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Chapter

Mitigating Climate Change: The Influence of Arbuscular Mycorrhizal Fungi on Maize Production and Food Security

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Abstract

Anthropogenic activities have contributed to the increased atmospheric concentration of greenhouse gases, which are an important contributor to climate change. From 1940 to 2004, global emissions increased by 70%, and projections suggest a continual increase by 2050 due to agriculture, forestry, and other land uses. Arbuscular mycorrhizal (AM) fungi are ubiquitous in undisturbed soils and form a symbiotic relationship with various plants. The relationship that enhances nutrient uptake and plant growth, among other benefits, is well known. Several soil management practices employed in agriculture adversely affect the symbiosis. *Zea mays* (maize) provides 30% of total caloric intake to 4.5 billion people worldwide and is an important staple crop, vulnerable to climate change. Higher temperatures can result in increased water demand, while changes in precipitation can result in crop failure. AM fungi can be applied as inoculants to maize. Resulting in improved plant growth, yield, and nutrient uptake and providing superior food quality properties, such as increased antioxidants, vitamins, and minerals. AM fungi are considered a crucial biotechnological tool in crop production. This review illustrates their essential role in sustainable maize production and emphasizes the need to maintain AM fungal communities in the soil to mitigate the effects of climate change.

Keywords: *Zea may*, symbiotic benefits, drought and salinity, soil management, sustainable agriculture

1. Introduction

Crop production is the primary source of staple foods and is particularly sensitive to climate change. Activities such as synthetic fertilizer use, livestock rearing, change in land-use patterns, deforestation, waste disposal, burning of fossil fuels, industrial manufacturing and transportation have contributed to the increased atmospheric concentration of greenhouse gases, contributing to climate change [1]. Of the global anthropogenic greenhouse gas emissions, approximately 13% are attributed to agricultural practices [2]. Predictions indicate that by 2030 these emissions will rise

almost 40%, primarily due to increasing demand from a growing population and changing consumption patterns for food, including increasing demand for ruminant meats [3].

Between 1940 (pre-industrial) and 2004, global greenhouse emissions (GHG) increased by 70% [2]. Average temperatures have increased by 1.5–2°C. Urgent climate change mitigation is required to halt further increases. The effect on agriculture is severe, with adverse growing conditions such as drought and extreme weather events already evident [4]. Agriculture can reduce these negative effects, increasing carbon storage by improving cropping and land management practices [5].

Mitigation technologies may not be cheap and easy, but the cost and benefits will be less than the losses caused by climate change [6, 7]. The expected impacts of climate change will be most adverse in low- and middle-income countries, where millions of people depend on agriculture and are vulnerable to food insecurity [8, 9]. The impact on global food security will relate to food supply and food quality, food access and utilization, and the stability of food security resulting in reduced per capita calorie availability, childhood malnutrition, and child deaths [10]. Climate change may affect the nutritional properties of some crops. The concentrations of minerals in some crops (e.g., wheat, rice, and soybeans) were up to 8% lower under conditions of elevated carbon dioxide (CO_2) levels [11]. Studies on yields (primarily wheat, maize, rice and soybeans) under different climate change conditions indicate that climate change may significantly reduce these in the long run [12].

Maize (*Zea mays* L.) is known globally as the queen of cereals because it can be grown throughout the year, is photo-thermo insensitive and has the highest genetic yield potential among cereal crops. Maize provides 30% of total caloric intake to 4.5 billion people worldwide [13]. The grain contains about 72% starch, 10% protein, 4.8% oil, 5.8% fiber, 3.0% sugar, and 1.7% ash [14]. The major maize-producing countries are the USA, China, Brazil, Argentina, Ukraine, Indonesia, India and Mexico [15]. Globally, maize is grown mainly for livestock feed, food, and industrial materials [16]. Regarded by most people as a breakfast cereal, maize is also a source of fuel (ethanol) and starch in processed form. Enzymatically maize starch is converted into products such as sorbitol, dextrin, sorbic and lactic acid and appears in household items such as beer, ice cream, syrup, shoe polish, glue, fireworks, ink, batteries, mustard, cosmetics, aspirin, and paint [17]. In South Africa, maize is the most important grain crop for feed and is a staple of most of the population [17]. Of the total maize produced in South Africa, approximately 60% is white (for human consumption), and 40% is yellow (mainly for animal feed) [18]. Adverse effects of climate change on agricultural production will be most severe in the global south, particularly South Asia and Sub-Saharan Africa, many regions of which remain underdeveloped [19]. Finding ways to improve the productivity of agriculture, particularly of staple crops such as maize, is one means of meeting these future challenges.

2. Improving nutrient uptake

Management technologies, crop species, and soil type play a significant role in soil microbial diversity [20]. Arbuscular mycorrhizal (AM) fungal diversity positively contributes to nutrient and water use efficiency [20]. The frequent use of soil amendments such as fertilizers, organic residues, and pH adjustments to improve crop yields can change the soil properties, which leads to variations in plant and fungal responses that can modify the outcome of the symbiosis [21].

In many soils worldwide, low phosphorus (P) availability can limit plant growth [22]. Availability and acquisition of P in terms of plant root architecture and mycorrhizal association is controlled by rhizospheric chemical and biological processes which compensate for this limitation [23]. Maize has a high requirement for nitrogen (N) and P nutrients, and these are applied in large quantities to realize high yields [24]. Not all applied fertilizer is absorbed. For example, maize absorbs only 55–60% N [25], around 20% P [26], 50–70% potassium (K) [27] and 33% sulfur (S) [28]. One strategy to reduce fertilizer usage, especially P, is to use AM fungi to improve maize nutritional status and growth [29].

AM colonized plants absorb more P (nearly 80% of the plant P uptake) at lower concentrations in the soil solution than non-mycorrhizal plants [30–32]. The AM fungi forms an extraradical mycelium (ERM) network that effectively exploits the soil environment in the search of nutrients [33, 34], providing access to more soluble forms of phosphate [35, 36], and promotes plant N uptake [37]. Acquisition of other soil nutrients such as copper (Cu), iron (Fe), K, zinc (Zn), calcium (Ca) and S, especially when plants are grown in nutrient deficient soils are also improved by the symbiosis [38–41].

Different AM fungal species exhibit different levels of effectiveness. A study by Bi et al. [42] on maize's growth and nutrient uptake showed that the effect of two AM fungi, *Funneliformis mosseae* and *F. versiforme*, increased plant growth when compared with non-inoculated controls. *F. mosseae* being the most effective. In a field experiment, commercial AM fungal inoculants applied to maize improved plant growth, yield, and P uptake under both un-fertilized and P-fertilized treatments [43]. Inoculation of maize with *Glomus caledonium* increased soil organic C content in maize straw-amended soils, likely due to enhanced rhizosphere acidification and increased nutrient (notably P) uptake in the seedling period.

Intercropping can also improve plant nutrient uptake [44] because intercropping systems can better use one or more agricultural resources both in time and in space [45]. He et al. [46] reported N transfer from N_2 fixing legumes to maize and other crop species. Marzban et al. [47] demonstrated that intercropping maize and green bean could increase root growth of maize (about 7.2% more than in monocropping). Biological nitrogen fixation is heavily dependent on P, which provides energy for converting atmospheric N to useable N compounds. Arbuscular mycorrhizal fungi form a tripartite association with N-fixing rhizobia and legumes assisting in acquiring P [48].

Plant nutrient uptake involves two pathways, the direct pathway (DP) involves uptake of nutrients from the rhizosphere by the root epidermis and root hairs [49]. The mycorrhizal pathway (MP) develops behind the root hair zone and involves uptake of nutrients by the ERM, rapid translocation over many centimeters, delivery to the symbiotic interfaces, and transfer to the plants [34]. The two pathways are potentially independent and involve different cell types and different nutrient transporters, providing capacity for independent and coordinated regulation and nutrient access from different regions and volumes of soil [39, 41]. The conserved P-sensing pathway regulates the direct and indirect P acquisition pathways, centered on phosphate starvation response (PHR) transcription factors [50]. PHR transcription factor was characterized in many plant species [51, 52]. Xu et al. [53] identified 18 ZmPHR genes involved in relocating inorganic P across different maize plant tissues.

The mycorrhizal pathway involves the uptake of orthophosphate (Pi) by AM fungal high-affinity Pi transporters in the ERM, followed by translocation of P

along the hyphae to intracellular structures in the root cortex and then transfers P to the root [34, 54–56]. Polyphosphate (polyP: linear chains of Pi residues linked by phosphoanhydride bonds) accumulate in the hyphae, where it buffers cytoplasmic Pi concentration, providing temporary P storage, and translocate P along hyphae [50, 57] resulting in rapid, long distance P translocation from sites of uptake in the ERM to sites of transfer to the plant [58]. Pi and polyP are known to carry negative charge, which cations must balance. In soil-grown plants, K^+ and Mg^{2+} may play this role [59, 60]. H^+-ATPases, which energize perifungal membranes surrounding arbuscules, are involved in all Pi-uptake steps [61–63].

The advantage of the AM symbiosis for plants in acquiring P is that AM fungi provide a very effective pathway, the AM pathway, for scavenging P from large volumes of soil and rapidly delivering to cortical cells within the root bypassing direct uptake [34]. Research by Smith and colleagues [34, 64] revealed that the AM pathway plays a significant role in P uptake, regardless of how an AM plant benefits in terms of increased growth or P uptake.

In addition, AM fungi can deliver substantial amounts of N to the host plant [65]. Researchers have different opinions on the mechanisms of N transfer to the host plant. Smith et al. [66] suggested that N might be transferred from the fungus to the host in the form of amino acids (AA) or amides. While Kaldorf et al. [67] suggested transfer in the form of NO_3^-, Bago et al. [68] postulated that N is transferred to the host as NH_4^+. The allocation of C to the AM fungi has been reported to depend on the N status of the mycorrhizal root, which indicates that the stoichiometry of C and N regulates the nutrient exchange between the fungus and the host plant [69]. The ERM absorbs various forms of N with 21% of total N taken up by the fungal ERM transferred to roots in root organ culture [70]. Additionally it was demonstrated that 74% of the total N in the leaves of maize was derived from the slow-release urea added to the hyphal compartment [71].

Studies showed that the AM fungus *Glomus hoi* enhanced degradation of organic residues and N uptake by the host plant [72, 73]. Jin et al. [74] demonstrated that urea or NH_4^+ were absorbed more rapidly than NO_3^-, amino acids (AA), and proteins when supplied as N sources for AM fungal uptake. Assimilation of NH_4^+ is the principal means of N absorption in AM fungal systems mediated by a specific carrier [75]. GintAMT1, which encodes the high-affinity NH_4^+ transporter in the AM fungus *Rhizophagus intraradices* [76] is one such carrier. The uptake of NO_3^- is linked to an H^+ symporter that alkalinizes the external mycelium. It has been shown that mycorrhizal roots growing in a NO_3^- amended soil induced an initial (30 d) alkalinization of the mycorrhizosphere, which was followed (at 60 d) by strong acidification. This acidification of the mycorrhizosphere would be the consequence of the unmasking of other cation/anion balances involved in different nutrient uptake processes once the nitrate is depleted [77, 78].

3. Carbon sequestration

The AM symbiosis represents a significant link between atmospheric and soil-contained carbon (C). Soil is one of the planet's largest C sinks. It stores at least twice as much C as currently occurs in the world's vegetation plus atmosphere. The estimated total soil organic carbon (SOC) to 2-meter depth is 2400 Pg, which is three times the amount of CO_2 currently in the atmosphere (~830 Pg C) and 240 times current annual fossil fuel emissions (~10 Pg) [79]. Carbon storage depends on the

balance between carbon sequestration by plant photosynthesis and carbon release to the atmosphere through soil respiration [79, 80]. Atmospheric CO_2 concentrations will reach 550 ppm by 2100, accompanied by an increase in global average annual temperature of $4.4 \pm 0.5°C$ for 2070–2099 [81]. One of the consequences of this increase may be increased carbon availability to fungi to develop the mycorrhizal mycelium [82]. AM fungi receive increased levels of photosynthates under elevated CO_2 before other soil microbes [83, 84], increasing AM fungal colonization [85, 86]. Treseder and Allen [87] reported that mycorrhizal dependent plants allocate 5–20% of the net photosynthate to maintain symbiosis [88] increasing the sink effect and movement of photo-assimilates from aerial parts to the roots [89]. CO_2 enhancement of AM fungi might alter terrestrial ecosystem C dynamics by stimulating the decomposition of soil organic C in AM fungal active zones [90]. Globally forest soils release approximately 24Pg carbon per year into the atmosphere via CO_2 efflux and generate CO_2 from a wide variety of belowground organisms, with AM fungi as the dominant carbon source [91]. Elevated CO_2 increases allocation to AM hyphae in the soil outside plant roots [86, 92] due to carbon sequestration [93]. Research conducted in a German grassland community reported that AM fungi stimulated soil respiration of pasture soil, leading to elevated CO_2 levels and temperature, with most carbon sequestered in belowground parts [94, 95].

High-temperature stress negatively affects plant morphological, physiological, and biochemical growth, leading to reduced plant productivity [96, 97]. Hatfield et al. [98] showed that temperatures above 35°C affected maize vegetative and reproductive growth, from germination to grain filling. Temperature also regulates mycorrhizal fungal growth and metabolic activity [99], with colonization peaking during the growing season when temperatures are warm [100]. Changes in atmospheric CO_2 concentration and temperature and resulting changes in soil physicochemical properties and microbial activity [101] can influence mycorrhizal symbiosis on various scales [102].

Crop growth and development are critical factors in determining the impact of a changing environment. Increasing temperatures affect all major grain crops [103]. Maize is one of the most important crops grown in tropical countries and tolerates temperatures up to 32–33°C. Beyond this range, crop growth and yield starts to decline [103]. Photosynthesis is one of the most heat-sensitive processes in plants and is essential to maintaining the mycorrhizal symbiosis [104, 105]. The AM fungal network provides the host plant with nutrients and water from the soils and enhances the plant's tolerance to various abiotic stresses [106] and can thus alleviate additional stress placed on crop plants due to climate change.

4. Tolerance to drought, temperature and salinity

Environmental factors are stressors that impact plant growth [107]. Drought is a significant challenge [108] resulting from low precipitation and a high rate of evapotranspiration causing reduction in plant cell division and proliferation of roots, closure of stomatal pores, changes in plant and water uptake efficiency, and high production of abscisic acid, which further decreases evapotranspiration by controlling stomatal pores [109]. Plants have developed various mechanisms to retain water under these conditions.

The ability of AM fungi to exploit soil resources assists the host plants' ability to grow under drought stress [110]. The AM fungal hyphae can absorb water by entering

soil pores that are too small for root hairs to access [111, 112]. AM fungal mycelia can also improve soil moisture retention by enhancing soil aggregation [113]. Glomalin is a hydrophobic protein [113] present in AM fungal hyphal walls [114], which forms an insoluble glue with a strong cementing capacity that stabilizes soil aggregates [92, 115–119]. Glomalin is quantified by measuring several glomalin related soil-protein (GRSP) pools [92]. The glomalin compound contains 30–40% C, which protects the soil from drying out [120], 0.9–7.3% of N, 0.03–0.1% of P and metal ions [121]. Hyphae and glomalin contributed up to 15% of soil organic C in a grassland [122]. As a result, a considerable amount of C allocated to AM fungi is used in glomalin production, governed by plant productivity [122]. The regulation of plant nutrient uptake, stomatal conductance, leaf water potential, photosynthesis, and transpiration [123, 124] help plants to produce significantly higher yields under stressful conditions. The AM fungi modify the root hairs allowing plants to overcome drought [123]. They assist in maintaining high relative water content of the leaf, improving water use efficiency [125], increasing leaf area, delaying senescence [126] and maintaining ion balance [127]. Li et al. [128] observed that in the arbuscule-enriched cortical cells and ERM of maize roots, the expression of two functional aquaporin AM fungal genes i.e., GintAQPF1 and GintAQPF2, were enhanced under drought stress. Maize is sensitive to drought and heat stress, particularly at the reproductive stages of development reducing grain yield [129]. Some AM fungal species, such as *Funneliformis mosseae*, minimize the adverse effects of drought by the accumulation of AA, increase in trehalose content and higher trehalase activity [130]; *Rhizophagus intraradices* increased plant dry weight, uptake of P, N, K, and Mg in shoot, and water use efficiency [131].

In many parts of the world, maize production occurs in semi-arid environments where high temperatures and water scarcity [132, 133] are common challenges. In China 60% of crops in maize growing regions are often subjected to spells of heat and drought, resulting in 30% yield losses per year [133]. These climate change-induced stresses will significantly threaten maize yields and decrease world maize production by 15–20% annually [133, 134]. AM fungi play an essential role in improving drought tolerance. They mediate the increase in nutritional status by increasing the developing root surface area, enhancing the uptake of P [131, 135, 136], increasing resistance to withering [137], increasing proline accumulation levels in roots [138, 139] and by increasing photosynthetic activity as detected by the increase in chlorophyll [140, 141]. Temperature is another important environmental factor that determines the growth and productivity of crops [142]. Temperature stress (low and high temperature) can occur during the growing season [97, 143] resulting in the disruption of physiological and biochemical processes and functions. This results in injuries such as damage of cell membrane structure and lipid composition, cellular leakage of electrolytes and amino acids, peroxidation of membrane lipids, a diversion of electron flow to alternate pathways, denaturation and aggregation of proteins, redistribution of intracellular calcium ions, inactivation of enzymes in chloroplast and mitochondria, and production of toxic compounds and reactive oxygen species (ROS) [97, 136, 144, 145]. AM symbiosis can alter plant physiology to deal with these stress conditions [146].

Zhu et al. [136] reported that *Claroideoglomus etunicatum* could be used to reduce high temperature effects on maize by reducing membrane lipid peroxidation, membrane permeability and increasing accumulation of osmotic adjustment compounds and antioxidant activity. At 35°C and 40°C, positive net photosynthesis rate, transpiration rate, stomatal conductance, chlorophyll and carotenoid contents, relative water content and negative intercellular CO_2 concentrations were recorded [136, 142].

Soil, water and the environment can influence crop salt tolerance [89]. Among abiotic stresses, soil salinization is probably one of the most important in the world [147]. Globally, arid and semi-arid soils are significant factors limiting agricultural productivity due to the high soil salinity [148]. More than 800 million hectares of land worldwide is affected by either salinity (397 million hectares) or sodicity (434 million hectares) [149]. The accumulation of soluble salts in the rhizosphere can reduce water potential and, consequently, water availability to plants. Under such circumstances, the uptake of these salts can affect the physiological processes of plants growing in these environments [150, 151] and poses the biggest challenge to food security [152]. *Rhizophagus intraradices* and *Funneliformis geosporum* increased leaf length, plant height, leaf number, chlorophyll a content, photosynthetic rate, stomatal conductance, and transpiration rate in maize [106]. Farooq et al. [153] found that AM fungal colonization and symbiosis improved salt resistance in maize due to better nutrient availability, increased potassium/sodium ratios in plant tissues, and better osmotic adjustment.

Increased temperatures and resultant drought and salinity are not the only legacies of climate change. Anthropogenic activities, which include industrial activities (mining, metal processing, fossil fuel combustion) and agricultural practices (application of fertilizers, fungicides, and sewage sludge disposal), have been described as the primary contaminants of the environment with heavy metals and are not included in this review [154, 155], however these and other growth benefits to maize are illustrated in **Figure 1**.

5. Soil management for enhanced maize production

Severely disturbed land is a global concern because changes in land use are one of the biggest threats to biodiversity and ecosystem services worldwide. This is exacerbated by increased demand for agricultural production. Studies conducted have shown that disturbance not only reduces AM fungal abundance, diversity and infectivity but can also result in drastic shifts in the AM fungal community [156]. AM fungal hyphae and root litter are the most abundant carbon source in the soil [157], providing energy for other soil microbes to flourish [92]. They may increase the diversity and abundance of microorganisms beneficial to plant growth and health [157]. Hyphae are highly susceptible to disturbance and disturbance results in reduced infective potential of AM fungi [157]. As the scale of degradation increases, the abundance and diversity of AM fungi reduces [158].

Tillage management plays a central role in ecological and biological stability, which is closely related to soil quality, by influencing the activities of soil microbial communities [159–161]. Soil disturbance, caused by tillage or plowing, decrease AM fungal colonization, disrupt AM hyphal networks [162–166], reducing spore numbers [167, 168], AM fungal species richness [156, 169] and glomalin production [170].

Conventional or conservation tillage are soil management methods employed [171]. Conservation tillage results in less disturbance when compared with conventional tillage and tends to benefit the soil by conserving aggregate stability and organic matter content [172]. Other reported benefits include higher microbial biomass in conservation tillage due to less disruption and preservation of the hyphal network, contributing to aggregate stability [173, 174]. Reduced tillage increased the abundance of AM fungal and saprotrophic fungal lipids in shallow soil layers [175].
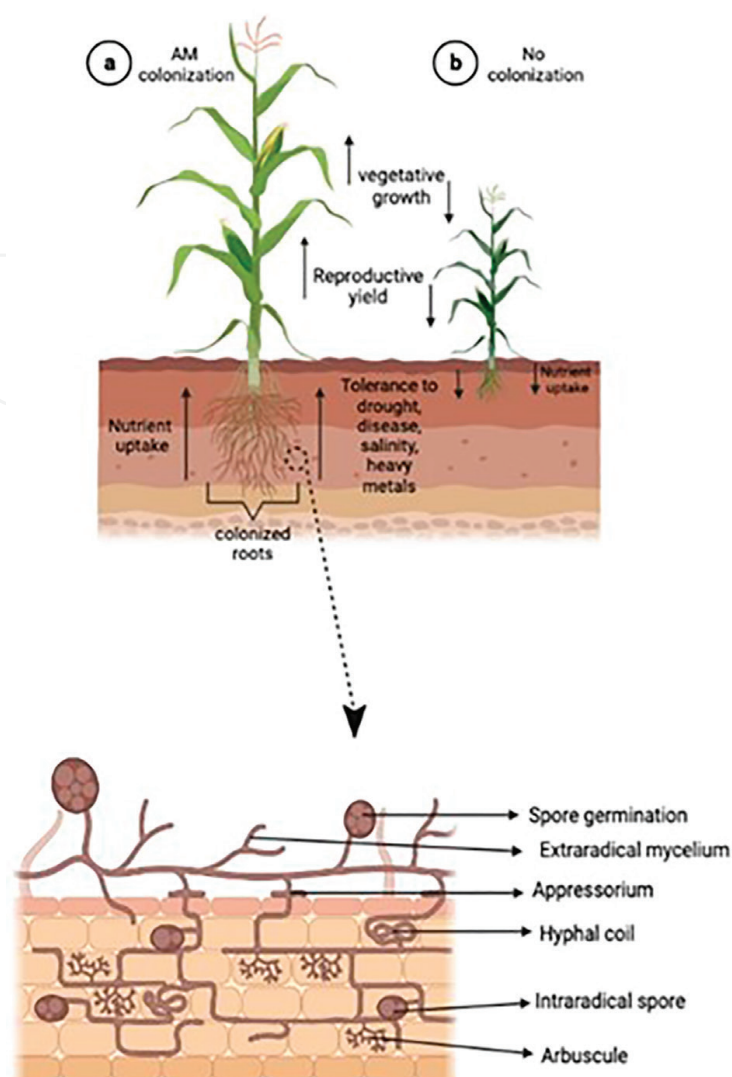
Figure 1.
Schematic representation of the effect of AM fungi on maize crop: (a) extensive roots on plant colonized by AM fungi, (b) reduced roots on plant with no colonization. (17/02/2021 - Biorender.com).

Soil disturbance reduced P uptake from the soil by maize plants, while the uptake of P by canola was not affected [176]. Canola, a non-mycorrhizal host plant, supports the hypothesis that soil disturbance reduces the effectiveness of the mycorrhizal association. McGonigle et al. [177] found that tillage reduced colonization of maize, and the P and Zn contents of maize shoots. The alteration of AM fungal communities by tillage has been reported under field conditions [178]. They demonstrated that colonization by AM fungi from the genus *Scutellospora* was depressed by intensive tillage, while members of the genus *Glomus* were not affected. Fairchild and Miller [179] demonstrated improved AM colonization of maize growing in the undisturbed soil compared to the disturbed soil when amended with P.

Globally, the prevalence of low fertility soils requires amendment with large amounts of inorganic fertilizers and application of pesticides to achieve maximum plant growth and crop yield [180, 181]. The excessive and inappropriate application of chemical fertilizers can cause a series of environmental problems and soil degradation. Balzergue et al. [182] found that the high P concentrations in plants induced by high P fertilization inhibited mycorrhizal symbiosis. Symbiosis modulating

compounds in root exudates such as strigolactone are also reduced under high P conditions [183]. Under these conditions plants are less reliant on mycorrhizal mediated P uptake and reduce carbohydrate sharing [184–186], this results in a decreased supply of soluble carbohydrate in roots reducing appressorial formation and new colonization [183, 184]. These phenomenal impact AM colonization, arbuscule formation and active P transfer to plants [187]. Some AM fungi can be relatively susceptible to fungicides, particularly when applied to the seed or the soil [188] while other fungicides can also stimulate mycorrhizal growth [189]. Fungicides such as flutolanil, azoxystrobin, fenpropimorph and fenhexamid can inhibit spore germination of *Rhizophargus irregularis* [190, 191]. The insecticide, oxamyl reduced root colonization by a commercial *Funneliformis mosseae* inoculum [192], and azadirachtin inhibiting *Claroideoglomus etunicatum* in the field causing a significant shift in the AM fungal community [193].

The response of AM fungi to agrochemicals is both substance- and dose-dependent. A field experiment showed that most AM fungi belonging to the *Glomus* group were sensitive to high levels of herbicide nicosulfuron which accumulated in soil due to repeated applications in later culture cycles [194]. Atrazine has been used as an agricultural herbicide worldwide, mostly on maize, sorghum, and sugarcane. Studies on maize showed a significant reduction in AM fungal spores [181] and AM colonization [195]. Makarian et al. [196] found a significant effect of the herbicide (metribuzin) on maize dry weight where an increase in herbicide concentration resulted in a decrease in the maize dry weight. Low herbicide concentrations resulted in increased shoot height of AM plants than when applied at high concentrations suggesting that mycorrhizal fungi can alleviate crop stress under lower doses of the herbicide [196].

The extensive use of agrochemicals reduces ecosystem functioning, contributing to soil and water degradation [197]. It also exerts deleterious effects on human health, mainly through the exposure of workers [198–200] and the intake of contaminated food crops [201]. Therefore, increasingly, the enhancement of more biologically based cultivation for safer and healthier food is a rising need, along with finding alternatives to replace agrochemicals in plant production [202–204]. The use of biofertilizers appears to be a natural option, particularly in low agrochemical input systems, because of their capacity to maintain long term soil fertility and sustainability by improving the uptake efficiency and availability of nutrients to plants [205]. Plants inoculated with AM fungi not only have improved growth but also have superior food quality properties, such as increased antioxidants, vitamins, and minerals [206]. AM fungal benefits related to maize are summarized in **Table 1**.

Monoculture is the cultivation of a single crop over a large area over consecutive years [241] and was adopted as a means to increase production [242]. Cultivated crops usually have identical genetic similarities, uniform growth patterns, and resistance to certain common diseases in monoculture. This system includes crop varieties uniquely suited to the specific conditions of a particular location [243]. This approach is criticized for its environmental impacts and is known as one of the major causes of soil degradation due to nonrotational cropping [244].

Hijri et al. [243] found that in continuous maize monoculture diversity of AM fungi decreased but found high diversity in long term field experiments where low-input agriculture involving crop rotation provided better conditions for their preservation. Sangabriel-conde et al. [245] investigated the AM fungal symbioses in native maize landraces at different levels of phosphorus fertilization. They showed a high diversity of AM fungi, most of which colonized several maize varieties, was best achieved at a moderate P level.

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Parameter (p/f)[*]	Benefits	Reference
Nutrient uptake (p)	Increased - N; P; K; Ca; Mg; Na	[37, 186, 207–223]
Nutrient uptake (f)	Increased - P; K; Ca; Mg; Fe	[221, 224–226]
Vegetative growth (p)	Increased - shoot and root biomass; root length; plant, leaf and tassel length; stem girth	[186, 203, 205, 206–209, 211, 213, 214, 216, 219, 221–229]
Vegetative growth (f)	Increased - shoot and root biomass; root length; plant height; leaf mass and area	[217, 221, 224, 226, 230–234]
Yield (p)	Increased - cob and grain yield; number of grains per cob	[215, 221, 235–237]
Yield (f)	Increased - cob and grain yield; number of grains per cob; silage yield	[226, 231, 233, 234, 238]
Salinity tolerance (p)	Increased - shoot and root biomass; K+; Na+; root volume and diameter; Reduced Cl and Na in shoots;	[208, 211, 239]
Salinity tolerance (f)	Increased – soil macroaggregates; soil bacterial diversity; nutrient uptake; photosynthesis and chlorophyll; K+; Na+	[217, 240]

p/f indicates whether the experiment was conducted under pot (p) trial or field (f) trial conditions.

Table 1.
Compendium of studies showing effect of arbuscular mycorrhizal (AM) fungi on maize.

One of the most important soil properties is its structure [246]. Soil structure results from the iterations of the soil's chemical, physical and biological factors [247, 248]. Soil management practices, especially tillage systems, affect almost all soil properties, including AM fungi activity, diversity, and glomalin production [248].

Arbuscular mycorrhizal fungi have essential functions in the construction of the soil structure by acting on the formation and stabilization of the aggregates [247, 249–251]. The effect of AM fungi on soil aggregation is a result of ERM growth into the soil matrix creating the skeletal structure that physically entangles soil particles which along with roots enable microaggregates to form in the soil. Microaggregates form larger aggregated [251] via the production of a soil glycoprotein, glomalin [247, 252–254].

AM fungi account for 5–50% of the biomass of soil microbes [255]. Approximately 10–100 m mycorrhizal mycelium per cm root has been estimated [164], the biomass of the ERM may amount to 54–900 kg/ha [256]. Rilling et al. [120] estimated that pools of organic carbon such as glomalin produced by AM fungi might even exceed soil microbial biomass by a factor of 10–20. Glomalin is present in the soil in large amounts. The concentration of glomalin in soil depends on the vegetation cover and the manner of soil management [257] and ranges from 1.6 to 2.3 mg/g soil [258]. Some examples of glomalin concentration in diverse ecosystems include; Agricultural land 0.3–0.7 mg/g [114, 259]; Boreal forest 1.1 mg/g [260]; Desert 0.003–0.13 mg/g [170, 261]; Temperate forest 0.60–5.8 mg/g [170, 262, 263]; Temperate grassland 0.23–2.5 mg/g [263–265]; Tropical rainforest 2.6–13.5 mg/g [170, 266] and Antarctic region 0.007–0.15 mg/g [267]. For example, in the top 10 cm of a tropical rain forest in Costa Rica up to 12.5 mg of glomalin cm^{-3} was reported [266] and up to 60 mg of glomalin cm^{-3} in a chrono sequence of Hawaiian soils [120]. Glomalin has a longer residence time in soil than hyphae, allowing for a long persistent contribution to soil aggregate stabilization. For hyphae, the residence time varies from days to months

[86, 266], while for glomalin, it varies from 6 to 42 years [120]. The effects of AM fungi on soil aggregation are probably more easily detected in nutrient-poor soils with neutral or alkaline soil pH [268]. The management of mycorrhizal fungi and diversity in the soil can be considered a biological approach to improving soil structure [269, 270]. Improved soil structure results in improved water infiltration and can mitigate raindrop impact through higher soil stability, increasing resistance to slaking and reduced particles detachment [271]. Significant decreases in AM fungi hyphae and GRSP concentrations have been correlated to losses of C and N protected in macroaggregates as a result of reduced aggregate stabilization [272].

Maize is an obligatory mycorrhizal species (**Table 1**) readily colonized by many non-host-specific AM fungi [273]. Agricultural techniques employing direct sowing and reduced tillage interfere as little as possible with the soil structure and do not cause tearing of the trunks of mycorrhizal fungi [273, 274] resulting in an increase and activity of soil microorganisms and enzymes, especially in the top 20 cm layer. Roldán et al. [275] examined the effect of different management practices on the soil profile distribution of organic matter and physical and microbiological soil quality indicators in a maize field under subtropical conditions. They concluded that the tillage system significantly affected aggregate stability and glomalin. The increases in glomalin suggested that the proliferation of AM fungi could have mediated the improvement in soil aggregate stability under no-tillage. Investigating the influence of tillage and no-tillage on the mycorrhizal status of a field cultivated with maize or bean [276] revealed that GRSP was greater under no-tillage Maize plants (with a root mass of 450 g m^{-3}) had a more marked effect on improving soil aggregate stability than bean plants (with a smaller root mass of 42 g m^{-3}).

6. Conclusions and recommendations

Adoption of good agriculture management practices can increase productivity, reduce erosion, increase soil fertility, and increase the soil's water-holding capacity. For farmers, it is often easier to use the agricultural systems that they are familiar with and that are supported by existing research and existing industries rather than search for the necessary solutions. Some of these systems do not consider the differences of the agroecological zones, cultures and resource limitations which tend to fail in most of the areas where they are applied. Improved soil fertility is critical. Therefore, strategies must include biologically based systems to rebuild soil fertility. Populations and space pressures are forcing farmers to use land more intensely. Reducing land degradation and replenishing soil fertility requires an integrated sustainable approach that promotes agricultural management practices that enhance AM fungal diversity. AM fungi are a key ecosystem partner that relates to sustainable management in their activity contributing to many ecosystem functions, including soil aggregation, reduced nutrient losses, and improved plant nutrient acquisition, which may reduce the amounts of fertilizer required to achieve elevated yields. Because mycorrhizal networks can create indefinitely large numbers of fungal linkages connecting many plants in a community, AM fungal formation could be a critical element in the plant succession of ecosystems and reducing greenhouse gases. The distribution pattern of AM fungi and glomalin are helpful components in monitoring desertification and soil degradation [277].

Mitigating of climate change cannot ignore the role of AM fungi and their symbiotic interaction with important crops such as maize. Adoption of soil management

approaches that sustain AM fungal populations whether indigenous or introduced are therefore essential.

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