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Arbuscular Mycorrhizal Fungi: An Environment-Friendly Approach for Sustainable Agriculture

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Abstract

The sustainable intensification of agriculture emphasizes the importance of beneficial soil microorganisms in minimizing chemical fertilizer and pesticide use while boosting plant nutrition and health. Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with land plants, facilitating nutrient absorption through extraradical networks of hyphae that spread from colonized roots into the soil. AMF protects plants from abiotic and biotic stressors while also regulating antioxidant enzymes and phytochemicals such as polyphenols, anthocyanins, phytoestrogens, and carotenoids. Recent research has raised concerns about using AMF symbionts to improve the nutritional and therapeutic value of food. Plant species have vast physiological and genetic variety, but only a few AMFs have been employed, restricting their full use. This review study focuses on the impact of AMF on plant secondary substance biosynthesis on health. It also discusses selecting the optimal symbionts for sustainable biotechnological applications in creating healthy and safe food. The article aimed to investigate how AMF improves soil qualities, including physical, biological, and chemical aspects. This study highlights information gaps and suggests potential areas for future research. This will enhance our understanding of AMF, promote more research, and help preserve soil fertility.

Keywords: Amf Functional Diversity; Sustainable Agriculture; Arbuscular Mycorrhizal Symbionts; Nutraceutical Value

Introduction

Sustainable intensification in agriculture prioritizes beneficial soil microorganisms to reduce synthetic fertilizer and pesticide use while improving plant health and nutrition value [1]. Agriculture must be intensified to meet the rising population's food needs. Intensification poses significant environmental problems, including climate change, biodiversity loss, land degradation via salinization, erosion, compaction, depletion, and pollution. The use of synthetic pesticides and fertilizers during the green movement has significantly degraded the quality and condition of our natural assets, including water, air, and soil. This has resulted in depleted and polluted water resources, rising production costs, shrinking farmers, and declining rural populations [2]. Synthetic pesticides control nutrition, hormone balances, growth regulators, nutrient discharge, and disease prevention [3]. Rather than agrochemicals, Sustainable agriculture relies on biological interactions to promote plant development and growth. Mycorrhizae are fungi in the soil that help plants absorb nutrients and water. Mycorrhizae can increase root surface area, improving plant nutrition and water absorption across large soil volumes [4]. Research suggests that mycorrhizal organisms react differently depending on the plants they are attached to [5]. Modifying the strength of mycorrhizal fungi, which regulate plant-plant interactions, might affect plant development. Mycorrhizae, which provide critical nutrients to plants, are unharmed by fungicides and herbicides. Arbuscular Mycorrhizal Fungi (AMF), a group of beneficial soil microorganisms from the Glomeromycotina subphylum, are gaining global recognition. AMF or endomycorrhizae, containing fungi, belong to the newly created phylum Glomeromycota [6]. Approximately 80% of plants have a mutualistic interaction with the AMF in soil [7]. Some families, such as Chenopodiaceae, Polygonaceae, Cyperaceae, Amaranthaceae, Caryophyllaceae, Brassicaceae, and Juncaceae, have no known relationship to other families. Abiotic stress, including drought, nutritional imbalance, and temperature, can reduce crop output by up to 70% [7]. AMF-inoculated plants improved stomatal conductance and hydration, enhanced photosynthesis, and reduced oxidative stress [8,9,10,11]. Research indicates that AMF improves plant tolerance to biotic stress, leading to increased growth and productivity [12,13]. AMF has been shown to improve soil characteristics such as aggregation, nutrient availability, microbial activity, acidity correction, water retention, nitrogen, carbon, and phosphorus cycling, as well as plant growth and productivity [14,15,16]. Numerous studies suggest that they play an important role in plants' stress tolerance systems. This review aims to summarize facts on AMF symbiosis, focusing on its benefits for soil. The initial focus is on AMF's impact on soil chemical, biological, and physical properties. This article explains how AMF impacts soil aggregation, nutrient availability, and the proliferation of beneficial bacteria. The interactions between AMF and other soil microorganisms are analyzed for their diversity and relevance.

Mycorrhizal Fungi: Origin and Evolution

According to genetic research, the earliest mycorrhizal relationship occurred approximately 450 million years ago between some primitive, most likely aquatic fungi and charophycean algae, which are the algae that gave rise to plants. Nevertheless, this theory is not supported by any fossil evidence. The 407-million-year-old Rhynie chert provides the earliest conclusive fossil evidence of a plant-fungus interaction [17-19]. From their aquatic origins, green algae gave rise to semi-aquatic and ultimately terrestrial plants. Between 490-409 mya, when these semi-aquatic algae first invaded, they had to contend with a hostile environment that was devoid of organic matter and solely composed of mineral nutrients. Three distinct waves of mycorrhizal evolution can be identified based on all the data collected. The first wave represents the start of AM association during the Ordovician Period, which we have already discussed. AM fungus spores were detected in substrates 50 million years older than the Ordovician Period [20]. During the Cretaceous Period, the Orchidaceae, Ericaceae, and other plant families with non-mycorrhizal orectomycorrhizal roots, as well as some N2 fixing symbionts, emerged [18,21]. The ectomycorrhizal Pinaceae, which first appeared in the Late Triassic or Jurassic Period [8-10], are an exception to this rule. The third wave began in the Palaeogene Period (65 mya) and is still ongoing. The term 'New Complex Root clades' refers to plants that have recently acquired root characteristics and are typically unstable [16-18]. Temperature, environment, and soil complexity can all influence root types and mycorrhizal types in vegetation [20-22]. The NCR (New Complex Root) plant group is typically found in Australia, where the soil is old, deep, and severely leached. Over time, some plant lineages transitioned from non-mycorrhizal to ectomycorrhizal roots [15] or from ericoid mycorrhizal to ectomycorrhizal roots to a balanced mycoheterotrophy [23].

Fungal biodiversity and its functions in rhizospheric soil

Mycorrhizae are classified into two categories according to their hyphae structure. The name "ectomycorrhizal fungi" refers to fungal hyphae that do not infiltrate individual cells within the roots, while "endomycorrhizal fungi" invade and break through the cell wall (Figure 1) [24]. According to Heijden and Martin [25], there are four types of mycorrhizae: ectomycorrhizae, arbuscular mycorrhizae, ericoid mycorrhizae, and orchid mycorrhizae. Arbutoid mycorrhizae are classified as ectomycorrhizae, while monotropoid mycorrhizae are a separate category. Endomycorrhizae consist of arbuscular, orchid, and ericoid mycorrhizae. The rhizosphere refers to the soil around a root, where root activity affects the microbial ecology. Soil microbiota includes fungi that decompose organic matter and promote element release through mineralization [26]. Rhizosphere fungal communities are influenced by various factors, including root exudates, organic carbon concentration, and plant type [27]. Research indicates that while soil contains millions of fungus, its diversity is substantially smaller than that of the air [29], as illustrated in Figure 2. There is limited understanding of how agricultural activities impact microbial diversity and function, despite research indicating that AMF fungi play important roles in several ecosystems [30]. The impact of a diverse sustainable ecosystem on microbial diversity, as well as its role and function, remains unclear [31]. Identifying fungi can be done by various methods, including examining fruiting bodies or utilizing soil samples to create cultures. Molecular approaches were used to estimate over 3000 fungal species within a 400 Ha area, providing the most accurate data available [32]. A scientific investigation found that the most common fungi in soil samples were Basidiomycota, Zygomycota, and Ascomycota, with averages of 4.1%, 13.3%, and 68.7%, respectively [33]. Microorganisms, likely phototrophic and prokaryotic, are thought to have colonized land during the pre-Cambrian period, marking the beginning of life. Although recent evidence suggests that terrestrial plants may have evolved during the Ordovician period, the late Silurian period was traditionally thought to be when they first appeared. Vegetation evolves from green aquatic algae to semi-aquatic plants, followed by fully terrestrial plants, the first land plants. Semiaquatic algae colonized land 490 million years ago and faced severe environmental conditions. Mycorrhiza was first discovered in a fossilized arbuscule from the early Devonian period, around 400 million years ago. According to Simon, arbuscular mycorrhizal fungus originally emerged during the Silurian, Ordovician, and Devonian periods (462-363 mya) [32-33]. The dates coincide with the emergence of terrestrial plants. Fossils and genomic research show that AM fungus have historically developed symbiotic colonies in terrestrial habitats. This implied a symbiotic interaction between fungi and vascular land plants. Mycorrhizal interactions can involve multiple plant and fungal species. Approximately 80% of plant species and 92% of plant families develop symbiotic relationships with Arbuscular mycorrhizal fungus, which belongs to the phylum Glomeromycota [34].

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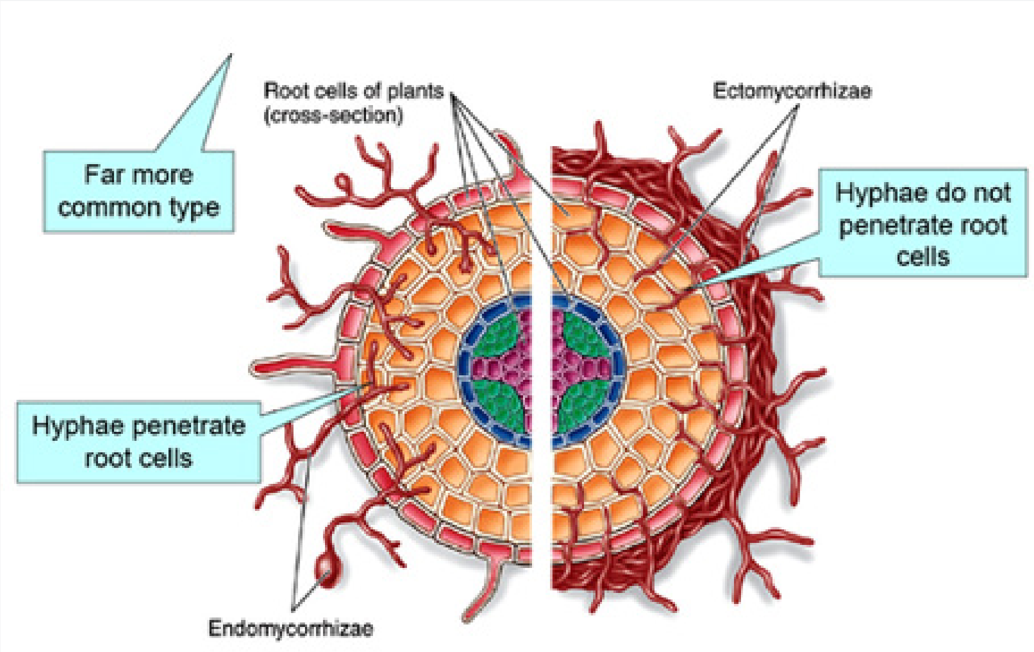

Figure 1: Types of Mycorrhiza.

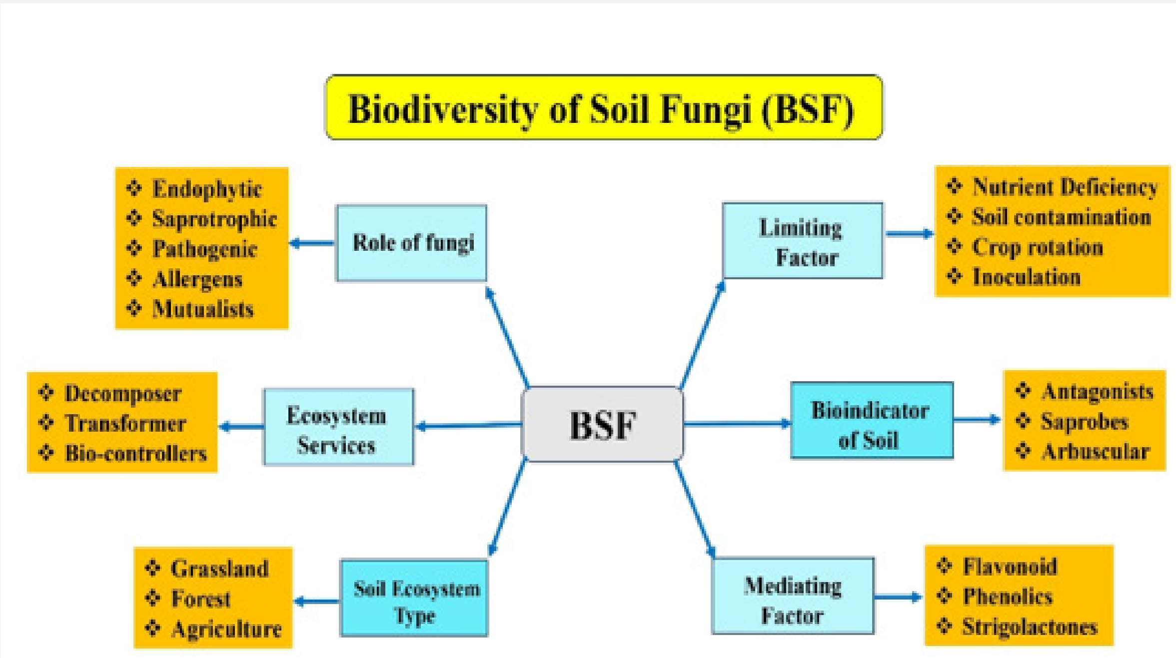

Figure 2: Features of the biodiversity of soil fungi.

Analysis of Fungal Morphology

Fungal morphology analysis is based on size and structure. Fungi are made up of mycelia, which sprout from the tips of their bodies, similar to how trees do. Fungi can be recognized from other species as they lack a hyphal septum. The spores are the key distinguishing feature of fungi. To study the morphologies of fungus, it's required to isolate representative ones [35]. Fungi are typically viewed using microscopes, such as compound microscopes, scanning electron microscopes, and stereomicroscopes. Recent

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advancements in image and particle analysis, micromechanical devices, and morphological data have increased researchers' understanding of microbial architectures [36].

Mycorrhizal Growth and Plant Interactions

Arbuscular mycorrhizal fungi may not produce hyphae during the symbiotic stage when no host plants are present. When root exudates are present, spores reach the pre-symbiotic stage, characterized by significant hyphal branching [19-21]. Appressoria can occur when a fungus meets a root surface before entering the epidermis. After symbiotic colonization, internal arbuscules (tree-like, highly branching structures) develop in the root cortical tissue. Simultaneously, an additional radical mycelium is produced. Plants play a significant role in regulating arbuscular mycorrhizal infection, leading to the possibility that cortical cell colonization causes similar alterations. Symbiotic partners need to converse and exchange signals, as well as communicate molecules between arbuscular mycorrhizae and plants, for proper development. Mycorrhizae-colonized roots use two nutrient uptake processes: the plant uptake route (PP) and the mycorrhizal uptake pathway (MP) (Figure 3).

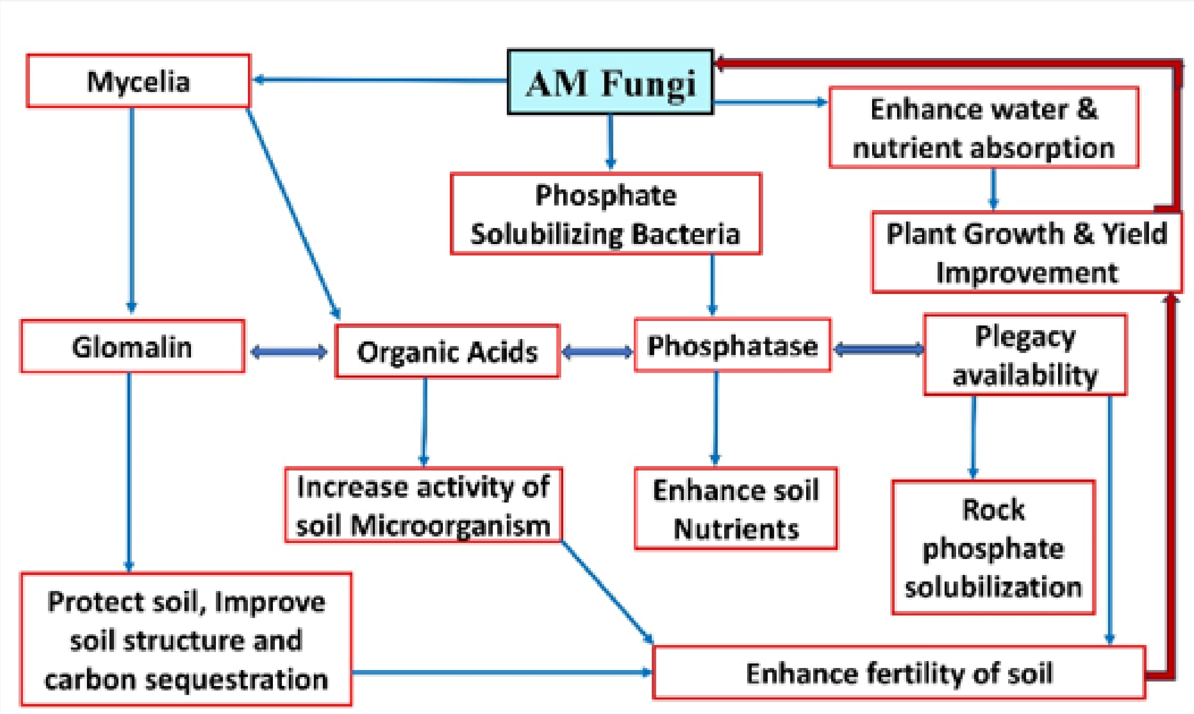

Figure 3: Soil fertility enhance by arbuscular mycorrhizal fungi.

The PP process absorbs nutrients directly from the root epidermis and hairs via a transporter. Mycorrhizal interactions in the MP rely on transporters in the extraradical mycelium (ERM) of fungi to move nutrients from the Hartig net to the intraradical mycelium (IRM) in the inner cell walls, as seen in the mycorrhizal interface. Mycorrhiza-inducible plant transporters absorb the interfacial apoplast through the periarbuscular membrane. The visible fungi show the several fungal species that have colonized a single host root, each with their own distinct colonization ability.

Mycorrhizal fungi can mitigate the abiotic pressures caused by climate change that impact tree growth in temperate and boreal forests (Figures 4A & 4B).

Mycorrhizal Plants Produce Phytochemicals

Studies show that AM symbiosis affects plant physiology and host cell metabolism [37]. Phytochemicals such as genistein, biochanin A, daidzein, and formononetin can prevent degenerative diseases, sesquiterpene lactones, menopausal symptoms, and osteoporosis [38]. They also inhibit cell proliferation and tumor growth [39]. Furanocoumarins (angelicin, mycorrhizal, and plant psoralen), pterocarpans (erybraedin C and bitucarpin A), and forskolin are chemotherapeutic compounds that induce apoptosis in human colon cancer cell lines [15-17]. After mycorrhizal colonization, phytochemicals in aromatic and therapeutic plants were analyzed. Basil shoots contain higher quantities of antioxidant chemicals, including rosmarinic acid, caffeic acid, and essential oils [39-41]. Research on the phytochemical composition of mycorrhizal plants grown for human food focuses on a few species, including maize, strawberry, onion, pepper, lettuce, artichoke, sweet potato, and tomato (Table 1). Most studies on edible plant products focus on single species, with few comparing cultivars and variants within the same species. Only a few green

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and red leaf lettuce cultivars outperformed the control group in terms of anthocyanins, carotenoids, chlorophyll, tocopherol, and total phenolics, as well as antioxidant activity (Table 1).

AMF	Evaluated Phytochemicals	Host Plant	Plant Part	Ref.
Acaulosporalongula	Total phenols, total flavonoids and total tannins	*Anadenanthera colubrina* (Vell.) Brenan	Leaves	[46]
Gigaspora albida	Phenols, flavonoids and lignin	*Cucumis sativus L.*	Leaves	[46]
F. mosseae				[47]
R. intraradices	Phenols and antioxidant activity	*Cynara cardunculus L. var. scolymus F.*	Leaves and flowers	[48]
F. mosseae				[48]
Glomus mix				[49]
R. intraradices	Flavonoids	*Fragaria x ananassa* Duch	Fruits	[49]
Glomus sp.	Anthocyanin	*Fragaria x ananassavar.* Selva	Fruits	[50]
R. intraradices				[51]
F. mosseae	Anthraquinone derivatives	*Hypericum perforatum L.*	Shoots	[50]
Mix (Funneliformisconstrictum, F. geosporum, F. mosseae and R.intraradices)				[52]
R. fasciculatus Commercial inoculant (F. mosseae and R.intraradices)	Soluble phenols	*Lactuca sativa L. var.* Longifolia	Leaves	[52]
R. fasciculatus	Anthocyanins	*L. sativa L. var.* Capitata	Leaves	[52]
G. albida	Total flavonoids	*Libidibia ferrea (Mart. ex Tul.) L.P.Queiroz var. ferrea*	Leaves	[53]
A. longula				[53]
Glomus etunicatum				[54]
G. albida	Total flavonoids and total tannins	*L. ferrea*	Leaves	[53]
A. longula				[54]
G. albida		*MyracrodruonurundeuvaAllema˜o*		[54]
F. mosseae				[54]
R. fasciculatus	Quercetin	*Vitis vinifera L. var. shahroudi*	Leaves and stem tissues	[53]
R. intraradices				[53]
F. mosseae				[54]
R. fasciculatus	Total phenols	*V. vinifera L.*	Leaves and roots	[55]
R. intraradices				[55]

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R. fasciculatus	Saponins	*Chlorophytum borivilianum*	Tuber	[55]
R. intraradices				[56]
F. mosseae				[56]
F. mosseae	Fixed oil	*Helianthus annuus cv.* Alester	Seeds	[52]
C. etunicatum				[52]
R. intraradices	Thymol derivatives	*Inula ensifolia L.*	Shoots	[51]
R. clarus	7-isobutyryloxy methyl ether	*I. ensifolia*	Roots	[52]
Glomus fasciculatum (Taxter sensu Gerd.) Gerd. and *Trappe*	Carotenoids	*L. sativa L. var.* Capitata	Outer leaves	[52]
Commercial inoculum (mixture of R. intraradices and *F. mosseae)*	Carotenoids	*L. sativa L. var.* Capitata	Leaves	[52]
F. mosseae	Essential oil	*M. arvensis*	Fresh herbage	[57]
Glomus aggregatum				[57]
R. fasciculatus				[52]
R. intraradices				[58]
C. etunicatum				[58]
Glomus lamellosum	Essential oil	*Mentha viridis L.*	Leaves	[58]
C. etunicatum				[58]
Glomus lamellosum	Essential oil	*Moringa oleifera L.*	Leaves	[59]
R. intraradice				[59]
F. mosseae	Carotenoids	*Moringa oleifera L.*	Leaves	[58]
C. etunicatum	Essential oil	*Origanum onites L.*	Leaves	[59]
C. lamellosum				[60]
R. intraradices	Essential oil	*O. basilicum*	Shoots	[59]
C. etunicatum				[60]
R. fasciculatus				[60]
G. aggregatum	Essential oil	*Pogostemoncablin* Benth		[61]
R. fasciculatus				[62]
R. intraradices	Lycopene	*Solanum lycopersicum L. var.* Money marker	Fruits	[60]
F. mosseae				[60]
R. intraradices				[63]
R. fasciculatus	Stevioside and rebaudioside A	*Stevia rebaudiana* (Bertoni)	Leaves	[64]
F. mosseae				[65]
R. intraradices	Sesquiterpenic acids	*Valeriana officinalis L.*	Rhizome	[62]
Mix (Six Glomus species)				[62]
G. aggregatum	Alkaloids	*Catharantus roseus (L.)* G. Don	Leaves	[59]
R. fasciculatus				[59]
R. intraradices				[59]
F. mosseae				[59]
R. intraradices	Glucosinolates (monoacetyl isomer I)	*M. oleifera*	Leaves	[59]
F. mosseae				[52]

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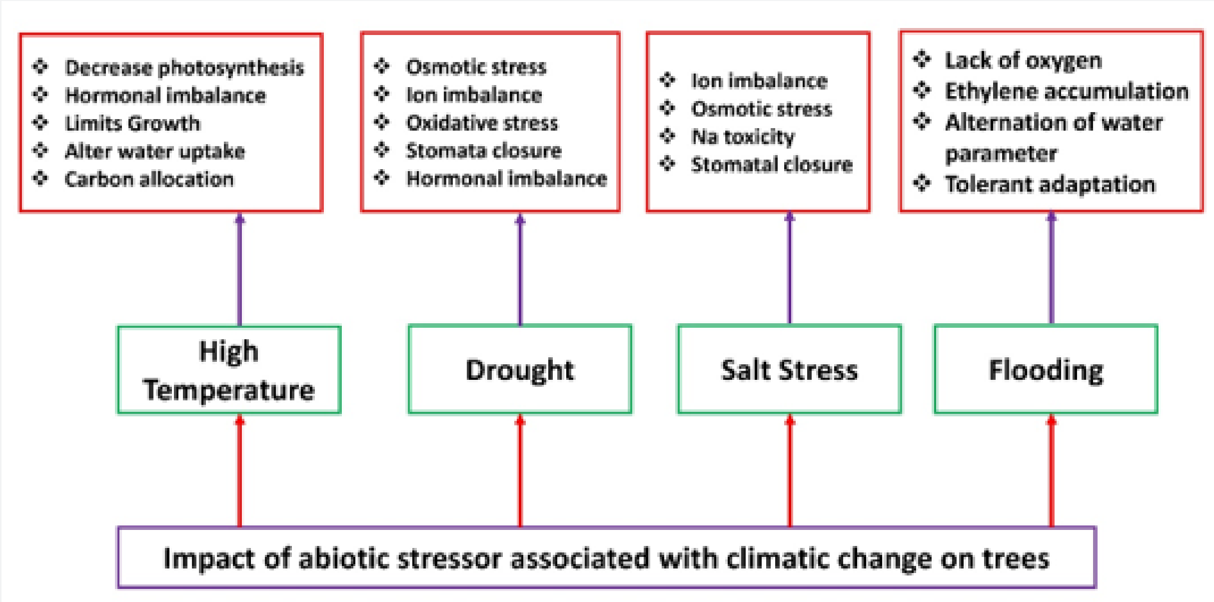

Figure 4: (A) Climate change-induced abiotic stressors, such as flooding, drought, fooding, high temperatures, and salt stress, have an impact on trees..

Strawberry mycorrhizae cultivars differed in their quantities of anthocyanins, anthocyanidins, and vitamin C in fruits (Table 1). There are numerous new and ancient kinds available for research and selection based on their ability to produce beneficial chemicals through mycorrhizal inoculation. However, current studies have limited their scope. Selection is crucial for functional foods such as globe artichoke, which has hepatoprotective, anticarcinogenic, antioxidative, and antibacterial properties, and tomato, which has been shown to reduce the risk of cancer and cardiovascular disease [12-14]. Growing artichoke and tomato on AMF-inoculated plants resulted in higher antioxidant activity and health-promoting compounds (Table 1). Plant hormones such as ABA and jasmonates may influence the accumulation of these compounds in plant reactions to abiotic and biotic stressors, potentially influencing long-distance signaling and defense responses in mycorrhizal fungus [42-44]. Gene expression studies on food plants and model plant species (Table 1) reveal differential expression of key enzymes involved in biochemical pathways leading to health-promoting secondary metabolites [45]. RNA-Seq. technology in food plants revealed upregulation of genes in various functional classes, including post-translational regulation, transport, signaling, biotic and abiotic stressors, and hormone metabolism [46-65]. These genes were differentially expressed in leaves, fruits, and roots compared to controls. The majority of the RNA-Seq. data utilized to uncover mycorrhizal regulated genes in plants such as Litchi chinensis, *Cucumis sativus, Oryza sativa, Citrus sinensis, Vitis vinifera, and Helianthus annuus* came from their roots. Next studies should concentrate on the edible sections of food plants in order to understand more about the genes directing the production of health-promoting chemicals, mediated by mycorrhizal symbioses. Gene expression varies among plant organs (Table 1).

Inorganic and Organic Fertilizers Affect AM Diversity

Fertilizer application affects various aspects of agricultural soil, including organic matter, nutrient content, humic acid, soil aggregation, microbial diversity, pH, and more. However, the AMF community's response to fertilization varies based on the amount or dose applied. Mycorrhizal fungi are symbiotic with plants and help mobilize minerals. The availability of various nitrogen sources in soil impacts the diversity of mycorrhizal fungus and the communities they form. Applying P fertilizers reduced mycorrhizal colonization, arbuscule colonization, and hyphal density, but did not significantly alter the structure of the mycorrhizal community [66].

Effects of AMF on Soil's Physical, Chemical, and Biological Properties

Arbuscular Mycorrhizae are fungi that improve soil structure. These mycelia, also known as hyphae, can generate strong soil aggregates. Mycorrhizal fungi's extramatrical mycelia produce glomalin, a glycoprotein that acts as a soil binding agent [67]. Glomalin is hydrophobic, heat-tolerant, and can endure warm soil temperatures. Senescent mycelia produce the majority of glomalin, which has hydrophobic characteristics and provides

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water resistance to soil aggregates. The soil's structure is generated by the decomposition of dead mycelia, and the mycelia network regenerates continuously [68]. These solutions reduce soil compaction and improve fertility [49]. It is unclear how long glomalin remains in soil and how cultural actions like bush burning affect it.

AMF's Effect on Improving Soil Chemical Properties

Arbuscular Mycorrhizae Fungi symbionts have an important part in soil biogeochemical cycles (C, P, and N). In this condition, mycorrhizal development is more effective. Phosphorus is a critical component that affects the availability of AMF's after it. It is found in several molecules, such as ATP, nucleotides, phospholipids, enzymes, and coenzymes [50]. Gianinazz et al. found that accumulated P in soils can sustain crop output for around 100 years. Soil cations absorb inorganic orthophosphate, which is the primary source of P. The amount of calcium (Ca), iron (Fe), and aluminum (Al) oxides affects the availability of P in soil. These oxides fix phosphorus into tricalcium phosphate [$Ca3(PO_4)_2$], aluminum phosphate ($AlPO_4$), and iron phosphate ($FePO_4$) [69]. Plants have access to less than 1% of the legacy phosphorus [70]. P from reservoirs must be hydrolyzed before it can be absorbed by plants in soil. AMF provides the necessary soluble P for plant physiological functions. This process increases the conversion of P into bioavailable forms through chemical and biological interactions [71]. Recent research indicates that AMF do not disseminate phosphatases into soil [72]. Instead, they attract PSB bacteria, which can produce phosphatase. The phosphatase enzyme converts phosphoric acid monoesters into P ions and molecules with free hydroxyl groups, releasing P from organic or inorganic orthophosphate [38]. The fructose secreted by AMF stimulates phosphatase synthesis, which is further boosted by the double inoculation of *Rahnella aquatilis* and *R. irregularis*. This leads to improved inorganic P solubilization [73]. AMFs improve the effectiveness of rock phosphate fertilizers (RPs), which are typically inefficient. RP has limited efficacy. According to Billah et al. (2019), adding fertilizer only makes a portion of it available to plants, while the rest becomes insoluble. AMF transforms insoluble P to soluble forms by generating acids during metabolic activities [74]. It's unclear if P can trigger AMF to initiate a root infection. Plants prefer nitrogen in the form of nitrate (NO_3) and will only absorb a portion of ammonium. The AMF mycelium can absorb nitrogen in the form of ammonium ions ($NH+_4$), nitrates (NO_3), and amino acids [75]. Local transporters in the AMF hyphae require access to nitrogen to function properly. AMF's Impact on Soil Carbon Cycle and Arbuscular Carbon Sequestration. Mycorrhizae-forming fungi play a critical role in the global carbon cycle. Research indicates that mycorrhizal roots increase the demand for carbon sinks. The host plant achieves its C requirement through photosynthesis [76, 77]. AMF improves soils' ability to absorb trace elements such Fe, Mg, Ca, Cu, Zn, Mn, K, and Co [78].

The Biological Properties of Soil and the Effect of AMF

Effects of AMF and soil biological properties One of the most crucial aspects of soil is the existence of microorganisms. Soil serves as a continuous biological reactor for a number of biochemical reactions and vital ecological processes. These beneficial interactions improve soil fertility, plant tolerance to biotic stimuli, biological control of root diseases, and nutrient uptake by plants [79]. AMF communities impact the physicochemical environment of the rhizosphere and control a variety of soil microbial interactions [80, 81]. Examples of interactions between AMFs and other microbes are shown in Table 1. However, other variables, such as the availability of phosphorus and nitrogen, also affect these interactions [82]. However, there are still many unanswered questions and a lack of expertise. How might soil microbes interfere with or completely prevent AMF's operations? What function does AMF serve in the trophic chain? Stated differently, are soil microorganisms able to parasitize or prey on AMFs? It is also necessary to conduct research on the interactions between free native nematodes and AMF and how they impact cereal crop growth in water stress situations.

The Function of AM Fungus in Agriculture Sustainability and Nutrient Acquisition

Mycorrhizal fungi help improve the availability of nutrients that are neither mobile or diffuse. Plants with mycorrhizae have a huge surface area of fungal hyphae on their external roots, which improves their ability to absorb inorganic nutrients [83]. Mycorrhizae benefit plants by increasing their phosphorus absorption. Fungal AMT1 family transporters, including GintAMT1 with *Glomus intraradicies*, mostly absorb ammonia as the primary source of nitrogen [84]. AM symbiosis can improve crop quality by increasing macro- and micronutrients, as well as plant nutrition [72].

Aggregation and Stabilization of Soils

The AM fungal mycelial network improves soil structure by attaching to it. Glomalin, a hydrophobic proteinaceous substance released by AM fungus, contributes to soil stability and water retention. A dense hyphal network and glomalin secretion help stabilize soil aggregates, improving structural stability and quality [85].

Mitigation of Abiotic Stress

Mineral depletion, drought, salinity, heavy metals, and heat are common issues in arid and semi-arid locations worldwide. Improving soil quality and crop productivity under difficult edaphoclimatic conditions is crucial for the agricultural industry [86]. AM fungi have been shown to enhance plant tolerance to abiotic stress situations [87]. These chemicals reduce osmotic potential, resulting in lower leaf water potential. Plant's lower potentials allow them to maintain high levels of organ hydration

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and turgor pressure, supporting overall cell physiology, including photosynthesis [88]. AM plants can better withstand oxidative stress from drought or salinity by producing more antioxidant molecules that scavenge ROS and boost the activity of antioxidant enzymes [89]. AM root colonization can enhance root growth, hydraulic features, and architecture, leading to the development of a highly effective root system for water and nutrient uptake. Several mycorrhizal fungal strains, including Glomus intraradices and Glomus Fungal hyphae and arbuscules are the primary sites for heavy metal accumulation. Fungal hyphae can cling to metals, immobilizing heavy metals. AM fungi enhance root Pi uptake and buffer cadmium uptake, reducing its negative impact on plant growth [90, 91-100]. Reduction of biotic stresses Plants are attacked by different species, including fungi, bacteria, viruses, and nematodes. Arbuscular mycorrhizal (AM) symbiosis with plant hosts can minimize insect pests and pathogens. AM symbioses have been shown to reduce the negative impact of soil-borne diseases. Research indicates that some fungus, bacteria, and oomycetes, such as *Aphanomyces, Phytophthora, and Pythium*, as well as bacteria like *Erwinia carotovora*, can reduce the frequency and severity of root rot and wilting. Several mechanisms have been proposed to explain how AMF protects host plants against diseases. Mycorrhizal mediated biotic stress tolerance by host plants can be attributed to various mechanisms, including increased root thickness and chemical alterations. AM plants contain high quantities of amino acids, including arginine. Mycorrhizal symbiosis transforms the host plant's physiological state. Carbon sequestration and AM Fungi AM fungi, in exchange for host photosynthetic carbon, perform ecological functions that promote host fitness at all scales, from individual to community [101]. AM fungi store carbon in soil by transferring photosynthates from host plants to their intraradical and extraradical hyphae [102]. Glomalin may stabilize soil aggregates, affecting carbon storage indirectly [59]. There is a strong correlation between glomalin levels in soil, hyphal length, and aggregate stability. The AM symbiosis can produce secondary metabolites that enhance plant resilience to stresses and benefit human health through antioxidant activity. Field-grown plants had up to 50% higher Zn levels in shoots and fruits compared to mutant plants with reduced mycorrhizal colonization [103].

Challenges of AMF Application

Although mycorrhiza associations, such as AMF, can improve soil fertility, plant growth, crop yield, and stress resistance, they may not always be as effective as they could be. To fully understand the benefits of mycorrhizal fungi, large-scale field trials are necessary to select appropriate AM combinations for various plants. There is a significant problem associated with indigenous AMF in soils. Native and new mycorrhizal fungi compete with each other if new AMF are introduced into the soil. These native mycorrhizas could occasionally take over and produce superior results than the new ones. Mycorrhizal species can produce different effects based on their geographic location [104,105]. To address this issue, isolate indigenous mycorrhizal strains to produce inoculum, then reintroduce them on a broad scale [104].

Conclusion and Future Prospective

Arbuscular mycorrhizal fungi play a critical role in soil biology. AMF's help plants absorb water, consume nutrients, and withstand biotic and abiotic stressors. The role of AMF in improving soil fertility has long been known, but our understanding of the underlying mechanisms remains limited. Several research have examined how AMF affects the chemical, physical, and biological aspects of soil. This review provides a comprehensive explanation of how AMF symbiotic interactions with crops improve soil chemical, physical, and biological properties. One way AMF affects soil fertility is by the synthesis of glomalin, which improves carbon storage and stability. AMF's beneficial interactions with other soil bacteria, like Phosphate Solubilizing Bacteria that create phosphatase enzyme and mineralize organic phosphate, were highlighted. Future research should explore how soil affects the performance of AMF. Future studies should use molecular approaches, such as transcriptome, gnomonic, and fungal mutants, to investigate N regulation and uptake from soil during AMF symbiosis. Further research is needed to determine the effectiveness of glomalin in improving carbon sequestration efficiency across different soil types and climatic situations. This could help solve soil deterioration caused by climate change. Evaluate the accumulation and lifetime of glomalin in soil fertility indices under different climatic, agricultural, and management conditions. The impact of AMF on soil basal respiration is also being investigated. The obligatory biotrophic nature of AMFs makes understanding their function in soil challenging. More field research is needed to determine how plant biodiversity affects AMF diversity and operation. All these research issues should be founded on innovative methodologies, such as recent methodological developments in molecular biotechnology, physiology, and agroecology integrated into both laboratory and field circumstances. Such measures are crucial for our ability to initiate a fresh "green revolution" that is in line with the circumstances needed to create a sustainable development that is rooted in agricultural production.

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References

1. Philippot L, Raaijmakers JM, Lemanceau P, Van Der Putten WH (2013) Going back to the roots: the microbial ecology of the rhizosphere. Nature Reviews Microbiology 11(11): 789-799.

2. Velten S, Leventon J, Jager N, Newig J (2015) What Is Sustainable Agriculture? A Systematic Review. Sustainability 7(6):7833-7865.
3. Abbasi M, Maleki A, Mirzaeiheydari M, Rostaminiya M (2022) The Symbiosis Effect of Mycorrhizal Fungi and Nano-fertilizers on Qualitative and Quantitative Traits, Biochemical Characteristics and Water Use Efficiency of Mung Bean Under Water Stress Conditions. Gesunde Pflanzen 74: 817-828.
4. Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M (2014) The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnology advances 32(2): 429-448.
5. Ortas I, Ustuner O (2014) The effects of single species, dual species and indigenous mycorrhiza inoculation on citrus growth and nutrient uptake. European Journal of Soil Biology 63: 64-69.
6. SCHÜßLER A, Schwarzott D, Walker C (2001) A new fungal phylum, the Glomeromycota: phylogeny and evolution. Mycological research 105(12): 1413-1421.
7. Prasad R, Bhola D, Akdi K, Cruz C, KVSS S, et al. (2017) Introduction to mycorrhiza: historical development. Mycorrhiza function, diversity, state of the Art, p. 1-7.
8. Brundrett MC (2009) Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. Plant and Soil 320: 37-77.
9. Saxena J, Chandra S, Nain L (2013) Synergistic effect of phosphate solubilizing rhizobacteria and arbuscular mycorrhiza on growth and yield of wheat plants. Journal of soil science and plant nutrition 13(2): 511-525.
10. Augé RM, Toler HD, Saxton AM (2015) Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: a meta-analysis. Mycorrhiza 25(1): 13-24.
11. Quiroga G, Erice G, Aroca R, Chaumont F, Ruiz-Lozano JM (2017) Enhanced drought stress tolerance by the arbuscular mycorrhizal symbiosis in a drought-sensitive maize cultivar is related to a broader and differential regulation of host plant aquaporins than in a drought-tolerant cultivar. Frontiers in plant science.
12. Amirnia R, Ghiyasi M, Siavash Moghaddam S, Rahimi A, Damalas CA, et al. (2019) Nitrogen-fixing soil bacteria plus mycorrhizal fungi improve seed yield and quality traits of lentil (Lens culinaris Medik). Journal of Soil Science and Plant Nutrition 19: 592-602.
13. Chitarra W, Pagliarani C, Maserti B, Lumini E, Siciliano I, et al. (2016) Insights on the impact of arbuscular mycorrhizal symbiosis on tomato tolerance to water stress. Plant Physiology 171(2): 1009-1023.
14. Mirshad PP, Puthur JT (2016) Arbuscular mycorrhizal association enhances drought tolerance potential of promising bioenergy grass (Saccharum arundinaceumretz.). Environmental Monitoring and Assessment 188: 1-20.
15. Fiorilli V, Vannini C, Ortolani F, Garcia-Seco D, Chiapello M, et al. (2018) Omics approaches revealed how arbuscular mycorrhizal symbiosis enhances yield and resistance to leaf pathogen in wheat. Scientific Reports 8(1): 1-8.
16. Bernaola L, Stout MJ (2021) The effect of mycorrhizal seed treatments on rice growth, yield, and tolerance to insect herbivores. Journal of Pest Science 94(2): 375-392.
17. Sadhana B (2014) Arbuscular Mycorrhizal Fungi (AMF) as a biofertilizer-a review. Int J Curr Microbiol App Sci 3(4): 384-400.
18. Jamiołkowska A, Księżniak A, Gałązka A, Hetman B, Kopacki M, et al. (2018) Impact of abiotic factors on development of the community of arbuscular mycorrhizal fungi in the soil: a review. International Agrophysics 32(1).
19. Parihar M, Rakshit A, Meena VS, Gupta VK, Rana K, et al. (2020) The potential of arbuscular mycorrhizal fungi in C cycling: a review. Archives of Microbiology 202: 1581-1596.
20. Siddiqui ZA, Pichtel J (2008) Mycorrhizae: an overview. Mycorrhizae: sustainable agriculture and forestry p. 1-35.
21. Zancarini A, Lépinay C, Burstin J, Duc G, Lemanceau P, et al. (2013) Combining Molecular Microbial Ecology with Eco physiology and Plant Genetics for a Better Understanding of Plant Microbial Communities' Interactions in the Rhizosphere. Molecular microbial ecology of the rhizosphere 1: 69-86.
22. Spatafora JW, Chang Y, Benny GL, Lazarus K, Smith ME, et al. (2016) A phylum-level phylogenetic classification of zygomycete fungi based on genome-scale data. Mycologia 108(5): 1028-1046.
23. Smith SE, Read DJ (2010) Mycorrhizal symbiosis. Academic press.
24. Dal Cortivo C, Ferrari M, Visioli G, Lauro M, Fornasier F (2020) Effects of seed-applied biofertilizers on rhizosphere biodiversity and growth of common wheat (Triticum aestivum L.) in the field. Frontiers in Plant Science 11: 72.
25. Dowarah B, Gill SS, Agarwala N (2022) Arbuscular mycorrhizal fungi in conferring tolerance to biotic stresses in plants. Journal of Plant Growth Regulation 202: 1-6.
26. Zhu Y, Lv GC, Chen YL, Gong XF, Peng YN, et al. (2017) Inoculation of arbuscular mycorrhizal fungi with plastic mulching in rainfed wheat: A promising farming strategy. Field Crops Research 204: 229-241.
27. Espidkar Z, Yarnia M, Ansari MH, Mirshekari B, Asadi Rahmani H (2017) Differences in nitrogen and phosphorus uptake and yield components between barley cultivars grown under arbuscular mycorrhizal fungus and pseudomonas strains co-inoculation in rainfed condition. Applied Ecology and Environmental Research 15(4): 195-216.
28. Suri VK, Choudhary AK (2013) Effects of vesicular arbuscular mycorrhizae and applied phosphorus through targeted yield precision model on root morphology, productivity, and nutrient dynamics in soybean in an acid alfisol. Communications in Soil Science and Plant Analysis 44(17): 2587-2604.
29. Erman M, Demir S, Ocak E, Tüfenkçi Ş, Oğuz F, et al. (2011) Effects of Rhizobium, arbuscular mycorrhiza and whey applications on some properties in chickpea (Cicer arietinum L.) under irrigated and rainfed conditions 1—Yield, yield components, nodulation and AMF colonization. Field Crops Research 122(1): 14-24.
30. Sharma V, Sharma S, Sharma S, Kumar V (2019) Synergistic effect of bio-inoculants on yield, nodulation and nutrient uptake of chickpea (*Cicer arietinum* L) under rainfed conditions. Journal of Plant Nutrition 42(4): 374-383.
31. Rezaei-Chiyaneh E, Jalilian J, Seyyedi SM, Barin M, Ebrahimian E, et al. (2021) Isabgol (Plantago ovata) and lentil (Lens culinaris) intercrop responses to arbuscular mycorrhizal fungi inoculation. Biological Agriculture & Horticulture 37(2): 125-140.
32. Trewin NH, Rice CM (2004) The Rhynie hot-spring system: geology, biota and mineralisation. Trans. Roy. Soc. Edinburgh, Earth Sci 94: 285-521.
33. Pirozynski KA, Dalpe Y (1989) Geological history of the Glomaceae with particular reference to mycorrhizal symbiosis. Symbiosis.
34. Redecker D (2000) Specific PCR primers to identify arbuscular mycorrhizal fungi within colonized roots. Mycorrhiza 10(2): 73-80.
35. Brundrett MC (2002) Coevolution of roots and mycorrhizas of land plants. New phytologist 154(2): 275-304.

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36. Raven JA, Andrews M (2010) Evolution of tree nutrition. Tree Physiology 30(9): 1050-1071.

37. Li X, Zhang J, Gai J, Cai X, Christie P, et al. (2015) Contribution of arbuscular mycorrhizal fungi of sedges to soil aggregation along an altitudinal alpine grassland gradient on the Tibetan Plateau. Environmental microbiology 17(8): 2841-2857.

38. Zanne AE, Tank DC, Cornwell WK, Eastman JM, Smith SA, et al. (2014) Three keys to the radiation of angiosperms into freezing environments. Nature 506(7486): 89-92.

39. Smith SE, Smith FA (2011) Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. Biol Annu Rev Plant 62: 227-250.

40. Brundrett MC (2017) Global diversity and importance of mycorrhizal and nonmycorrhizal plants. Biogeography of mycorrhizal symbiosis. pp. 533-556.

41. Swaty R, Michael HM, Deckert R, Gehring CA (2016) Mapping the potential mycorrhizal associations of the conterminous United States of America. Fungal Ecology 24: 139-147.

42. Brundrett MC (2002) Coevolution of roots and mycorrhizas of land plants. New phytologist 154(2): 275-304.

43. Freudenstein JV, Broe MB, Feldenkris ER (2016) Phylogenetic relationships at the base of Ericaceae: implications for vegetative and mycorrhizal evolution. Taxon 65(4): 794-804.

44. Szabó K, Böll S, Erős-Honti ZS (2014) Applying artificial mycorrhizae in planting urban trees. Applied ecology and environmental research 12(4): 835-853.

45. van Der Heijden MG, Martin FM, Selosse MA, Sanders IR (2015) Mycorrhizal ecology and evolution: the past, the present, and the future. New phytologist 205(4): 1406-1423.

46. Pellegrino E, Bedini S (2014) Enhancing ecosystem services in sustainable agriculture: biofertilization and biofortification of chickpea (Cicer arietinum L.) by arbuscular mycorrhizal fungi. Soil Biology and biochemistry. 68: 429-439.

47. Prasad R, Bhola D, Akdi K, Cruz C, KVSS S, et al. (2017) Introduction to mycorrhiza: historical development. Mycorrhiza function, diversity, state of the Art p. 1-7.

48. Cervantes-Gámez RG, Bueno-Ibarra MA, Cruz-Mendívil A, Calderón-Vázquez CL, Ramírez-Douriet CM, et al. (2016) Arbuscular mycorrhizal symbiosis-induced expression changes in Solanum lycopersicum leaves revealed by RNA-seq analysis. Plant Molecular Biology Reporter 34: 89-102.

49. Castellanos-Morales V, Villegas J, Wendelin S, Vierheilig H, Eder R, et al. (2010) Root colonisation by the arbuscular mycorrhizal fungus Glomus intraradices alters the quality of strawberry fruits (Fragaria× ananassa Duch.) at different nitrogen levels. Journal of the Science of Food and Agriculture 90(11): 1774-1782.

50. Lingua G, Bona E, Manassero P, Marsano F, Todeschini V, et al. (2013) Arbuscular mycorrhizal fungi and plant growth-promoting pseudomonads increases anthocyanin concentration in strawberry fruits (Fragaria x ananassa var. Selva) in conditions of reduced fertilization. International journal of molecular sciences 14(8): 16207-16225.

51. Zubek S, Blaszkowski J, Seidler-Lozykowska K, Baba W, Mleczko P (2013) Arbuscular mycorrhizal fungi abundance, species richness and composition under the monocultures of five medicinal plants. Acta Scientiarum Polonorum. Hortorum Cultus 12(5).

52. Baslam M, Qaddoury A, Goicoechea N (2014) Role of native and exotic mycorrhizal symbiosis to develop morphological, physiological and biochemical responses coping with water drought of date palm, Phoenix dactylifera. Trees 28: 161-172.

53. da Silva IR, de Mello CM, Neto RA, da Silva DK, de Melo AL, et al. (2014) Diversity of arbuscular mycorrhizal fungi along an environmental gradient in the Brazilian semiarid. Applied Soil Ecology 84: 166-175.

54. Eftekhari M, Alizadeh M, Mashayekhi K, Asghari HR (2012) In vitro propagation of four Iranian grape varieties: influence of genotype and pretreatment with arbuscular mycorrhiza. Vitis 51(4): 175-182.

55. Dave S, Tarafdar JC (2011) Stimulatory synthesis of saponin by mycorrhizal fungi in safed musli (Chlorophytum borivilianum) tubers. Int Res J Agric Sci Soil Sci 1: 137-141.

56. Geneva MP, Stancheva IV, Boychinova MM, Mincheva NH, Yonova PA (2010) Effects of foliar fertilization and arbuscular mycorrhizal colonization on Salvia officinalis L. growth, antioxidant capacity, and essential oil composition. Journal of the Science of Food and Agriculture 90(4): 696-702.

57. Garg N, Bharti A (2018) Salicylic acid improves arbuscular mycorrhizal symbiosis, and chickpea growth and yield by modulating carbohydrate metabolism under salt stress. Mycorrhiza 28 (8): 727-746.

58. Karagiannidis N, Thomidis T, Lazari D, Panou-Filotheou E, Karagiannidou C (2011) Effect of three Greek arbuscular mycorrhizal fungi in improving the growth, nutrient concentration, and production of essential oils of oregano and mint plants. Scientia horticulture 129(2): 329-334.

59. Cosme M, Fernández I, Declerck S, van der Heijden MG, Pieterse CM (2021) A coumarin exudation pathway mitigates arbuscular mycorrhizal incompatibility in Arabidopsis thaliana. Plant molecular biology 106(4-5): 319-334.

60. Rasouli-Sadaghiani M, Hassani A, Barin M, Danesh YR, Sefidkon F (2010) Effects of arbuscular mycorrhizal (AM) fungi on growth, essential oil production and nutrients uptake in basil. J Med Plants Res 4(21): 2222-2228.

61. Mishra V, Gupta A, Kaur P, Singh S, Singh N, et al. (2016) Synergistic effects of Arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria in bioremediation of iron contaminated soils. International journal of phytoremediation 18(7): 697-703.

62. Ratti N, Verma HN, Gautam SP (2010) Effect of Glomus species on physiology and biochemistry of Catharanthus roseus. Indian Journal of Microbiology 50: 355-360.

63. Giovannetti M, Volpe V, Salvioli A, Bonfante P (2017) Fungal and plant tools for the uptake of nutrients in arbuscular mycorrhizas: a molecular view. Mycorrhizal mediation of soil, pp. 107-128.

64. Mandal S, Evelin H, Giri B, Singh VP, Kapoor R (2013) Arbuscular mycorrhiza enhances the production of stevioside and rebaudioside-A in Stevia rebaudiana via nutritional and non-nutritional mechanisms. Applied soil ecology 72: 187-194.

65. Nell M, Wawrosch C, Steinkellner S, Vierheilig H, Kopp B, et al. (2009) Root colonization by symbiotic arbuscular mycorrhizal fungi increases sesquiterpenic acid concentrations in Valeriana officinalis L. Planta Medica 80: 393-398.

66. Miura C, Yamaguchi K, Miyahara R, Yamamoto T, Fuji M, et al. (2018) The mycoheterotrophic symbiosis between orchids and mycorrhizal fungi possesses major components shared with mutualistic plant-mycorrhizal symbioses. Molecular Plant Microbe Interactions 31(10): 1032-1047.

67. Qin Z, Zhang H, Feng G, Christie P, Zhang J, et al. (2020) Soil phosphorus availability modifies the relationship between AM fungal diversity and mycorrhizal benefits to maize in an agricultural soil. Soil Biology and Biochemistry 144: 107790.

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68. Chen S, Zhao H, Zou C, Li Y, Chen Y, et al. (2017) Combined inoculation with multiple arbuscular mycorrhizal fungi improves growth, nutrient uptake and photosynthesis in cucumber seedlings. Frontiers in Microbiology.

69. Shen SK, Wang YH (2011) Arbuscular mycorrhizal (AM) status and seedling growth response to indigenous AM colonisation of Euryodendron excelsum in China: implications for restoring an endemic and critically endangered tree. Australian Journal of Botany 59(5): 460-467.

70. Rodrigues MÂ, Piroli LB, Forcelini D, Raimundo S, da Silva Domingues L, et al. (2021) Use of commercial mycorrhizal fungi in stress-free growing conditions of potted olive cuttings. Scientia Horticulturae 275: 109712.

71. Zaidi A, Khan MS (2007) Stimulatory effects of dual inoculation with phosphate solubilising microorganisms and arbuscular mycorrhizal fungus on chickpea. Australian Journal of Experimental Agriculture 47(8): 1016-1022.

72. Zhang H, Liu Z, Chen H, Tang M (2016) Symbiosis of arbuscular mycorrhizal fungi and Robinia pseudoacacia L. improves root tensile strength and soil aggregate stability. Plos one 11 (4): e0153378.

73. Nizar KM, Tan CC, Masya ME (2023) Psychological Effects of Arbuscular Mychorrhiza Fungi Reducing Chemical Fertilizer on The Growth of Oil Palm Seedling. IOP Conference Series: Earth and Environmental Science 1167(1): 012017.

74. Kalayu G (2019) Phosphate solubilizing microorganisms: promising approach as biofertilizers. International Journal of Agronomy p. 1-7.

75. Faghihinia M, Jansa J, Halverson LJ, Staddon PL (2023) Hyphosphere microbiome of arbuscular mycorrhizal fungi: a realm of unknowns. Biology and Fertility of Soils 59(1): 17-34.

76. Parihar M, Chitara M, Khati P, Kumari A, Mishra PK, et al. (2020) Arbuscular mycorrhizal fungi: Abundance, interaction with plants and potential biological applications. Advances in Plant Microbiome and Sustainable Agriculture: Diversity and Biotechnological Applications pp. 105-143.

77. Hashem A, Kumar A, Al-Dbass AM, Alqarawi AA, Al-Arjani AB, et al. (2019) Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. Saudi journal of biological sciences 26(3): 614-624.

78. Alimi AA, Ezeokoli OT, Adeleke R, Moteetee A (2021) Arbuscular mycorrhizal fungal communities colonising the roots of indigenous legumes of South Africa as revealed by high throughput DNA metabarcoding. Rhizosphere 19: 100405.

79. Larimer AL, Clay K, Bever JD (2014) Synergism and context dependency of interactions between arbuscular mycorrhizal fungi and rhizobia with a prairie legume. Ecology 95(4): 1045-1054.

80. Agarwal AN, Singh JA, Singh AP (2017) Arbuscular mycorrhizal fungi and its role in sequestration of heavy metals. Trends Biosci 10(21): 4068-4077.

81. López-Pedrosa A, González-Guerrero M, Valderas A, Azcón Aguilar C, Ferrol N (2006) GintAMT1 encodes a functional high-affinity ammonium transporter that is expressed in the extraradical mycelium of Glomus intraradices. Fungal Genetics and Biology 43(2): 102-110.

82. Bedini S, Avio L, Sbrana C, Turrini A, Migliorini P, et al. (2013) Mycorrhizal activity and diversity in a long-term organic Mediterranean agroecosystem. Biology and Fertility of Soils 49: 781-790.

83. Blanco-Canqui H, Lal R (2009) Crop residue management and soil carbon dynamics. Soil carbon sequestration and the greenhouse effect 57: 291-309.

84. Khalvati M, Bartha B, Dupigny A, Schröder P (2010) Arbuscular mycorrhizal association is beneficial for growth and detoxification of xenobiotics of barley under drought stress. Journal of Soils and Sediments 10: 54-64.

85. Lucas WJ, Groover A, Lichtenberger R, Furuta K, Yadav SR, et al. (2013) The plant vascular system: evolution, development and functions f. Journal of integrative plant biology 55(4): 294-388.

86. Solaiman ZM (2018) Use of biochar for sustainable agriculture. J Integr Field Sci 15: 8-17.

87. Gherbi H, Markmann K, Svistoonoff S, Estevan J, Autran D, et al. (2008) SymRK defines a common genetic basis for plant root endosymbioses with arbuscular mycorrhiza fungi, rhizobia, and Frankia bacteria. Proceedings of the National Academy of Sciences 105(12): 4928-4932.

88. Seeram NP (2008) Berry fruits: compositional elements, biochemical activities, and the impact of their intake on human health, performance, and disease. Journal of agricultural and food chemistry 56(3): 627-629.

89. Cavagnaro TR, Barrios-Masias FH, Jackson LE (2012) Arbuscular mycorrhizas and their role in plant growth, nitrogen interception and soil gas efflux in an organic production system. Plant and soil 353: 181-194.

90. García A, Labidi J, Belgacem MN, Bras J (2017) The nanocellulose biorefinery: woody versus herbaceous agricultural wastes for NCC production. Cellulose 24: 693-704.

91. Colombo RP, Ibarra JG, Bidondo LF, Silvani VA, Bompadre MJ, et al. (2017) Arbuscular mycorrhizal fungal association in genetically modified drought-tolerant corn. Journal of environmental quality 46(1): 227-231.

92. Nemec S (1981) Virus-Glomus etunicatus interactions in citrus rootstocks. Phytopathology.

93. Shaul O, Galili S, Volpin H, Ginzberg I, Elad Y, et al. (1999) Mycorrhiza-induced changes in disease severity and PR protein expression in tobacco leaves. Molecular Plant-Microbe Interactions 12(11):1000-1007.

94. Zhang HS, Qin FF, Qin P, Pan SM (2014) Evidence that arbuscular mycorrhizal and phosphate-solubilizing fungi alleviate NaCl stress in the halophyte Kosteletzkya virginica: nutrient uptake and ion distribution within root tissues. Mycorrhiza 24: 383-395.

95. Ozgonen H, Erkilic A (2007) Growth enhancement and Phytophthora blight (*Phytophthora capsici* Leonian) control by arbuscular mycorrhizal fungal inoculation in pepper. Crop Protection 26(11): 1682-1688.

96. Siddiqui ZA, Sayeed Akhtar M (2009) Effects of antagonistic fungi, plant growth-promoting rhizobacteria, and arbuscular mycorrhizal fungi alone and in combination on the reproduction of Meloidogyne incognita and growth of tomato. Journal of General Plant Pathology 75: 144-153.

97. Pozo MJ, Azcón-Aguilar C (2007) Unraveling mycorrhiza-induced resistance. Current opinion in plant biology 10(4): 393-398.

98. Pradhan M, Baldwin IT, Pandey SP (2023) Argonaute7 (AGO7) optimizes arbuscular mycorrhizal fungal associations and enhances competitive growth in Nicotiana attenuata. New Phytologist 240(1): 382-398.

99. Bordoloi A, Nath PC, Shukla AK (2015) Distribution of arbuscular mycorrhizal fungi associated with different land use systems of Arunachal Pradesh of Eastern Himalayan region. World Journal of Microbiology and Biotechnology. 31: 1587-1593.

100. García-Garrido JM, Ocampo JA, García-Romera I (2002) Enzymes in the arbuscular mycorrhizal symbiosis. Marcel Dekker, New York.

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101. Sundram S, Othman R, Idris AS, Angel LP, Meon S (2022) Improved Growth Performance of Elaeis guineensis Jacq. Through the Applications of Arbuscular Mycorrhizal (AM) Fungi and Endophytic Bacteria. Current Microbiology 79(5): 155.

102. Chen S, Zhao H, Zou C, Li Y, Chen Y, et al. (2017) Combined inoculation with multiple arbuscular mycorrhizal fungi improves growth, nutrient uptake and photosynthesis in cucumber seedlings. Frontiers in Microbiology 8: 2516.

103. Khaosaad T, Staehelin C, Steinkellner S, Hage-Ahmed K, Ocampo JA, et al. (2010) The Rhizobium sp. strain NGR234 systemically suppresses arbuscular mycorrhizal root colonization in a split-root system of barley (Hordeum vulgare). Physiologia plantarum 140(3): 238-245.

104. Kour Divjot, Rana Kusam Lata, Kaur Tanvir, Yadav Neelam, Halder, et al. (2020) Potassium solubilizing and mobilizing microbes: Biodiversity, mechanisms of solubilization, and biotechnological implication for alleviations of abiotic stress.

105. Fierer N, Bradford MA, Jackson RB (2007) Toward an Ecological Classification of Soil Bacteria. Ecology 88(6): 1354-1364.

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