger [32]. The AM fungi ecosystem services are indispensable for sustainable and environmentally safe agriculture [11, 32].

AM fungus symbiosis in fruiting crops improves nutrient uptake and utilization, tolerance to adverse conditions, & soil fertility [33]. In viticulture, AM fungi promote the growth and nutrition of grapevines through nutrient acquisition, and the regulation of plant transport proteins was enhanced by the use of AM fungi [34]. They also provide enhanced resistance to water stress, salinity, and heavy metals, and protect roots from diseases [34]. Glycoproteins and hyphal networks of AM fungi stabilize the soil and retain nutrients, although P fertilization suppresses mycorrhization; cover crops in vineyards favor AM fungi development. These fungi improve the soil structure and fertility through the mycorrhizosphere of fruit crops [33, 34, 35]. They release (organic acids & glomalin), hence preventing soil erosion, chelating [heavy metals], and carbon storage enhancement. Besides, aggregation of soil and stabilized by AM fungi, which also impact the soil microbiomes by enriching the microbial diversity while promoting the growth of desirable bacteria [35]. In fruit crops, the AM fungi enhance seedling survival, growth, yield, fruit quality, and biotic & abiotic stress resilience [1, 10]. Given their application and advantages, AM fungi are very promising for sustainable agriculture [36]. These will allow plants to tolerate drought through mechanisms, such as hormonal regulation, which involves ABA, JA, and strigolactones [37]. This association improves growth during drought by enhancing water status, uptake of nutrients, osmotic adjustment & activity of antioxidants in plants [15]. The expression of genes during drought stress and AM fungi aids the transport of water through aquaporins [37]. These physiological alterations bring AM fungi into an integral part of managing drought pressure in agriculture [1]. VAM improves the absorption of water and drought resistance in fruits by extension of the surface area of roots and changing soil conditions. They encourage water absorption through external mycelia and improve root hydraulic conductivity, osmotic adjustment, and stomatal function [10].

VAM also stimulate antioxidant defense against drought–related oxidative stress [38], and enhances the uptake of nutrients, specifically P, which indirectly assists in water relations [1]. VAM fungi can also induce gene expression, which can alter aquaporins & root–to–shoot signals [38], all of which increase drought tolerance. These VAM fungi alter the water relations in water–stressed plants by enhancing the surface area of roots, the characteristics of the soil and nutrient uptake. Results from experiments show that VAM can supply up to 5–7 % of soil water to plants during drought, but the contribution is highly variable depending on host species and environment [11, 12, 13, 14, 15, 16]. In some cases, VAM did not enhance the water relations of citrus rootstocks during short droughts and even reduced root hydraulic conductivity [10]. VAM's effect on the water relations of drought is also dependent on the soil type and the available P, and this could imply a complex, context–dependent role of VAM in drought resilience. Kim *et al.* [39] and Bianciotto *et al*. [40] reported that the frequency rate of the root occupation of AMF is between 28.2 and 36.4%. AMF changed the pattern of primary and secondary metabolism. It increases phytochemical content, and thus it improves flavor that is healthy for the body. In field settings, AMF significantly improves fruit quality and enhances seed maturation with enhanced germination and plant resistance [41]. It was also reported that AMF inoculation increased the content of essential oils (leaves of plants) [41], while onion bulbs experienced a considerable increase in AOA upon inoculation with a mixture (Glomus + saprophytic fungi). Along with that, it was found that AMF increases in sugars, organic acids, vitamin C, flavonoids, and mineral content in plant tissues with the application of *Glomus versiforme*. Bagheri *et al.* [42] demonstrated a higher concentration of P, Zn, K, and Mn in Pistachio plants that had been inoculated with AMF when the environment of drought stress was applied. This improves N and P uptake, wherein between 20–75 percent of total N in the plants is linked with AM transfer through AM. A combination of AMF and humic substance has been reported to exhibit synergism in promoting growth, enhancing nutrient uptake, and increasing N and P contents. Fungal structures, such as arbuscular mycorrhizae, facilitate the interchange of inorganic nutrients & carbon with (P), which increases the vigour of the host plant [43]. AMF associations are particularly advantageous under P-limited conditions to enhance P availability in the host plant.

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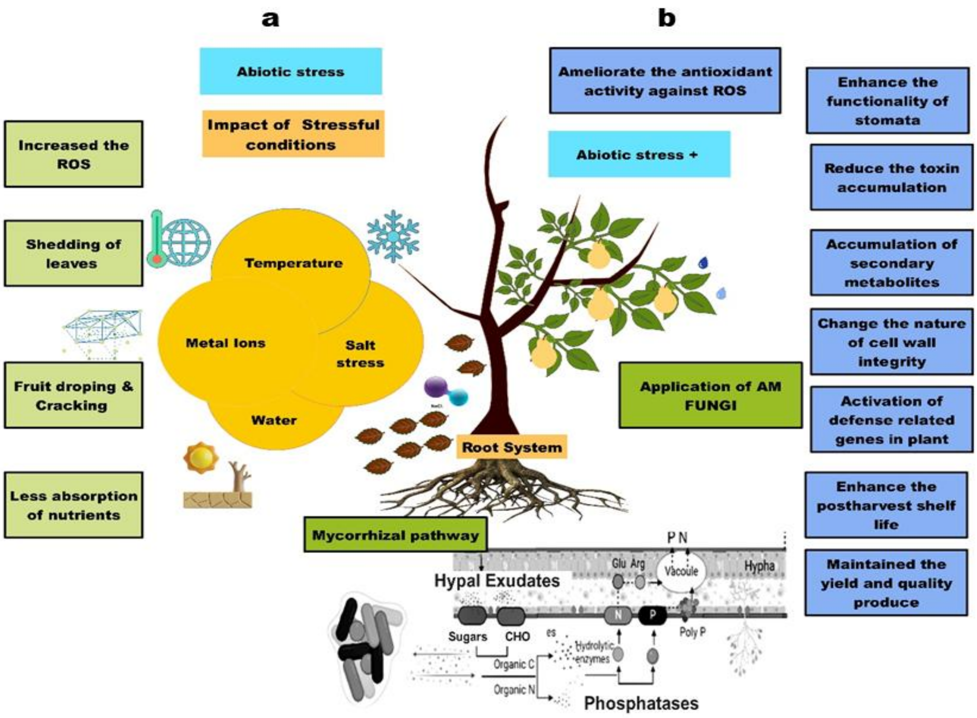


Figure 1: Role of AM Fungi in fruit crops in special reference to stresses; (a) providing effect of on the tree without AM Fungi application, and (b) Application of AM fungi and their impact on stress mitigation in fruit crops

## 2.2 Impact of arbuscular mycorrhiza on fruit crop growth and yield

AMF highly enhances the growth and productivity of fruits and other fruit crops. This can be shown using tomatoes, where high AMF root colonization has resulted in longer plants with higher production and higher yield of tomato fruits [10]. The colonization by AMF improves quicker flowering, and greater development in fruit maturity in addition to improvement of better fruit quality and a larger quantity of amino acid produced in fruit crops [1, 11, 12, 20]. In field situations, the mycorrhizal tomato seedlings get enhanced marketable yields with higher levels of nutrients and effective photosynthesis under both sufficient and drought-stress conditions [10]. AMF increases the seedlings' survival, fruit quality, and tolerance to different stresses, mainly through improved acquisition of nutrients and water in addition to increased exudation of sap from increased development of roots [18, 19, 20]. Generally, AMF contribute significantly to fruit crop yield under environmental stresses. The symbiotic relationship of AMF & root systems of plants boosts their increased crop yields and growth. It has been proven that AMF increases crop yields by about 25% compared to tomato production under both optimal and deficit irrigation conditions [44]. AMF–colonized roots increase nutrient absorption, mainly phosphorus and nitrogen, thereby increasing chlorophyll contents and photosynthesis [10, 44]. Inoculation with AMF had shown an increase in 12–47 % increase in growth parameters in the case of peppers. Cherry tomatoes inoculated with *Glomus mosseae* were further enhanced with growth, more production, and quality of fruits in fruits. AMF also improved the resilience of crops in that water–use efficiency will enhance uniform flowering and thus good fruit consistency in diverse fruits [10]. Collectively, these studies put forward AMF as a sustainable way of promoting fruit crop production and quality.

The AMF symbiosis is critical in plant growth regulation through phytohormone signaling. For example, gibberellins are critical to the formation of arbuscules in pea roots through colonization by AM. The response is mediated by DELLA proteins [45]. Development of AM is controlled with the aid of strigolactones, auxins, and gibberellins; the effect of strigolactones is to cause fungal activation before colonization and that of auxin on colonization is quantitative. AM symbiotic effects are greater on flowering, fruit formation, and fruit quality compared to roots. For instance, in tomatoes, the effect of AMF results in hastened flowering and fruiting, increased yields, and altered transcriptome and amino acid content in the fruit with increased glutamine and asparagine [11, 12]. For instance, AMF inoculation increased plant height, flowers, and fruit production in cherry tomatoes, melons, and field tomatoes [41]. AMF enhanced fruit quality through enhanced sugar content, carotenoid concentration, and fruit size [41]. Through AMF inoculation, nutrient absorption rate increases with special attention being paid towards nitrogen and phosphorus uptakes that have positive influences on crop growth [Bowles *et al*., 2016]. During stress due to water scarcity, AMF improve stomatal conductance as well as photosynthesis for enhanced utilization of water, resulting in high yields [44]. In addition, AMF enhances flowering, seed quality, and greater germination percentages [41, 10]. Generally, AMF enhances fruit crop production and stress tolerance. AMF inoculation enhances fruit crop growth and yield. For example, in tomatoes, AMF increased yields by 25% under both normal and limited irrigation and improved nutrient uptake, photosynthesis, and water relations [44]. Similarly, the Micro–Tom inoculated with Glomus mosseae grows to a greater height as compared to noninoculated plants. Their flowers are more numerous and the fruits that are produced are more in number. Moreover, fruit quality is also improved. As per Salvioli *et al*. [46], AM symbiosis even promotes flowering and fruiting in Micro–Tom tomatoes, modifies fruit transcriptome, and promotes amino acids such as glutamine and asparagine. These benefits have been realized in other fruits, such as strawberries, where AM fungi inoculation yielded higher in the farm than control plants, which proves the capability of AMF in enhanced productivity and high–quality fruit crops.

Fruit quality has been known to be improved by inoculation of AMF in various crops. In tomatoes, lycopene, β-carotene, and sugars were increased [47]. The fruits of pepper plants were larger and heavier in size, while citrus fruits showed enhanced quality attributes, size, weight, and soluble solids [47]. In melons, AMF caused earlier flowering and higher sugar and carotenoid levels, enhancing seed quality and germination [41] which resulted in AMF–increased nutrient uptake, followed by absorption of N, P, Fe, and Zn content in pepper leaf tissues and improved root health for the citrus. These findings provide significant evidence for AMF's role in maximizing fruit & crop yield in different species. The carbohydrates used are nutritional energy factors that reduce glycemic indexes, manage the intake of sugar, and aid to hydrolyse starch into its constituent pieces. The sugar content of crops, such as bitter oranges, usually increases with AMF inoculation [48]. On the other hand, water conditions sufficient for plant growth, and the introduction of *Rhizophagus irregularis* to inoculated apple trees did not affect their sugar content [49]. The mono– and polyunsaturated fatty acids were the largest accumulated from these isolates, and similar effects are reported, viz., aromatic plants [50]. Mycorrhizal lettuce contains higher vitamin E and vitamin C, which depend mainly on the variety and isolate of AMF. In cherry tomatoes, glutamate and aspartate increased, thus increasing the umami flavor [51]. More °Brix was reported in eggplant (3%) and grapes (10%), and glucose and fructose content were increased with inoculation by *Septoglomus viscosum* in strawberries [52]. Anthocyanins and flavonoids increased in the berry of *Vitis vinifera* by the inoculation of AMF [53]. In many crops, AMF showed a positive towards plant growth. *Glomus macrocarpum*, *G. coledonicum*, and *Acaulospora* enhanced height, stem diameter, and biomass in trifoliate and Troyer oranges. *Gigaspora rosea* and *G. mosseae* improved grape rootstock growth, and AM inoculation increased the lateral root development in olive trees [1, 11, 20]. In strawberries, the phosphorus application combined with AM fungal application was found to have an impact on total dry weight, fresh weight, leaf area, and number of leaves, which was more under different levels of phosphorus than that of phosphorus application alone. Vegetative growth and nutrient content in peaches were reported to improve. For instance, *G. fasciculatum* enhanced the banana cultivars height (Dwarf Cavendish and Robusta), while guava trees inoculated (AMF and *Bacillus megaterium*) showed twinning increase in length of shoots [54].

## 3. Arbuscular mycorrhiza and fruit quality

By inoculation, the arbuscular mycorrhizal fungi showed great promise for improving the fruit quality and nutrition of different kinds of crops (Tables 1 & 2). For example, chlorophyll content, the nutrient levels in the leaves, and fruit size of pepper crops cultivated in greenhouses increased due to inoculation [55]. In this way, the quality of tomatoes is enhanced by AMF as well, in particular the levels of lycopene, β-carotene and sugars, especially when the phosphorus level is low [56]. AMF improved the important phytochemical properties of strawberries grown in fields as their pH and soluble solids, and phenolic compounds, which increased most of the key physicochemical properties of field fruits. Similarly, AMF inoculation in citrus trees improved the root activity as well as the fruit quality measured by fruit size, weight, and SS content [47]. In addition, AMF aids in the absorption of nutrients (P, N, Zn, and Cu) and positively affects the uptake (K, Ca, and Mg) in acidic soils. In this case, high (N, P, Fe, and Zn) levels were observed in the AMF-inoculated greenhouse pepper leaves along with improved fruit quality and size [55]. In the study of AMF field application on citrus plants, there were increases in levels of several nutrients such as P, K, Mg, manganese, copper, and zinc, which resulted in fruit of better quality [57]. In the experiments on fruit trees conducted in Sahel regions, induced AMF increased aboveground N, P, and K uptake, whereas the response of species and provenances to ash growth and the dependence on mycorrhiza was different [29]. AMF application in strawberry crops increased pH, soluble solids, and phenolic content [58].

For tomatoes, AMF boosted glucose and malate concentrations and nitrogen, manganese, and hydrophilic phenolic content of processing tomato were elevated by AMF [59]. Strawberry growth in the combined AMF together with optimal levels of N enhanced certain minerals and phenolic compounds when compared with the strawberries. Tomatoes' biochemical quality was improved by the application of green compost because of the influence of AMF [18, 10, 11]. Generally, inoculation with AMF, especially in combination with balanced fertilization strategies, would benefit the nutritional status and accumulation of functional ingredients of the fruits as well as their appearance and taste after harvest for consumers. The application of AMF tends to even more increase the level of antioxidants in fruits [18, 20]. The application of AMF with Pseudomonas species reduced the chemical fertilizer application and improved the quality of strawberries [3]. Tomato AMF application together with plant growth–promoting rhizobacteria increased lycopene, antioxidant activity, and TSS in tomatoes. Field inoculation was conducted in a trial using citrus trees, which enhanced the juice and leaf antioxidant defences of fruits in Beni–Madona tangor [60]. Such studies concluded that the application of AMF is sustainable for enhancing fruit quality as well as nutritional value.

In addition to these, AMF has a positive impact on other horticultural crops. In strawberries, the treatment with AMF increased pH, soluble solids, and phenolic content [58]. In peppers grown in the greenhouse, AMF enhanced the size of the fruit and its weight [55]. In tomatoes, the application of AMF with green compost enhanced glucose, malate, and carotenoid content and reduced nitrite content [41]. Citrus trees inoculated in the field with AMF showed better fruit quality by having larger and heavier fruits, deeper coloration, and higher soluble solids [47]. Collectively, all of the above results have, therefore, reinforced the prospects of using AMF as a good biotechnological tool to enhance fruit nutrition and quality. It was shown that AMF highly influenced secondary metabolite production in medicinal plants, including phenolic acid, flavonoid alkaloids, and terpenoids [1, 61]. AMF symbiosis, fuelled by improved uptake of nutrients, enhanced photosynthetic efficiency, and induction of biosynthetic pathways, is promising in the context of enrichment [secondary metabolites] in medicinal and aromatic crops [62]. AMF has further contributed to sustainable agriculture by improving nutrient uptake, for example, P, Zn, and Cu, while showing increased resistance to drought and growth [10]. Such symbiosis can enhance the levels of protein, lipid, and sugar and can bind heavy metals while making them more tolerant to salinity [10, 20]. AMF plays a pivotal role in bioremediation by enhancing root health, soil stability, & drought tolerance, thereby enhancing plant biodiversity to support sustainable agricultural systems [2]. In fruit production, AMF symbiosis accelerates flowering, improves yield, and alters fruit composition. In tomatoes, AMF increased marketable yield by 25% under normal and water-deficit conditions [4]. This water regulation advantage also extends to cherry rootstocks and tomatoes, which can have reduced risk of fruit cracking [63]. Enhanced fruit quality and stress resilience due to AMF make the fungus a valuable asset in sustainable agricultural practices [41, 42, 44].

The AMF inoculation has been extensively researched for its benefits on fruit quality, nutrition, & stress tolerance of different crops. In greenhouse–grown peppers, AMF increased chlorophyll content, nutrient uptake, and fruit size, especially chlorophyll and essential leaf nutrients [55]. In tomatoes, AMF treatment under low-phosphorus conditions significantly increased lycopene, β-carotene, & sugar content in the fruits [56]. For strawberries grown under field conditions, AMF improved important physicochemical properties, including pH, soluble solids, and phenolic compound contents [58]. Citrus field applications also showed advantages; in this case, AMF improved root vitality, size of fruit, its weight, and TSS [47]. AMF enhances nutrient uptake, including P, N, Zn, Cu, K, Ca, and Mg, particularly in acidic soils [10]. In pepper plants, AMF raises nutrient content (N, P, Fe, and Zn) and improves fruit quantity and quality [56]. Besides, AMF improved fruit quality in citrus, boosting soluble solids and mineral nutrients like P, K, Mg, Mn, Cu, and Zn [57]. However, the effectiveness of AMF may vary based on host species and geographical location, as seen in the Sahelian region, where AM impacts mycorrhizal dependence and N, P, and K uptake [29].

Recent researches stress that AMF may increase nutritional values and contents of antioxidants in fruits. For example, treatment with AMF increases pH and soluble solids besides enhancing phenolic content in strawberries [58]. Malate and glucose contents rise with AMF inoculation in tomatoes. AMF enhanced phenolic compounds and essential minerals in strawberry fruits when applied with moderate nitrogen levels, thereby showing the potential of inoculation with AMF together with optimized fertilization for the enrichment of nutrients within fruits as well as bioactive compounds for better post–harvest quality [10, 11, 12]. In addition to crop plants, AMF improved secondary metabolites in medicinal plants, which promotes the production of phenolics, flavonoids, & terpenoids that could lead to better health conditions and plant resistance [61]. Cordeiro *et al*. [58] mentioned that AMF elevated the levels of bioactive compounds in strawberries with increased pH and soluble solids, along with phenolic levels. Other research works state the role of AMF that can be termed as efficient for sustainable agriculture, the factors include the production of protein, lipid, as well as sugars in higher amounts in the plants because of the association of symbiotic mycorrhiza with them; besides resisting stress, soil quality, and so on [2]. In addition, the combined application of AMF along with PGPR enhanced the lycopene, antioxidant activity, and TSS of tomatoes, while the former also showed its potential in eco–friendly agriculture [58, 59, 60].

AMF has also been reported to increase shelf life and post–harvest quality. The firmness and loss of weight in papaya during storage were maintained and reduced by MF [64]. Seed formulations with AMF have demonstrated a very long shelf life and could retain microbial viability for up to six months at 25°C [65]. Such outcomes indicate that inoculation with AMF and carrier formulations of advanced types may open very promising applications for sustainable agriculture by increasing the growth of plants, nutrient content, & crop quality in different types of horticultural systems. Fruit flavour is the synthesis of volatile compounds [esters, terpenes, aldehydes, lactones, and alcohols] are reported [66]. On AMF-inoculated tomatoes, the percentage increase was reported to be 60 %, 28 % and 18.5 % in phosphorus, zinc, and lycopene content when compared with the control. The capacity of antioxidants in onions was elevated in combination with Glomus spp. and other mycophilous fungi [67]. Furthermore, inoculated onions had higher contents [protein, soluble sugars, and proline] in the leaves, besides enhancing stress tolerance factors [10]. Inoculation of AMF seedlings increased the survival rate and shoots phosphorus and zinc concentrations in cucumber. In tomatoes, AMF increased uniform fruit ripening flowered much more, yielded better with higher quality, and supported earlier flowering and maturation, thereby enhancing market worth. AMF–treated plants yielded improved seed germination as well as plant fitness [41]. In addition, AMF inoculation increased the yield of essential oils in plant leaves [41], and keeping the inoculated plants under humid conditions increased antioxidant capacity by 70 percent more than the control [68, 69]. Roots released organic acids by caused acidification of soil and enhanced nutritional efficiency by allowing easier uptake or transport of P & Fe in the xylem, thus enhancing the growth of plants [67]. AMF inoculation significantly improved (TSS, proteins, polyphenols, and antioxidants) activity [68]. AMF colonized strawberry plants have shown higher secondary metabolites and antioxidant activity. This has also enhanced crop dietary quality by increasing the carotenoids and volatile compounds levels owing to the impact on the crops. The beneficial impacts of AMF treatment on the quality of tomatoes [69] as higher sugar, organic acid, vitamin C, flavonoid & mineral contents recorded during inoculation with *Glomus versiforme*. In tomatoes, citric acid content was also enhanced by AMF application [69]. Due to their health benefits, AMF treatments are thought to enhance the shelf life of tomatoes [51].

## 4. Stress tolerance induced by arbuscular mycorrhiza

Stress refers to any condition or agent that impinges upon, hinders, or interferes with the metabolic, growth, or developmental processes in a plant. There are many natural and human–induced sources of such stresses. For example, abiotic stress is caused by environmental factors that inhibit the growth and productivity of plants below their potential. Some of the key stress factors include extreme salinity, temperature variation, imbalance in soil pH, drought, flooding, and injurious UV exposure, which stress the plants and result in a decline in crop yield not only in terms of quantity but also in quality [70]. The organoleptic attributes, like the shape and firmness of the fruit, are also decreased due to the decline in yield. The volume and agronomic characteristics of fruit size, resistance to pathogens, and yield are negatively affected. In addition, plants usually require significant energy for managing abiotic stress, energy consumption that arises from the productive energy that is generated, and reducing yield by as much as 60–70 % caused by climate–related stress factors, of which salinity and drought are the most toxic [71, 72].

Abiotic stress typically triggers oxidative stress and thereby initiates disruptions across key physiological, metabolic, biochemical, and anatomical functions, thus lowering the yield of value [1, 10, 17]. Such plant biostimulants as the key agents supporting the resilience of crops under such adverse conditions. In addition to abiotic stresses, other organisms that result in significant crop yield reduction are the pests and pathogens that bring about biotic stressors. Both can interact further to increase crop yield losses [56]. The use of pesticides is also a conventional means of pest management. However, they pose a serious risk to the environment in matters relating to water resources, food products, and other health implications, among other things, apart from posing a considerable burden on farmers to bear a heavy cost. Use of synthetic pesticides is progressively minimized and substituted by environmentally–friendly alternatives [73]. Many such beneficial microorganisms, including Plant Growth–Promoting Rhizobacteria and AMF; these fungi are in mutualisms that contribute to crop protection against pathogens, stress decrease, and decrease the severity of disease outbreaks [10]. As an example, AM fungi are commonly found in many soils, and they enhance crop yield safely, meaning that their use is sustainable in agriculture because of the reduction in dependence on pesticides, as it contributes to crop protection and sustaining high productivity in crops [1, 2]. There are well-known microbial biostimulants known as SWE, prepared from green, red, or brown algae, very commonly and vastly used in horticulture, and there is a remarkable number of products available commercially [74]. All the SWE preparations used displayed a positive influence in the direction of promoting growth for a range of crops, including conditions for growth of *Vicia faba*, which elicited optimal crop growth and enhanced quality of the crop with enhanced tolerance to several biotic such as anti–phytopathogenic fungicidal and bacteriostatic, and abiotic stress factors like higher absorption of water and essential nutrients. Biological stimulants positively influence stress tolerance through various physiochemical adaptations, including fortification of the root system, improved photosynthesis and leaf hydration, production of osmolytes (e.g., sorbitol, proline, betaine, and glycine), and reduced oxidative stress (e.g., lower $H_2O_2$ and MDA, increased CAT and SOD activity). They also enhance water use efficiency (WUE), regulate detoxification genes, and modulate the epiphytic microbial community for growth promotion [75]. These mechanisms help to improve plant resistance to drought and salinity, and contribute to sustainable agriculture in stress–prone environments (Table 3 and Figure 1).

### 4.1 AMF and biotic stresses

AM fungi enhance the resistance capacity of the plant against biotic stresses through various mechanisms, which may include improvement of plant nutrition, enhancement in photosynthesis and growth, anatomical as well as chemical defense structure reinforcement, and immune system priming of the plant. Therefore, AM fungi decide how the plant would interact with the pathogens and pests to provide modified phenotypes of tolerance or resistance [76, 77].

#### 4.1.1 Mycorrhiza improved tolerance

Resistance and tolerance are two primary strategies determining the phenotype of plant defence against the attacks of either pathogens or herbivores [18, 20, 78]. Tolerance relies more on physiological properties in plants and on resource availability than does resistance. AM symbiosis is thought to facilitate improved access to nutrients and impact plant physiological function, hence enhancing the resistance of plants against herbivores and pathogens. This may be promoted through host responses by AM, which include enhanced photosynthesis activity, shifts in resource allocation, carbohydrate mobilization, and altered timing of developmental events of a plant. Such responses are supposed to help compensate plants against adverse effects caused by attackers [10, 20, 78]. However, the specific function of such mechanisms in enhancing tolerance against pathogens and pests by AM fungi is still unknown. However, it has been suggested that AM symbiosis can enhance the plant’s tolerance to herbivory by improving the ability of mycorrhizal plants to absorb Pi from the soil [79].

#### 4.1.2 Mycorrhiza–induced resistance

This will be followed by a profound and massive transcriptional and metabolic response in the root, albeit to a lesser degree also in the aerial part, by AM colonization [1, 80]. Some of these are a higher basal content of some secondary metabolites; changed hormone levels; wall reorganization in the cell walls of the plant cells, and may be linked with a higher resistance of those MIR–induced plants. MIR appears to depend heavily on a condition of heightened defence status in mycorrhizal plants, which allows for priming of defences more easily at the time of attack, called ”defence priming”. Important in this regard is the fact that this priming effect is not restricted to the colonized root tissues but extends to other, more distant parts of the plant [80, 81]. Defence priming as a form of plant immunological memory; a first–time stimulus by a priming trigger has to be seen as some form of warning, which should induce but a short and weak activation of the defensive reactions. This learning enables plants to respond more rapidly and strongly to subsequent attacks by pathogens or insects [10, 11, 12]. As an adaptive strategy, priming conserves energy by avoiding continuous defence activation while maintaining readiness for future threats. Microbe–induced resistance (MIR) exemplifies this mechanism, being dependent on plant genotype and graft-transmissible, which suggests root-to-shoot signal transfer [82]. Although the key signals remain unclear, root–derived metabolites like lignans (e.g., yatein) have been implicated in conferring protection against foliar fungal pathogens [80, 81].

### 4.2 AMF and abiotic stresses

#### 4.2.1 Drought stress

Drought stress strongly affects plants by reducing water availability to roots, hence lowering the rate of transpiration and inducing oxidative stress [10]. Drought often coincides with temperature stress, which causes soil desiccation that enhances the harmful effects on plant growth through the inhibition of enzyme function, disrupted ion absorption, and assimilation of nutrients [83, 84]. Most importantly, AMF has indicated its potential for drought tolerance across various fruit crops. This is achieved through soil exploration involving networks of root and extra–radical hyphae that improve water and nutrients [20, 38, 40]. This increased uptake is believed to be a result of hyphal penetration and glomalin synthesis that improve soil structure and water relationships [85]. Improved growth is a result of increased stability and health of the soil, improved osmoregulation, and water–use efficiency with decreased levels of reactive oxygen species (ROS) in AMF–treated plants. AMF inoculation protects photosynthetic functions, stomatal conductance, gas exchange, transpiration, and water–use efficiency at times of drought stress.

#### 4.2.2 Salinity stress

Salinity stress is one of the major problems threatening global food security by impeding plant growth, delaying vegetative development, and productivity [84]. High salinity further boosts the excessive generation of reactive oxygen species, causing more devastation to the health of the plant [83]. It promises to be a way out to mitigate the adverse effects of salinity by improving growth and yield under such conditions. Inoculation with AMF has been known to increase water uptake, and photosynthesis, regulate nutrient homeostasis, and activate antioxidant defense systems [20, 21, 22]. By increasing the uptake of ions and gaseous exchange, AMF alter root structure, hydraulic conductance, stomatal conductance, and uptake of nitrogen and potassium and thus salt tolerance is improved [38, 44, 48].

#### 4.2.3 Heavy metal stress

The industrial processes release lead, cadmium, and mercury that increase the soil concentration to a higher extent, causing the retardation of plant growth and causing hazardous effects due to crop contaminants [1, 10]. AMF symbiosis enhances the establishment of plants in metal–contaminated soils through the induction of defense mechanisms that enhance growth and strength. For instance, AMF colonization of wheat improved nutrient uptake under aluminum stress. AMF can mitigate the constraints on plant growth, chlorosis, and death due to the presence of Cd and Zn in the soil [86]. AMF can be involved in modifying the metal toxicity of soil by changes in soil pH or incorporation of metals into polyphosphate granules, making them immobile and non–toxic. It has also been speculated that glomalin produced by AMF protects plants against the translocation of harmful metals such as cadmium and copper from the rhizosphere and into their leaves [18].

#### 4.2.4 Temperature stress

Temperature stress has a significant impact on growth, physiological activities, and stability in plant development. High temperatures can inhibit germination, reduce biomass, and suppress photosynthesis. Cold stress will destroy the

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osmotic balance of the plant and its membranes, resulting in decreased antioxidant activity [87]. Low temperature also reduces leaf area, delays growth, and affects photosynthesis, usually accompanied by wilting and chlorosis [20, 22, 10]. Studies on AMF have been conducted with regard to temperature–induced stress, which indicates variable effects on different species that vary in their tolerance. For instance, under high temperatures, lower colonization and hyphal growth of AMF occur in temperature–sensitive species. However, AMF colonization has been found to improve antioxidant activity, which allows the management of ROS accumulation during thermal stress [56]. In addition, AMF such as *Glomus etunicatum* can sustain their colonization at low temperatures, and thus may be potentially tolerant to temperature [1, 11, 12].

4.2.5 Nutrient stress

Nutrient availability is an essential factor for healthy plant growth, and nutrient deficiencies are known to change growth patterns, reduce photosynthetic capacity, and increase susceptibility to stress [87, 88]. AMF enhance nutrient uptake, particularly for non–mobile minerals such as zinc and copper [56, 58, 68]. These plants increase the content of essential nutrients like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) at the same time reducing toxic ions such as sodium (Na) when under saline conditions or cadmium (Cd) under metal–stressed soils [1, 10]. More importantly, AMF increases phosphate–solubilizing enzyme activity that improves nutrient availability and assimilation [10, 20, 32, 89].

## 5. Limitations and challenges

### 5.1. Variability in AM colonization

Various fruit crops have differential responses to AM Fungi. Fruit crops such as berry crops typically have a strong affinity for AM fungus, resulting in enhanced colonization. Nevertheless, specific crops, particularly those in the cole crops, generate root exudates that can impede AM colonization, hence diminishing the overall advantages. Crops possessing more fibrous and broad root structures (e.g., pome fruits) may facilitate greater colonization of roots by arbuscular mycorrhizal fungi compared to crops with taproots, hence influencing the efficacy of AM in both water and nutrient absorption. Various arbuscular mycorrhizal strains exhibit differing colonization capacities contingent upon environmental circumstances and plant species. For instance, *Rhizophagu*s irregularis can be especially productive for cold region crops, while *Funneliformis mosseae* might demonstrate superior performance in desert environments. The accurate association of AM strain with fruit crops is essential for effective inoculation.

**Table 1:** Assessment of Arbuscular mycorrhizal fungi on crop quality and soil health

| Particulars | Overall function | Nutrients Enhanced | Effect on Crop Quality | Improvement in Soil Properties | AM fungi | Reference |
|---|---|---|---|---|---|---|
| Nutrient Uptake | Enhances uptake of essential nutrients by increasing root surface area and improving nutrient solubilization. | N, P, K Cu, Mn, Zn | Increases nutrient density, taste, and colour of fruits Increases overall plant growth and fruit yield | Improves nutrient availability and soil fertility | *Glomus* spp., *Rhizophagus* spp. | [89] |
| Root Growth and Structure | Stimulates root growth and architecture, expanding the root zone for improved resource absorption. | P, Mg | Promotes uniform fruit size and weight | Enhances root penetration and soil aeration | *Gigaspora* spp., *Acaulospora* spp. | [90] |
| Water Absorption | Aids in water uptake and retention, providing | – | Helps maintain fruit size and quality during drought | Increases soil water–holding capacity | *Glomus intraradices* | [91] |

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| | drought resistance and reducing water stress. | | | | | |
| Soil Health | Improves soil structure, aggregation, and microbial diversity through enhanced organic matter. | – | Contributes to better fruit quality Promotes a healthy, balanced soil microbiome | Builds stable soil aggregates, reducing erosion | *Claroideoglomus etunicatum* | [92] |
| Plant Growth and Yield | Enhances growth and yield by improving nutrient and water availability and supporting root growth. | P, N | Results in higher yield and better fruit size | – | *Funneliformis mosseae* | [93] |
| Abiotic Stress Tolerance | Increases plant tolerance to salinity, heavy metals, and drought through nutrient balancing. | Na, Zn, Fe | Limits stress impact on fruit appearance and taste | – | *Rhizophagus irregularis* | [94] |
| Hormone Regulation | Modulates plant hormones, promoting growth and reducing negative impacts of environmental stress. | – | Encourages uniform ripening and fruit quality Reduces effects of stress–related hormones | – | *Acaulospora laevis* | [95] |
| Disease Resistance | Competes with soil–borne pathogens, reducing disease incidence by occupying root space and resources. | – | Reduces disease–related damage to fruits | Inhibits pathogen proliferation in soil | *Glomus* spp., *Diversispora* spp. | [96] |
| Symbiotic Efficiency | Forms mutualistic symbiosis, reducing dependency on chemical fertilizers and promoting nutrient cycling. | P, N | Supports nutrient–rich, high–quality fruits | Lowers chemical input requirement | *Funneliformis geosporum* | [97] |
| Nutrient Management | Integrated nutrient management enhances nutrient supply and soil health. | N, P, K, OM | Improved fruit weight, size, and taste through balanced nutrient application. | Increases soil organic carbon, nitrogen, and phosphorus levels; decreases soil pH. | *Glomus* spp. | [98] |
| Soil Properties | Soil conditions influence fruit characteristics; nutrients affect seed and kernel quality. | OM, Fe, Mn | Better shape and size of fruits; higher soluble solids content in fruits. | Improved soil structure and porosity; increased water retention capacity. | *Glomus intraradices* | [99] |
| Quality Factors | External conditions and Edaphic nutrients are important for fruit quality; balanced fertilization is crucial. | P, K, B | Higher vitamin C and soluble sugar content in fruits; improved taste and marketability. | Optimization of soil nutrients leads to better fruit quality parameters. | *Glomus mosseae* | [100] |
| Organic vs Chemical Fertilizers | Substituting chemical fertilizers with organic inputs can enhance soil health and fruit quality. | OM, N, P, K | Increased soluble solids, vitamin C content, and improved acidity ratios in fruits. | Enhanced soil pH and organic matter content; improved nutrient availability. | *Glomus aggregatum* | [101] |
| Combined Fertilizer Effects | Combining chemical and organic fertilizers boosts both soil nutrients and enzyme activities in orchards. | N, P, K, OM | Significant improvements in fruit quality metrics such as size and flavor profile. | Increased enzyme activity in the soil; enhanced microbial | *Glomus etunicatum* | [102] |

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| | | | | activity promoting nutrient cycling. | | |
| Soil Microbial Activity | The presence of AM fungi promotes beneficial soil microbial activity, which helps in nutrient cycling and organic matter decomposition. | Fe, Zn | Enhanced aroma and taste profiles | Increased microbial diversity and activity | *Scutellospora* spp., *Gigaspora* spp. | [69] |
| Carbon Sequestration | MF play a role in carbon sequestration by enhancing soil organic carbon storage through root exudates and fungal biomass. | C | Improved overall fruit production as a result of better nutrition | Improved soil structure aids in carbon retention | *Claroideoglomus etunicatum* | [103] |
| Nutrient Cycling | improve nutrient cycling by breaking down organic matter and facilitating the release of nutrients for plant uptake. | P, N | Enhanced fruit nutrition leads to better quality | Improved nutrient turnover and availability | *Ambispora* spp., *Acaulospora* spp. | [104] |
| Root Development | VAM fungi promote root development, resulting in a more extensive root system that can access more nutrients and water. | Mn, S | Improved fruit set and yield | Enhanced root structure improves soil binding | *Glomus mosseae* | [105] |
| Stress Mitigation | VAM fungi help plants cope with abiotic stresses such as salinity and heavy metal toxicity. | Se, Co | Improved fruit quality under stressful conditions | Decreased soil salinity levels | *Rhizophagus irregularis* | [106] |
| Water Availability | VAM fungi improve water availability by increasing the soil's water–holding capacity and enhancing plant access to moisture. | Ca, Mg | Better fruit firmness and flavor | Increased soil moisture retention | *Glomus intraradices* | [107] |
| Plant Growth Promotion | Enhances root and shoot growth, leading to increased yield | N, Ca, Fe | Larger, better–quality fruits with improved storage life | Enhances cation exchange capacity, soil structure, and nutrient cycling | Gigaspora spp., Funneliformis spp. | [108] |

Table 2: Impact of arbuscular mycorrhizal fungi on nutrient uptake and fruit quality

| Fruit Type | Nutrient Uptake | Mycorrhizal Colonization Rate | Fruit Quality and biochemical Content | Reference |
|---|---|---|---|---|
| Grapes | High nitrogen, potassium, and phosphorus uptake during fruit development | Moderate to high | Improved size, color, total soluble solids, and flavor due to balanced nutrition Enhanced anthocyanin and polyphenol levels | [111] |
| Strawberries | Elevated nutrient uptake with supplemental light; increased chlorophyll and anthocyanin concentrations | High with optimal conditions | Higher total soluble solids and improved acidity levels; enhanced flavor profile Increased anthocyanin content due to light spectrum effects | [120] |

| | | | | |
|---|---|---|---|---|
| Citrus | Balanced NPK application leads to improved nutrient status; higher phosphorus enhances sugar to acid ratio | Moderate to high depending on soil conditions | Improved fruit size, weight, and TSS; better color and firmness due to nutrient management<br>Increased flavonoids and phenolic compounds from adequate boron and calcium | [109] |
| Apples | High calcium [Ca] uptake is essential for firmness and storage quality; N and K critical for early growth stages | Moderate, varies with rootstock and soil type | Enhanced firmness, color, and storage potential; reduced postharvest disorders with proper Ca levels<br>Increased phenolic compounds contributing to flavor and health benefits | [112] |
| Apricots | Nutrient uptake is influenced by genotype and environmental factors; specific data not detailed in the results | Not specified; potential benefits from mycorrhizal associations | Physiological attributes, TSS, titratable acidity, pH, and phytochemical content affected by nutrient management<br>Phytochemical content varies significantly with management practices and soil fertility | [113] |
| Mango | Enhanced nitrogen, and potassium uptake | Moderate | Better aroma, improved flavor profile<br>Elevated polyphenols, terpenes | [113] |
| Banana | Higher phosphorus, and potassium absorption | Moderate to high | Enhanced sweetness and firmness<br>Increased phenolics and dopamine | [114] |
| Blueberry | Increased nitrogen and phosphorus uptake | Moderate | Improved antioxidant levels<br>Elevated anthocyanins and polyphenols | [115] |
| Tomato | Improved potassium, and calcium uptake | High | Higher levels of lycopene and carotenoids | [116] |
| Guava | Higher nitrogen, and phosphorus uptake | Moderate | Improved vitamin C, sweetness<br>Elevated flavonoids, carotenoids | [117, 118] |
| Cherry | Enhanced potassium, nitrogen uptake | High | Improved sweetness, antioxidant content<br>Higher anthocyanins, flavonoids | [118] |
| Fig | Higher calcium, and potassium uptake | Low to moderate | Improved sugar content, firmness<br>Increased polyphenols, flavonoids | [119] |
| Blackberry | Increased nitrogen, and phosphorus uptake | Moderate | Enhanced flavor, better color<br>Elevated anthocyanins, polyphenols | [121, 116] |
| Peach | Increased phosphorus and calcium | Moderate | Improved sweetness, firmness<br>Elevated phenolic compounds, carotenoids | [122] |
| Watermelon | Enhanced nitrogen, and potassium uptake | High | Improved sweetness, lycopene content<br>Higher lycopene and flavonoids | [123] |
| Pomegranate | Improved nitrogen, potassium uptake | Moderate | Higher juice yield, better color<br>Increased anthocyanins, ellagitannins | [124] |
| Pineapple | Enhanced potassium, nitrogen uptake | Moderate to high | Improved sugar content, acidity balance<br>Elevated bromelain, polyphenols | [125] |
| Avocado | Increased phosphorus and potassium | Moderate | Improved creaminess and oil content<br>Elevated tocopherols, sterols | [126] |
| Raspberries | High nitrogen and potassium uptake; sensitive to soil moisture levels. | High | Improved berry size, color intensity, and flavor profile.<br>Elevated anthocyanins contribute to color and health benefits. | [110] |
| Pepper | Increased phosphorus and potassium uptake, is essential for fruit formation and quality. | High | Improved color, size, and firmness; increased capsaicin content in hot varieties<br>Elevated phenolics, carotenoids, and capsaicin [in hot peppers], enhancing antioxidant and health benefits | [127] |
| Passion Fruit | Increased phosphorus, calcium, and potassium uptake, is critical for tropical fruit growth. | High | Enhanced fruit size, juice content, and acidity, leading to the improved flavor profile<br>Higher levels of flavonoids, carotenoids, and polyphenols, contribute to antioxidant and anti–inflammatory properties | [128] |
| Pears | Significant calcium and potassium uptake for cell wall strength; moderate nitrogen needs. | Moderate | Improved texture, sweetness, and overall flavor profile.<br>Increased sorbitol and phenolic compounds enhance taste. | [129] |

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| Cantaloupe | Enhanced phosphorus and potassium uptake, crucial for fruit quality and shelf life. | Moderate to high | Improved size, color, and firmness; enhanced sweetness and vitamin C content | [130] |
| Olive | Increased phosphorus, nitrogen, and potassium uptake, essential for fruit set and oil content. | High | Improved oil yield, flavor, and quality; higher levels of oleic acid and other essential fatty acids | [131] |
| Dragon Fruit | Enhanced nitrogen, phosphorus, and potassium uptake, which supports growth and fruit quality | Moderate | Elevated betalains, phenolics, and flavonoids, which enhance antioxidant and anti–inflammatory properties | [132] |
| Plums | Significant potassium uptake; moderate nitrogen needs for optimal fruit set | Moderate | Increased levels of phenolic compounds like chlorogenic acid. | [133] |
| Ber (Indian Jujube) | Improved nitrogen and potassium uptake, essential for fruit set and quality in arid conditions | Moderate | Elevated phenolic compounds and flavonoids, supporting antioxidant and anti–inflammatory properties | [134] |

Table 3: Assessment of Arbuscular mycorrhizal fungi on crop quality and soil health

| Stressor | Fruit crops | Fungus species | Roles | References |
|---|---|---|---|---|
| Drought | *Citrus*<br>*Poncirus trifoliata* | *Funneliformis mosseae, Paraglomus occultism* | Ameliorate the hyphal length, water absorption rate, and leaf WP | [135] |
| Drought | Olive<br>*Olea europaea* | AM Fungi | Mitigated drought effects and enhanced TP [Ψp] and mineral absorption | [136] |
| Drought | Lettuce and tomato | *Rhizophagus irregularis, Glomus intraradices* | Enhanced yield of biomass, Improved photosystem 2 productivity, accumulating<br>Synthesis of ABA and formation of strigolactones | [137] |
| Drought. | Strawberry<br>*Fragaria × annassa* | *F mosseae BEG25, F. geosporus BEG11* | Increased shoot and root fresh weights, WUE, and plant survival | [138] |
| High Temperature | Tomato | High Temperature | Augmented photosynthetic efficiency, Ameliorate root hydraulic conductivity.<br>Improved aquaporin prevalence | [139] |
| Drought | Pistachios (‘Badami Riz–Zarand’ and Pistacia vera ‘Qazvini’) | AMF<br>(*F. mosseae* and *R. intraradices*) | increased the utilization of essential minerals like Zn and P | [42] |
| Drought | Citrus | AMF | Reduced their osmotic potential | [72] |
| Salt Stresses | *Vitis vinifera* L. ‘Dogridge’, ‘1103’, ‘Paulsen’ and ‘Harmony’] | AMF such as *R. intraradices, F. mosseae* | improved plant height, stem diameter, and shoot/root biomass<br>Na and Cl levels decreased,<br>K and Mg concentrations increased in leaf tissues, potassium to sodium ratio increased. | [140] |
| Salt Stresses | *Citrus* spp. | *Paraglomus occultum* | Decreased the level of sodium<br>Higher concentrations of K and Mg in leaf tissues,<br>Increased potassium–to–sodium ratio | [141] |
| Salinity Tolerance | Date palm trees (*Phoenix dactylifera* L) | AMF and *putrescine amine*, PGPB (*Paenibacillus polymyxa, Azospirillum lipoferum, Bacillus ciraulan)* | Young leaves showed reduced lipid peroxidation<br>Increased diamine and polyamine oxidases. | [142] |

| | | | | |
|---|---|---|---|---|
| Frost Resistance | Strawberry | biostimulant containing animal–derived amino acids (porcine blood) | Produced more root biomass when the weather was cold | [143] |
| Low Temperature Tolerance | Blueberry from *Vaccinium ashei* ('Britewell') and *V. corymbosum* ('Misty') | AMF inoculated | Ameliorate the GMX, APX, SOD, and other antioxidant enzymes, Improving blueberry stem and foliage P and K uptake. | [144] |
| Tolerance To Aluminum (Al) Toxicity | Banana | *R. intraradices* (MUCL 41833) | Ameliorate nutritional status of Ca, K, and Mg, Restricted supply of Al to the aerial region, and cell membrane stability and integrity | [12] |
| High Temperature Stress tolerance | Grapevine | *Rhizoglomus irregulare, Funneliformis mosseae* | Growth rate, substrate carbon conversion efficiency, and stomatal conductance increased. | [1] |

### 5.2 Edaphic factors crop interaction

AM usually thrives to colonize well in sandy or loamy soils. Such soils easily penetrate the air and roots [144, 145]. However, clay soils cause less colonization since the roots tend to be shallow and narrow as a result of root–stunted development. Clay soil compaction leads to decreased effective growth as a result of the limited root development caused by it. The range at which AM fungi thrive is under a pH of 6.0–7.5. However, extremely acidic or basic soils lead to hardiness germination of spores of arbuscular mycorrhizal, leading to decreased colonization. This constraint is more relevant in areas where soil pH is high or salty, and thus reduces fruit yields. High SOM levels create an environment that favors the establishment of an environment that is conducive to AM, and such soils usually tend to suppress colonization when their levels are low. The plants grown in overly rich soil are less reliant on mycorrhizal arbuscular fungi to acquire nutrients and usually have fewer symbiotic associations.

## 5.3 Ecophysiological conditions

AM fungi are sensitive to soil temperature, moisture, and light conditions. Cold temperatures can slow spore germination and colonization, while drought and extreme heat can hinder root growth and fungal efficacy. In high–density orchards, shading may limit fungal development in lower canopy areas. AM fungi thrive in soils with moderate to high phosphorus levels, but excessive phosphorus fertilization can suppress their symbiosis and hinder spore germination. Additionally, agrochemicals, including systemic fungicides, can damage AM fungi, reducing their benefits to fruit crops.

## 5.4 Economic challenges and variability in field conditions

Commercial AM Fungi may be expensive to maintain, particularly for small-scale or limited-resource farmers. While the long–term advantages of AM inoculation may surpass the expenses, the initial financial burden may deter farmers from utilizing AM products, especially in underdeveloped nations. In underdeveloped nations, restricted availability of superior AM inoculants may hinder the application of AM in fruit cultivation, impacting the potential for yield and sustainability. The variability in field settings complicates the attainment of consistent outcomes using AM inoculation. In contrast to greenhouse or controlled environments, open–field application is influenced by numerous variables, including changeable weather conditions and soil health discrepancies. Field investigations indicate that AM colonization efficiency can be uneven, regardless of the same crop, resulting in unpredictable yield enhancements. The uncertainty complicates large–scale adoption, since farmers require dependable outcomes to validate their investments in AM products. The areas with extreme climatic restrictions, such as frequent floods or droughts, pose a problem with applying AM because of the survival issues associated with the fungi. Although specific strains of AM are suited for certain climates, large–scale applications over different sites would need to develop specialized formulations of AM that can adjust to local conditions. Maintaining the survival of arbuscular mycorrhizal (AM) fungus in climates of significant seasonality, and especially so where there is a dramatic differentiation between a dry season and a wet season, is difficult because AM spore viability is also affected by seasonal moisture and temperature conditions.

### 5.5 Crop interaction

A particular crop may have many varieties that can respond distinctly upon AM inoculation. Apple or grape cultivar response could be dramatic, whereas a minimum response is present with some of the plants. The heterogeneity required precise selection and matching for each specific type of crop, making its applications more complicated at high levels. Some plants' inability to form an effective arbuscular mycorrhizal symbiosis may relate to genetic predispositions. Yield and resistance to insects and disease are common goals of breeding programs for improving the cropping systems, but often ignore traits that enhance arbuscular mycorrhizal colonization. The consequence is that arbuscular mycorrhizal fungi are less compatible with current cultivars bred for increased productivity than they are with conventional or wild forms. Breeding for traits that favor arbuscular mycorrhizal colonization will shift the balance of competing agronomic features such as early maturation and disease resistance. The breeding efforts are to develop cultivars compatible with AM while meeting other production needs. Some other challenges like Regulatory and Quality Control Issues, and Lack of Standardization in AM Products. Regulatory Barriers to limited Certification and Accreditation are a major drawback.

## 6. Future prospects and research directions

Mitigating constraints on AM fungi efficacy in fruit production requires specialized inoculant formulations, region–specific species selection, and cost–effective delivery techniques for farmers. Future research and technology innovations will be key in addressing these challenges, expanding the applicability of AM across diverse agricultural contexts (Fig. 2).

### 6.1 AM Efficiency through breeding or genetic manipulation

Selective breeding initiatives can focus on developing crop genotypes with root structures or exudate characteristics that enhance AM colonization, improving nutrient absorption, stress resilience, and total fruit quality. Gene editing technologies like CRISPR/Cas9 can be used to enhance crops' susceptibility to AMF by targeting genes associated with mycorrhizal signaling, root architecture, or nutrient movement, optimizing symbiotic benefits. Understanding the molecular signals between plants and AMF is essential for improving symbiosis, particularly under suboptimal soil conditions. Research on genetic mechanisms and the impact of environmental stressors (e.g., salinity, temperature, water stress) on AMF signaling pathways will help develop AMF–optimized crops that perform well in challenging conditions, promoting sustainable fruit cultivation.

### 6.2 Sustainable agriculture and arbuscular mycorrhizal

Arbuscular mycorrhizal fungi (AMF) enhance water use efficiency and facilitate deeper moisture access, improving fruit crops' resilience to water stress and reducing irrigation dependence. The AMF also supports carbon sequestration by promoting root development and increasing soil organic matter (SOM). By enhancing nutrient absorption, AMF reduces the need for chemical–based fertilizers and further helps in greenhouse gas (GHG) mitigation. Incorporating AMF inoculation in fruit cultivation enables farmers to diminish their ecological footprint while sustaining high yields.

### 6.3 Potential role in organic farming and agroecology

Organic and agroecological methods of farming frequently utilize natural additions to improve soil quality and structure. Arbuscular mycorrhizal fungi provide a biologically based resource that complies with organic certification criteria, enhancing the cycling of nutrients and pest resistance in natural fruit orchards. Arbuscular mycorrhizal fungi enhance the diversity and resilience of the soil and the microbiome, which is essential for biological structures reliant on natural processes instead of synthetic inputs. By enhancing crop longevity, AM may support agroecological activities designed to foster diversification from the top to the soil. Organic farming often employs rotations of crops and polyculture to mitigate infestations and preserve soil health. Investigating the role of AM fungi in these systems may facilitate the identification of methods to optimize advantages across diverse crop cycles, especially through the selection of AM strains capable of associating with multiple cultivars.

### 6.4 Technology integration

Arbuscular Precision Horticulture tools like soil–based sensors and statistical analytics can optimize AMF cultivation by pinpointing precise areas in the orchard where AM colonization yields optimal results. Soil sensors monitor water and nutritional status, enabling targeted AM treatments in nutrient–deficient or susceptible to drought. Remote sensing technology, including satellite imaging and drones, assesses the influence of AM fungus on crop well–being and yield, improving application efficiency. Biotechnology advancements, including molecular approaches to identify and cultivate superior AM strains, enable researchers to develop inoculants that exhibit resilience, consistency, and efficacy across diverse environmental circumstances.

### 6.5 Promote arbuscular mycorrhizal fungi with technological tools

Innovative bioformulations that integrate AMF with advantageous microbes, biological stimulants, or organic compounds may augment the symbiotic advantages of AM application. These compositions would enhance nutrient absorption and plant vitality while providing defense against soil–borne pathogens. Nanotechnology provides intriguing alternatives for targeted AM applications. The nanoscale and carriers can safeguard AM spores from adverse conditions and facilitate their direct delivery to the root zone, hence enhancing colonization success rates, especially in challenging or fluctuating climates. Intelligent delivery devices, such as controlled–release capsules, could modulate the time and place of AMF release under plant growth and environmental circumstances. By aligning additive manufacturing supply with essential growth phases, intelligent systems could improve colonization efficiency and minimize waste, rendering AM implementation more practical and more profitable for farming.

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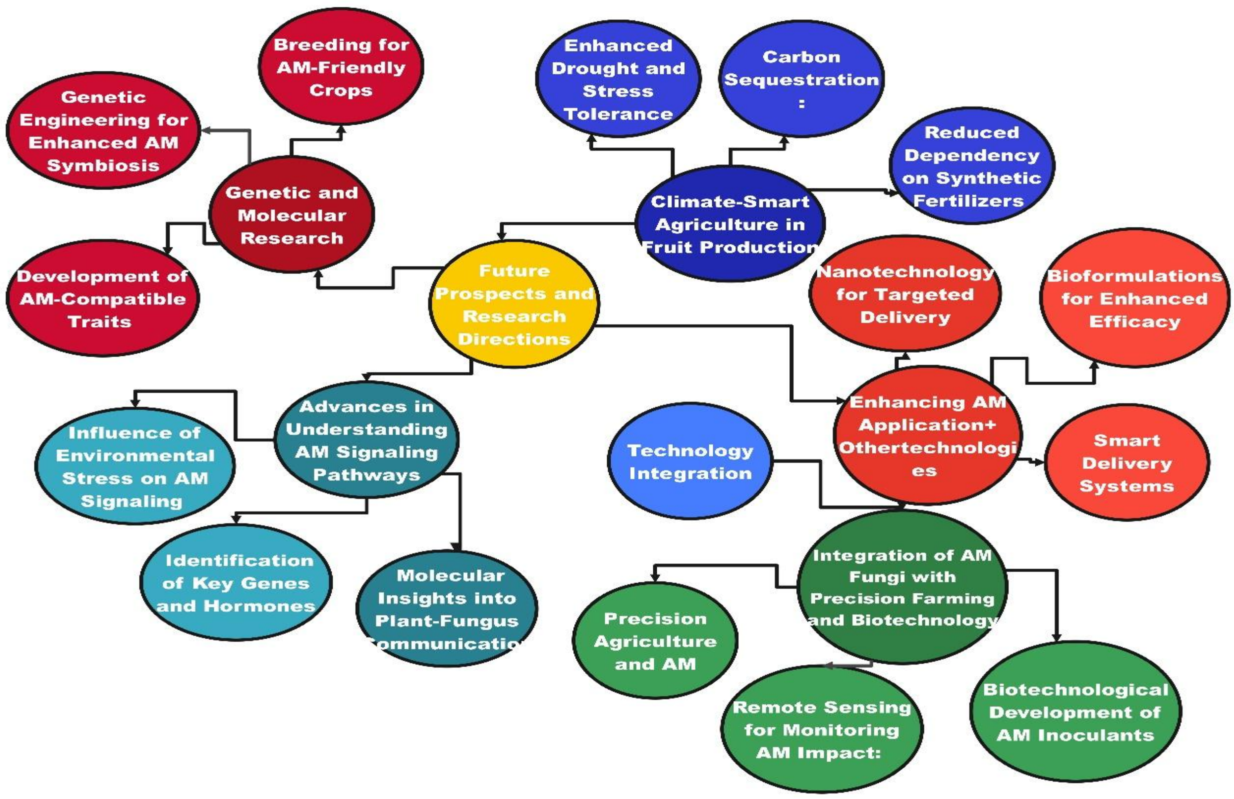


**Figure 2:** Different research prospects and Future direction for improving the role of AM fungi in fruit crops

## 7. Conclusion

Arbuscular mycorrhizal fungi (AMF) present a crucial opportunity to increase fruit production while contributing to sustainable and climate–resilient agriculture. By improving plant water and nutrient uptake, boosting plants' tolerance to abiotic stresses, and reducing reliance on synthetic inputs. AMF contribute directly to ecological health and sustainable agriculture. Their influence extends to improved root establishment, soil health restoration, and carbon sequestration, which are key strategies in mitigating climate change and soil degradation. The potential of AMF goes beyond individual crop improvement, favors agroecosystems, and allows organic farming and agroecology approaches. To fully exploit this potential, future research must focus on genetic and molecular research, precision agriculture, innovative bioformulations, and soil-specific inoculant optimization. Integrating AMF into mainstream agricultural practices offers not only a pathway to higher fruit yields but also a means of strengthening food security, enhancing environmental resilience, and supporting global sustainability goals. This review underscores the global implications of AMF in advancing sustainable horticulture and creating lasting impacts on both agriculture and the environment.

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