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REVIEW ARTICLE

Arbascular Mycorrhiza and sustainable agriculture: A green approach.

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Abstract

Agriculture is new paradigm, sustainable intensification, focuses back on beneficial soil microorganisms for their role in reducing chemical fertilizer and pesticide input and improving plant nutritional and health. More research has been done on arbuscular mycorrhizal fungi (AMF) because they form symbiotic relationships with the root systems of most land plants and make it easier for plants to absorb nutrients by creating extraradical networks of hyphae that spread out from colonized roots into the soil and serve as supplemental absorbents. Plants are protected from abiotic and biotic factors by AMF, and they also contribute in modulating the activity of antioxidant enzymes and secondary metabolites (phytochemicals), including polyphenols, anthocyanins, phytoestrogens and carotenoids. The employment of AMF symbionts to enhance the nutritional and medicinal value of active food items has come under more and more scrutiny in studies. Despite the wide physiological and genetic diversity of plant species, only a few AMFs have been used, thus limiting their full exploitation. This review study concentrates on the results of AMF on plant secondary substance biosynthesis that can improve health, as well as the standards for choosing the best symbionts to be utilized as sustainable biotechnological instruments to create food that is healthy and safe. The main objectives of the articlewas to examine the role AMF plays in improving soil's physical, biological and chemical properties. Regarding the information gaps found in this review, a discussion of potential future research is given. This will improve our understanding of AMF, encourage additional study, and aid in maintaining soil fertility.

Keywords

nutraceutical value; AMF functional diversity; arbuscular mycorrhizal symbionts; sustainable agriculture; healthy food; secondary metabolism; gene regulation; health-promoting phytochemicals

Introduction

The latest approach in agriculture, known as sustainable intensification, is concentrating attention on the role that beneficial soil microorganisms play in reducing the use of synthetic fertilizers and pesticides while enhancing plant health and nutrition [1]. The intensification of agriculture is requisite for production of food for growing population. Intensification, however, is associated with serious environmental risks, including climate change, biodiversity loss, land degradation due to salinization, erosion, compaction, depletion and pollution. Water resources are being depleted and polluted, production costs are increasing, farmers are shrinking, poverty and rural population is also declining [2]. The massive use of synthetic pesticides and fertilizers during the green movement has substantially degraded the quality and condition of our natural assets, especially the water, air, and soil [3].By controlling nutrition, hormone balances, creating growth regulators, discharging nutrients, and boosting disease resistance, mycorrhizal fungi play a crucial role in encouraging plant growth in such a situation. These interactions are essential for sustainable agriculture due to maintain the development and growth of plants by biological mechanisms rather than agrochemicals. Mycorrhizae are fungi that are present in the soil where plants grow and aid plants in absorbing nutrients and water. Furthermore, mycorrhizae can enhance root surface area, allowing plants to absorb nutrients and water from an extensive soil volume more effectively [4]. Further study has revealed that based on the plants in which they are linked; various mycorrhizal species show a range of reactions [5]. The potential for modifying the intensity of mycorrhizal fungi that influence plant-plant interactions will cause variations in plant growth. The developmental process of mycorrhizae, that play an important role in giving essential nutrients to plant life in which they are coupled with, is interestingly unaffected by fungicides or herbicides. Arbuscular Mycorrhizal Fungi (AMF), a significant functional group of advantageous soil bacteria pertaining to the subphylum Glomeromycotina, are receiving the attention they rightfully deserve on a global scale. (Spatafora et. al., 2016). Arbuscular mycorrhizal fungi (AMF) or endomycorrhizae, including fungi belongs to the recently established phylum Glomeromycota [6]. About 80% of plants which form a mutualistic relationship with the AMF in soil [7]. Some families are exceptional that don't show any link, including Chenopodiaceae, Polygonaceae, Cyperaceae, Amaranthaceae, Caryophyllaceae, Brassicaceae, and Juncaceae. In particular, the impacts of abiotic stress such as drought, nutrient imbalance and temperature regimes on plant growth finally have decreased crop yield up to 70% [7]. AMF-inoculated plants had a significant increase in stomatal conductance and hydration, increased photosynthesis[8,9]and mitigate oxidative stress [10,11]. Numerous studies have also shown that AMF increases plant tolerance to biotic stress, which in turn promotes plant growth and production [12,13]. AMF has been demonstrated to improve certain soil characteristics, including aggregation of soil, availability of soil nutrients, microbial activity, soil acidity correction, retention of water, nitrogen, carbon and phosphorus cycling, in addition to having an impact on the growth of the plants and overall productivity [14,15,16]. According to numerous studies, they are a key component of plants' stress tolerance mechanisms. This review attempts to consolidate data on AMF symbiosis, concentrating on the advantages for soil. AMF's effects on the chemical, biological, and physical attributes of the soil are initially considered. It is explained how AMF affects soil aggregation, availability of nutrients, and the growth of beneficial soil microbes. The diversity and significance of these interactions are then considered in connection to AMF and other soil microorganisms.

Origin and evolution of Mycorrhizal fungi

Genetic studies have shown that the first mycorrhizal association (about 450 million years ago) was between some primitive fungus that were presumably aquatic and algal progenitors of plants (charophycean algae). However, there is no fossil evidence to support this hypothesis. The first clear fossil evidence of interaction between plant and fungus comes from the 407 million years old Rhynie chert [17-19].Green algae that originated in the aquatic environment evolved into semi-aquatic plants and finally terrestrial plants. In the early stages of these semi aquatic algae invasion (between 490 and 409 million years ago) they faced a harsh environment devoid of organic matter and containing only mineral nutrients. Based on all the data gathered, three waves of mycorrhizal evolution can be distinguished. The first wave symbolizes the beginning of AM association at the Ordovician Period, which we have already explored. Spore like structures of AM fungi was found in substrates which are 50 Myr (million years) older than the Ordovician Period[20].The second wave includes the origin of the Orchidaceae, Ericaceae, plant families with non-mycorrhizal orectomycorrhizal roots and some N_2 fixing symbionts which takes place in the Cretaceous Period [18, 21].The exception to this rule is the ectomycorrhizal Pinaceae, which emerged in the Late Triassic or Jurassic Period [8-10].The third wave started in the Palaeogene Period (65 million years ago) and is still going on. It includes descendants of plants which recently acquired traits of roots and are often unstable; these are known as ‘New Complex Root clades' [16-18]. Changes in temperature, habitat, and soil complexity can lead to more specialized root types because this wave is highly dependent on these factors[22] and mycorrhizal types in vegetation [20-22]. NCR (New Complex Root) clade plant share usually found in Australia because the soil there is very old, deep and highly leached. As time passed, few plant lineages switched from non-mycorrhizal roots to ectomycorrhizal roots [15] or from ericoid mycorrhizal roots to ectomycorrhizal roots to from a balanced mycoheterotrophy in association [23].

Types and functions of fungal biodiversity in rhizospheric soil

Mycorrhizae are divided into two types based on the structure of their hyphae. The term "ectomycorrhizal fungi" refers to fungal hyphae that do not invade the individual cells found within the roots, whereas "endomycorrhizal fungi" refers to fungal hyphae that invade the cell membrane and break through the cell wall (Figure-1) [24]. Heijden and Martin also state that there are four main categories of mycorrhizal fungi: ectomycorrhizae, arbuscular mycorrhizae, orchid mycorrhizae, and ericoid mycorrhizae [25]. Arbutoid mycorrhizae can be categorized as ectomycorrhizae, while monotropoid mycorrhizae form a distinct category. In addition, endomycorrhizae include the arbuscular, ericoid, and orchid mycorrhizae.

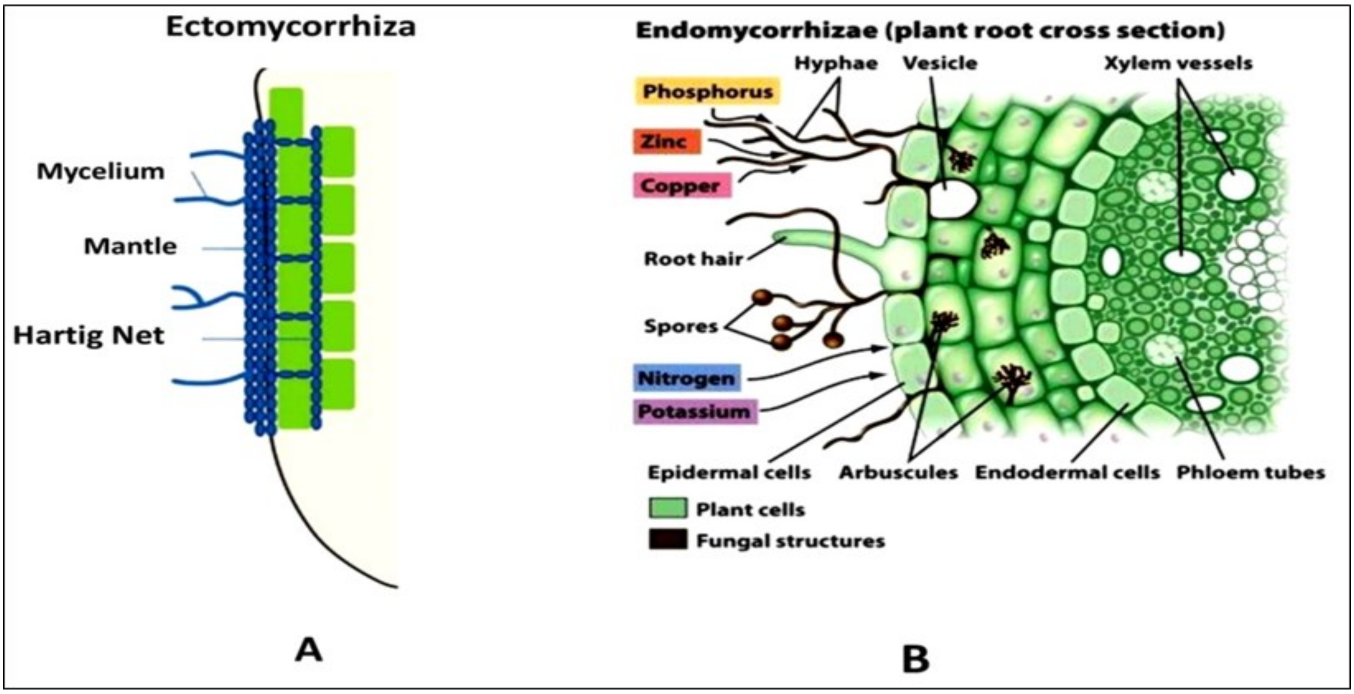

Figure -1:- Types of Mycorrhiza

The region of soil immediately surrounding a root where root activity influences the microbial community is known as the rhizosphere. Soil microbiota contains a variety of organisms like fungi which are a very important component of the soil and play a very beneficial role in soil by decomposing organic matter and promoting element release by mineralization [26]. The rhizosphere fungal communities are determined by many factors which include the root exudates, organic carbon content, and type of plant [27]. Several studies have found that millions of species of fungi exist in soil, but that soil diversity is significantly lower than that in the air[29] which is shown in figure-2. Very little is known about how agricultural practices induce selection pressure to change microbial diversity and its function, even though several studies have suggested that AMF fungi play a variety of roles in many ecosystems[30]. A varied sustainable ecosystem's induction of diversity of microbes and its role and function are equally little understood[31]. There are several ways to identify the different types of fungi, such as by looking at fruiting bodies or using a culture made from soil samples. Approximate 3000 fungal species was estimated from different site of 400 Ha area using molecular techniques when found the diversity of fungal species, which gives a most accurate data[32]. According to a scientific study, Basidiomycota, Zygomycota, and Ascomycota were the three fungi that were most prevalent in the soil samples, with an average of 4.1%, 13.3%, and 68.7%, respectively [33].

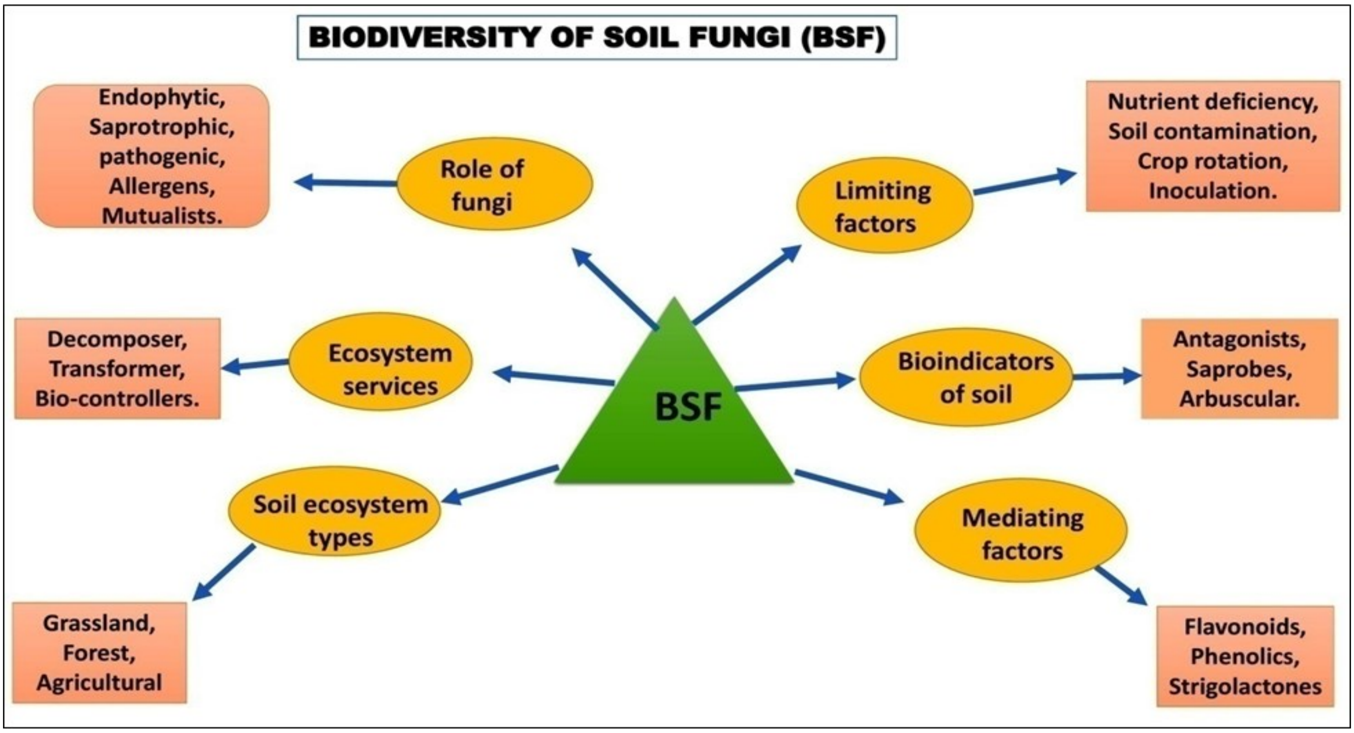

Figure -2. Aspects of soil fungal biodiversity

Life is considered to have emerged on land during the pre-Cambrian period and is supposed to have been it colonized by microorganisms, which are phototrophic in nature and were probably prokaryotic. The late Silurian periodonce indicated the establishment of terrestrial plants, despite recent evidence suggesting that they may have evolved during the Ordovician period. As the evolution of vegetation continues, the green aquatic algae evolve into semiaquatic plants and then fully terrestrial plants, which are the first land plants. Semiaquatic algae began to colonise land 490 million years back (mya) and confronted very challenging environmental conditions. The earliest known example of mycorrhiza is a fossilised arbuscule from the early Devonian, which dates to about 400 million years back (Mya). Simon noted that the Ordovician, Silurian, and Devonian periods, specifically between 462 and 363 Mya, was when arbuscular mycorrhizal fungus first appeared [32-33]. Their dates clearly situate them during the emergence of terrestrial plants. A long time ago, AM fungi established symbiotic colonies in terrestrial environments, as evidenced by fossils and genomic research. This implied that fungi and vascular land plants had a symbiotic relationship. Mycorrhizal partnerships can take many various forms and include a wide variety of plant and fungus species. It has been found that around 80% of plant species and about 92% families of plants [34] form symbiotic association with Arbuscular mycorrhizal fungus is the member of phylum Glomeromycota.

Fungal morphology analysis

Fungal morphology analysis depends on the sizes and its fungal structures. Fungi consist primarily of mycelia (tiny thread-like structures) that grow from the tips of their bodies, much like trees do. Because fungi lack a hyphal septum, they may be distinguished from other organisms. The spores are the main distinguish forms of fungi. Before observing their morphologies it is necessary to isolate specific representative fungi[35]. In general, microscopes like stereomicroscopes, compound microscopes, and scanning electron microscopes are used to view fungi. The development of new image and particle analysis, micromechanical devices, and morphological data has also improved [36], allowing researchers to get a more accurate view of microbe structures.

The growth of mycorrhizae and their interactions with plants

Mycorrhizae are formed by arbuscular mycorrhizal fungus after going through a number of developmental phases (Figure-3). Arbuscular mycorrhizal fungi have been observed to only sometimes grow hyphae during the symbiotic stage because host plants are not present. When root exudates are available, the spores reach the pre-symbiotic stage after germination, which is characterized by considerable hyphal branching [19-21]. Moreover, appressoria are formed if the fungus touches a root surface before it enters the epidermis. Following symbiotic colonization, internal arbuscules (tree-like, extremely branched structures) grow in the root cortical tissue. A

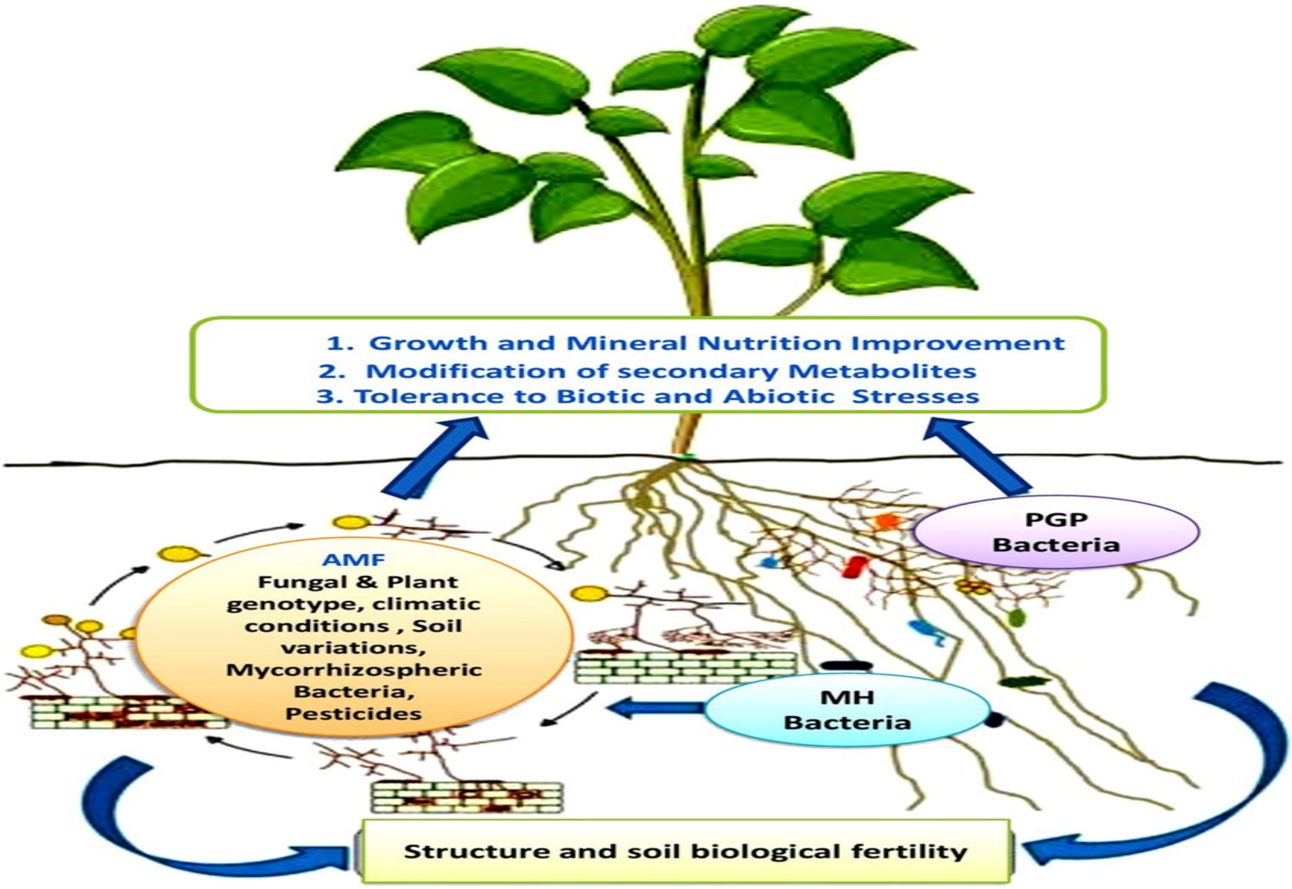

Figure - 3. An example of how beneficial bacteria and arbuscular mycorrhizal fungus (AMF) affect soil fertility and plant productivity. The life cycle of AMF and variables influencing its growth are depicted on the left; on the right, mycorrhizal helper (MH) and plant growth promoting (PGP) bacteria are shown cooperating with AMF.

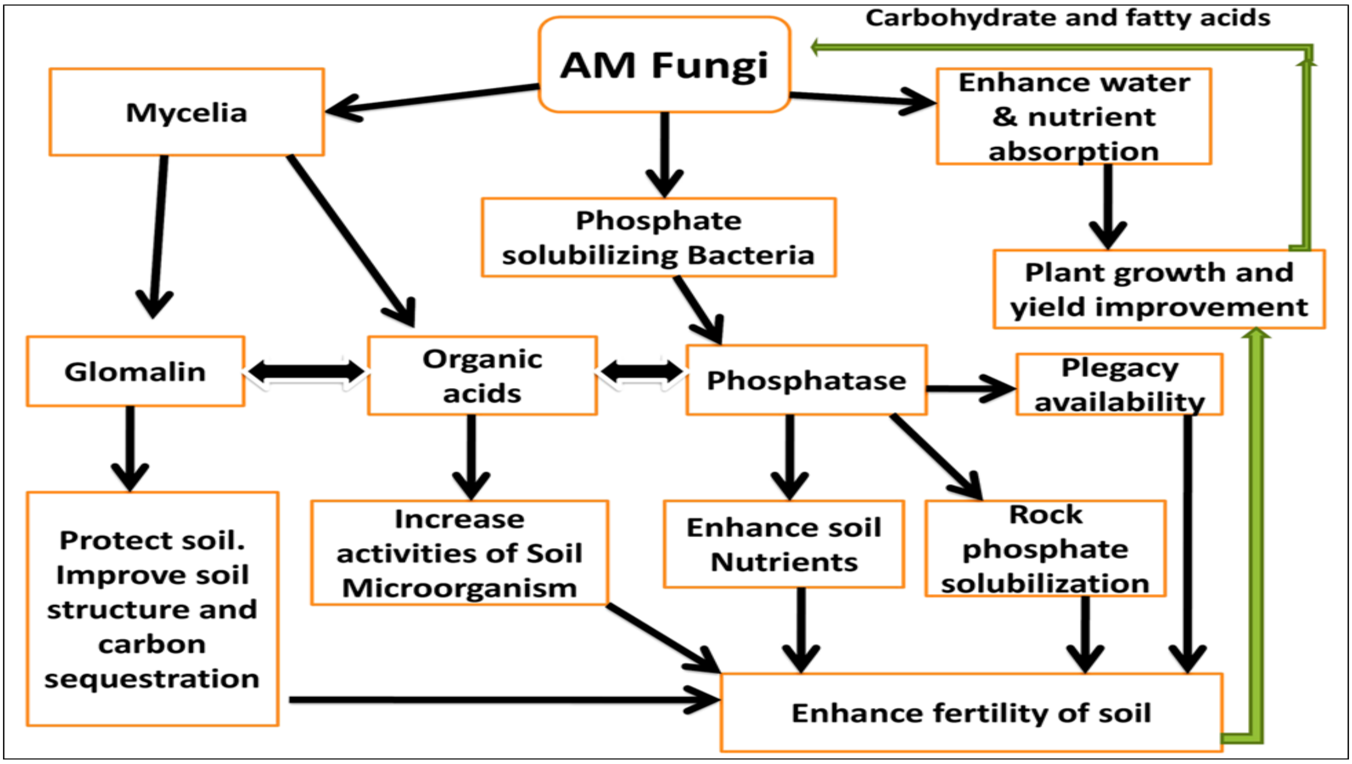

Figure 4. Soil fertility enhance by arbuscular mycorrhizal fungi.

separate extra radical mycelium is simultaneously formed at the same time. It is tempting to hypothesize that comparable changes occur when cortical cells are colonize, because the plants which are host of the major fungi play a major role in regulating the arbuscular mycorrhizal infection process. It is essential for these developmental processes for the symbiotic partners to communicate and exchange signals, as well as to communicate molecularly between arbuscular mycorrhizae and the plant. The two nutrient uptake processes for roots that have mycorrhizae colonisation are the plant uptake route (PP) and the mycorrhizal uptake pathway (MP) (Fig. 6). The PP involves nutrient absorption through the transporter straight from the root epidermis and root hairs. Mycorrhizal interactions in the MP require transporters in the extraradical mycelium (ERM) of fungi to carry nutrients from the Hartig net to the intraradical mycelium (IRM) in the inner cell walls (shown in the mycorrhizal interface. The interfacial apoplast is absorbed by mycorrhiza-inducible plant transporters in the periarbuscular membrane. The visible fungi represent the different fungal species that have colonized a single host root, each of which has a unique capacity for colonization.

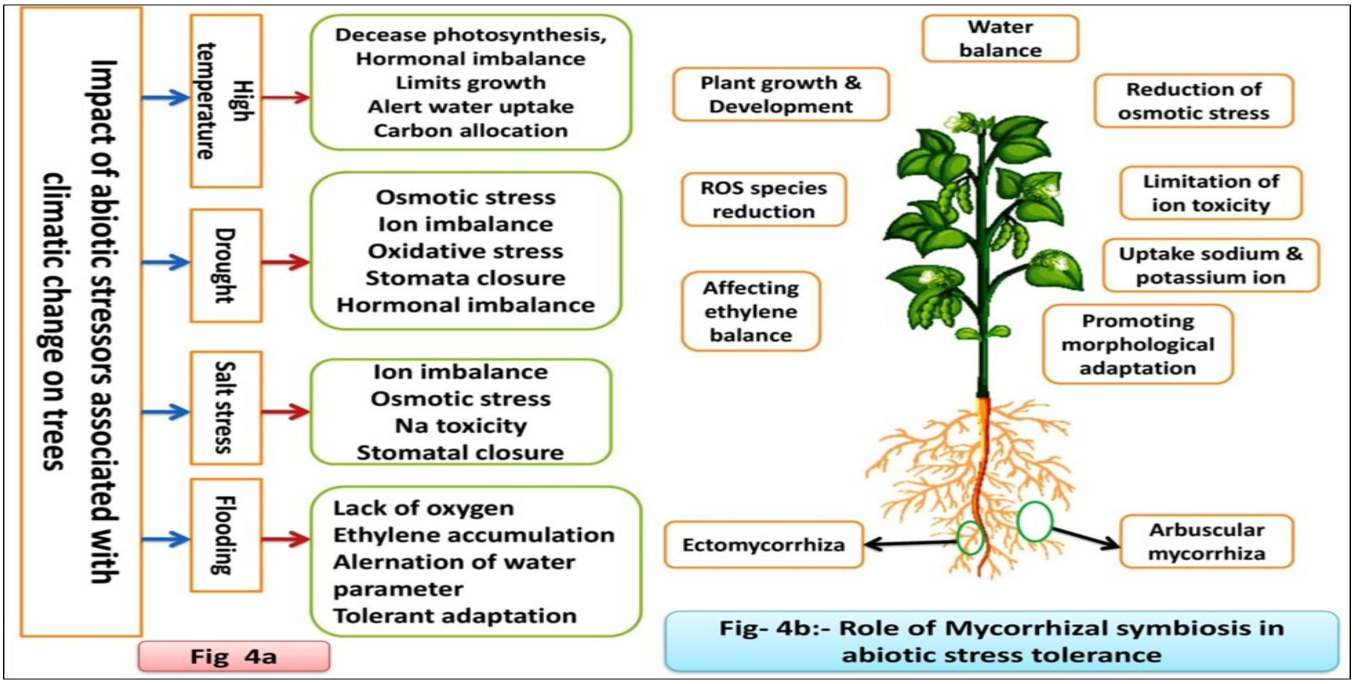

Figure 5. Climate change-related abiotic stresses affecting tree growth in temperate and boreal forests can be alleviated by mycorrhizal fungi. (A) Abiotic stress caused by climate change affects trees in the form of high temperatures, droughts, salt stress, and flooding. (B) Mycorrhizal fungi (ECM, ectomycorrhizal fungi and AM, arbuscular mycorrhizal fungi) improve the nutrition and growth of trees (including potassium K+) and help plants adapt to stressful environmental conditions (such as high salt levels in saline conditions.

The production of phytochemicals by mycorrhizal plants

Several studies have demonstrated that the development of AM symbiosis alters plant physiology and modifies the primary and secondary metabolism of the host cell [37]. The therapeutic phytochemicals genistein, biochanin A, daidzein, and formononetin show a preventive action in degenerative diseases, sesquiterpene lactones, menopausal symptoms, and osteoporosis [38] which can inhibit cell proliferation and tumor growth, were produced in greater quantities by mycorrhizal plants [39].Furanocoumarins (angelicin and psoralen), pterocarpans (erybraedin C and bitucarpin A), and Forskolinchemotherapeutic substances capable of inducing apoptosis in cancer cell lines of human colon [15-17]. After mycorrhizal colonisation, the phytochemical contents of various kinds of aromatic plants and medicinal plants were examined. According to the findings, basil has higher concentrations of antioxidant compounds in the shoots, like as rosmarinic acid, caffeic acid, and essential oils have [39-41]. Apart from medicinal plants and herbs, studies on the phytochemical content of mycorrhizal plants cultivated for human consumption concentrate on a small number of species, such as maize, strawberry, onion, pepper, lettuce, artichoke, sweet potato, and tomato (Table 1). The majority of edible plant product data are derived from studies of single species of plants, while only a few studies compare the responses of cultivars and varieties within the same species. When compared to plants in the control group, only a few green and red leaf lettuce varieties had higher levels of anthocyanins, carotenoids, chlorophyll, tocopherol, and total phenolics, and they also showed more antioxidant activity (Table 1). However, different strawberry mycorrhizae varieties did not show comparable levels of anthocyanins, anthocyanidins, and vitamin C in fruits (Table 1).

Given the vast array of new and ancient varieties that are currently grown throughout the world, which could be researched and chosen based on their capacity to create beneficial compounds upon mycorrhizal inoculation, this constitutes a limitation of the studies conducted thus far. Such a selection would be particularly important for some vegetable species considered functional foods, i.e., globe artichoke, for its hepatoprotective, anticarcinogenic, antioxidative and antibacterial activities, and tomato, for its ability to reduce the risks of cancer and cardiovascular disease [12-14]. Indeed, when grown on AMF-inoculated plants, artichoke and tomato demonstrated increased antioxidant activity and amounts of health-promoting chemicals (Table 1). These molecules, which are frequently accumulated in plants' reactions to abiotic and biotic challenges, may be influenced by plant hormones like ABA or jasmonates, which may be implicated in long-distance signalling and the priming of defense responses in mycorrhizal fungi [42-44].Gene expression studies performed on food plants (Table 1) and model plant species (Table 1) have shown that genes encoding key enzymes involved in biochemical pathways leading to health-promoting secondary metabolites are differentially expressed [45]. In food plants, the use of the RNA-Seq technology, allowing investigations of whole transcripts, revealed that many genes, belonging to different functional classes, i.e., post-translational regulation, signaling, transport, stressors that are biotic and abiotic and hormone metabolism, were upregulated upon AMF inoculation and differentially expressed in fruits, leaves and roots, compared with controls . Unfortunately, the majority of the RNA-Seq data used to identify the mycorrhizal regulated genes in the examined plants, including *Litchi chinensis*, *Cucumis sativus*, *Oryza sativa*, *Citrus sinensis*, *Vitis vinifera*, and *Helianthus annuus* only come from the roots of these plants. Next studies should concentrate on the edible sections of food plants in order to learn more about the genes governing the production of health-promoting chemicals, controlled by mycorrhizal symbioses. This is because different genes may be differentially expressed in the diverse plant organs (Table -1)

Effect of Organic and Inorganic Fertilizer and its Role in AM Diversity

Although the application of manure and fertilizers to agricultural soil affects its organic substances, nutrient content, amount of humic acid, soil aggregation, microbial diversity, and pH, and many other crucial aspects of the soil, the response of the AMF community to fertilization depends on the quantity or dose of fertilizers applied to the soils. Mycorrhizal fungi being symbiotic remain in association with plants and play a crucial role in mobilization of minerals. Diversity of mycorrhizal fungi dependents on the presence of different nutrients sources of soilthat affects the communities of soil fungi. However, application of P fertilizers resulted in a considerable decrease in the rate of mycorrhizal colonisation, arbuscule colonisation, and density of hyphal length rather than a major change in the mycorrhizal community's structure [66].

Impact of AMF on amending the physical, chemical, and biological properties of soil

Arbuscular Mycorrhizae fungi improve the structure of the soil. These mycelia or hyphae are capable of forming sturdy soil aggregations. Glomalin, a glycoprotein produced by the extramatrical mycelia of mycorrhizal fungi, serves as a long-term soil binding agent [67]. This glomalin is a hydrophobic, heat-tolerant, or thermo-tolerant substance that can withstand the warm soil temperature. Glomalin's hydrophobic properties confer on soil aggregates water resistance, and senescent mycelia generate the most of this chemical. Moreover, the structure of the soil is formed by the decomposition dead mycelia and the mycelia network continually regenerates [68]. These strategies all lower the dangers of soil compaction and increase soil fertility [49]. The longevity of glomalin in the soil and the impact of anthropological practices like bush burning on soil glomalin are also unknowns, though.

Table -1:- Different phytochemicals release from AMP associated plants

Host plant	Plant organ	Evaluated phytochemicals	AMF	Effect	References
Phenolic compounds					
Anadenanthera colubrina (Vell.) Brenan	Leaves	Total phenols, total flavonoids and total tannins	*Acaulosporalongula*	(?)	[46]
			Gigaspora albida	(?)	[46]
Cucumis sativus L.	Leaves	Phenols, flavonoids and lignin	*F. mosseae*	(?)	[47]
Cynara cardunculus L. var. *scolymus F.*	Leaves and flowers	Phenols and antioxidant activity	*R. intraradices*	(?)	[48]
			F. mosseae	(?)	[48]
			Glomus mix	(?)	[49]
Fragaria x *ananassa*Duch	Fruits	Flavonoids	*R. intraradices*	(?)	[49]
Fragaria x *ananassa*var. Selva	Fruits	Anthocyanin	*Glomus sp.*	(?)	[50]
*Hypericum perforatum*L.	Shoots	Anthraquinone derivatives	*R. intraradices*	(?)	[51]
			F. mosseae	(?)	[50]
			Mix (*Funneliformisconstrictum,F. geosporum*, *F. mosseae* and *R.intraradices*)	(?)	[52]
Lactuca sativa L. var. Longifolia	Leaves	Soluble phenols	*R. fasciculatus*	(?)	[52]
			Commercial inoculant (*F. mosseae* and *R.intraradices*)	(?)	[52]
L. sativa L. var. Capitata	Leaves	Anthocyanins	*R. fasciculatus*	(?)	[52]
Libidibia ferrea (Mart. ex Tul.) L.P.Queiroz var. ferrea	Leaves	Total flavonoids	*G. albida*	(?)	[53]
			A. longula	(?)	[53]
			Glomus etunicatum	(?)	[54]
L. ferrea	Leaves	Total flavonoids and total tannins	*G. albida*	0	[53]
			A. longula	0	[54]
			C. etunicatum	0	Dave and Tarafdar (2011)
MyracrodruonurundeuvaAllema˜o			*G. albida*	0	[54]
*Passiflora alata*Curtis	Leaves	Total phenols and total flavonoids	*G. albida*	(?)	Oliveira et al. (2014)
Salvia officinalis L.	Leaves	Total phenols and total flavonoids	*R. intraradices*	(-)	Geneva et al. (2010)
Vitis vinifera L. var. shahroudi	Leaves and stem tissues	Quercetin	*F. mosseae*	(?)	[54]
			R. fasciculatus	(?)	[53]
			R. intraradices	(?)	[53]
V. vinifera L.	Leaves and roots	Total phenols	*F. mosseae*	0	[54]
			R. fasciculatus	0	[55]
			R. intraradices	0	[55]
			Mix of the three species	(?)	Geneva et al. (2010)
Chlorophytum borivilianum	Tuber	Saponins	*R. fasciculatus*	(?)	[55]
			R. intraradices	(?)	[56]
			F. mosseae	(?)	[56]
Helianthus annuus cv. Alester	Seeds	Fixed oil	*F. mosseae*	(?)	[52]
			C. etunicatum	0	[52]
*Inula ensifolia*L.	Shoots	Thymol derivatives	*R. intraradices*	0	[51]

I. ensifolia	Roots	7-isobutyryloxy methyl ether	*R. clarus*	(?)	[52]
L. sativa L. var. Capitata	Outer leaves	Carotenoids	*Glomus fasciculatum (Taxter* sensu *Gerd.) Gerd. and Trappe*	(?)	[52]
L. sativa L. var. Capitata	Leaves	Carotenoids	Commercial inoculum (mixture of R. intraradices and F. mosseae)	(?)	[52]
M. arvensis	Fresh herbage	Essential oil	*F. mosseae*	(?)	[57]
			Glomus aggregatum	(?)	[57]
			R. fasciculatus	(?)	[52]
			R. intraradices		[58]
			C. etunicatum	(?)	[58]
*Mentha viridis*L.	Leaves	Essential oil	*Glomus lamellosum*	(?) (-)	[58]
Moringa oleifera L.	Leaves	Essential oil	*C. etunicatum*	(?)	[58]
			Glomus lamellosum	(-)	[59]
			R. intraradices	(-)	[59]
Moringa oleifera L.	Leaves	Carotenoids	*F. mosseae*	(-)	[58]
			Both fungi combined	0	[60]
*Origanum onites*L.	Leaves	Essential oil	*C. etunicatum*	(?)	[59]
			C. lamellosum	(?)	[60]
O. basilicum	Shoots	Essential oil	*R. intraradices*		[59]
			C. etunicatum		[60]
			R. fasciculatus		[60]
*Pogostemoncablin*Benth		Essential oil	*G. aggregatum*	(?)	[61]
			R. fasciculatus	(?)	[62]
			R. intraradices	(?)	[60]
			F. mosseae	(?)	[60]
*Solanum lycopersicum*L. var. Money marker	Fruits	Lycopene	*R. intraradices*	(?)	[63]
Stevia rebaudiana (Bertoni)	Leaves	Stevioside and rebaudioside A	*R. fasciculatus*	(?)	[64]
Valeriana officinalis L.	Rhizome	Sesquiterpenic acids	*F. mosseae*	(?)	[65]
			R. intraradices	(?)	[62]
			Mix (Six *Glomus* species)	(?)	[62]
Catharantus roseus (L.) G. Don	Leaves	Alkaloids	*G. aggregatum*	(?)	[62]
			R. fasciculatus	(?)	[59]
			R. intraradices	(?)	[59]
			F. mosseae	(?)	[59]
M. oleifera	Leaves	Glucosinolates (monoacetyl isomer I)	*R. intraradices*	(?)	[59]
			F. mosseae	(?)	[62]
			Both fungi combined	(?)	[52]

Table 2: Effect of AM fungi on different plant pathogen

AM fungi	Pathogen type	Effect	References
G. etunicatum	Citrus tristeza Virus and Citursurgose virus	Growth of *Citurs macrophylla* inoculated with tristeza virus (T-3 isolate) and Citursurgosevirus(CLRV-2) was not reduced by virus infection in mycorrhizal plants	[92]
G. intraradices	Tobacco mosaic virus	Higher incidence and severity of necrotic lesion in mycorrhizal than in non mycorrhizal plants	[93]
AM fungi	*P. solanacearum*	Disease decrease in eucalyptus seedlings injected with AM fungi	[94]
G. mosseae, *G. etunicatum*, *G. fasciculatum* *Gigaspora margarita*	*Phytophthora Capsici*	AM fungi significantly increased plant growth and reduced disease severity in pepper but *G. mosseae* reduced disease severity to a greater extent	[95]
G. fasciculatum	*F. oxysporum* f. sp. *Ciceris*	Reduced the disease severity in chickpea	[96]
G. intraradices	*M. phaseolina*	Combined application of *G. intraradices* with *P. alcaligenes* and *B. pumilus* caused a greater reduction in the root-rot of chickpea	[96]
G. mosseae *G. intraradices*	*P. parasitica*	*G. mosseae* was most effective in reducing disease symptoms produced by *P. parasitica* on tomato	[97]
G. fasciculatum *G. constrictum* *G. mosseae* *G. intraradices* *Acaulospora*sp. *Sclerocystis*sp	*M. incognita*	Individually all AM fungi reduced nematode reproduction but the greatest reduction was caused by *G. fasciculatum* on chickpea	[92]
G. intraradices	*M. incognita*	Combined use of AM fungus with *Pseudomonas straita* and *Rhizobium* caused greater increase in chickpea growth	[95]
G. fasciculatum	*M. incognita*	Reduced nematode population on tomato	[98]
G. intraradices	*M. hapla*	Reduced the no. of galls and egg sacs on tomato cv. ‘Hildares’ but bio control of nematode was not achieved in cv. ‘Tiptop	[88]
G. fasciculatum	*M. incognita*	Reduced galling and nematode population on brinjal	[99]
G. mosseae	*P. syringae*	Neither growth of tomato nor percentage VA infection was negatively affected by pathogenic bacteria	[100]

AMF's impact on ameliorating soil chemical properties

Arbuscular Mycorrhizae Fungi symbionts are known to play a crucial role in the development of soil's primary biogeochemical cycles (C, P, and N). In this condition, the development of mycorrhizal occurmore effectively. Phosphorus is a crucial component that effect on availability of AMFs past phosphorus. It is present in a variety of substances, including as adenosine triphosphate (ATP), nucleotides, phospholipids, certain enzymes, and coenzymes [50].According to research by Gianinazz and teammates, the accumulated P in soils can support crop output worldwide for about 100 years. The P is typically found as inorganic orthophosphate that has been adsorbed to soil cations. Consequently, the presence of iron (Fe), calcium (Ca), and aluminium (Al) oxides influences the availability of P in soil. These oxides fix phosphorus as tricalcium phosphate [$Ca_3(PO_4)_2$], aluminium phosphate ($AlPo_4$) and iron phosphate ($FePO_4$) [69]. Therefore, only a small proportion (<1%) of the legacy P is available to plants [70]. Before P from the reservoir to be absorbed by plants in the soil, it must first be hydrolyzed. The soluble P that plants need for their physiological processes is supplied by AMF. Basically, it accelerates the chemical processes and biological interactions that convert P into forms that are bioavailable [71]. Recent research, however, has shown that AMF are unable to disperse phosphatases into the soil [72]; instead, they attract bacteria called PSB, or Phosphate Solubilizing Bacteria, which are capable of producing phosphatase. The phosphatase hydrolyzes phosphoric acid monoesters into P ions and molecules with free hydroxyl groups in order to liberate P from organic or inorganic orthophosphate [38]. AMF exuded fructose increases the production of phosphatase, which is also stimulated by the double inoculation of *R. irregularis* and *Rahnella aquatilis*, resulting in better solubilization of inorganic P [73]. Moreover, AMFs increase the effectiveness of rock phosphate fertilizers (RPs), which are ineffective. RP has low effectiveness. This is because when fertilizer is added, only a portion is available to the plants, and the remainder is changed into an insoluble form(Billah et. al., 2019). AMF converts the insoluble P into soluble forms by producing acids throughout their metabolic processes [74]. If P can cause AMF to start a root infection, this is not fully understood. The ammonium form of nitrogen will only be partially absorbed by plants that prefer nitrogen in the form of nitrate (NO_3). Ammonium ions ($NH^{+4),}$ nitrates (NO_3), and amino acids are all forms of nitrogen that the AMF mycelium may take [75]. Nitrogen must be accessible for local transporters to be working in the AMF hyphae. AMF's Impact on the Soil Carbon Cycle and Arbuscular C Sequestration Fungi that form mycorrhizae are crucial to the global C cycle. Mycorrhizal roots have been shown to increase the demand for carbon sinks. The host plant meets this C requirement using the C fixed during photosynthesis [76, 77]. It is well known that AMF enhances soils' capacity to absorb small amounts of trace elements, such as iron (Fe), magnesium (Mg), calcium (Ca), copper (Cu), zinc (Zn), manganese (Mn), potassium (K) and cobalt (Co) [78].

Soil biological properties and the impact of AMF

Impact of AMF and biological characteristics of the soil the presence of microorganisms in soil is one of its most important characteristics. For several biochemical reactions and essential ecological processes, soil functions as an ongoing biological reactor. These advantageous interactions increase the uptake of nutrients by plants, biological control of root infections, plant tolerance to biotic stimuli, and soil fertility [79]. AMF communities regulate numerous soil microbial interactions and affect the rhizosphere's physicochemical environment [80,81]. Table 1 provides examples of interactions between AMFs and other microorganisms. However, these interactions are influenced by other factors, including phosphorus and nitrogen availability [82]. Nonetheless; there is a dearth of knowledge and open questions that require a response. How soil microorganisms may hamper or totally inhibit the activities and functioning of AMF? What is the role of AMF in the trophic chain? To put it another way, are AMFs susceptible to parasitism or predation by soil microorganisms? A study on the relationships between AMF and free native nematodes and how they affect the growth of cereal crops under water stress is also required.

Role of AM fungi in nutrient acquisition andagriculture sustainability

Mycorrhizal fungi are essential for improving the availability of nutrients that are not mobile and diffuse. Due to the greater surface area of fungal hyphae on the surface of their external roots compared to roots without mycorrhizae, plants with mycorrhizae are better able to assimilate inorganic nutrients [83]. The increase in the plant's absorption of phosphorus is the main advantage of mycorrhizae. Ammonia is believed to be the most predominant form of nitrogen absorbed via fungal-encoded AMT1 family transporters, such as GintAMT1 characterized by *Glomus intraradicies* [84]. AM symbiosis may have an effect on crop quality by enhancing macro- and micronutrients and improving plant nutrition [72].

Soil Aggregation and Soil Stabilization

AM fungal mycelial network can have a binding action on the soil and improve soil structure. Glomalin, a hydrophobic, "sticky," proteinaceous material secreted by AM fungus, is another factor in soil stability and water retention. According to them, a thick hyphal network and glomalin secretion act together to stabilise soil aggregates, which enhances the structural stability and quality of the soil [85].

Abiotic Stress Alleviation

In many parts of the world, especially in arid and semi-arid regions, major problems with mineral depletion, drought, salinity, heavy metals, or heat exist. Managing agricultural systems to improve soil quality and crop productivity in harsh edaphoclimatic conditions will be of utmost importance to the agricultural sector [86]. AM fungi have long been known to have the potential to increase plant tolerance in abiotic stress conditions [87]. These substances help to reduce the osmotic potential, which in turn lowers the leaf water potential. Because of their lower potentials, plants are able to sustain high levels of organ hydration and turgor, which support total cell physiological activity, particularly that of the apparatus of photosynthesis [88]. By producing more antioxidant molecules that scavenge ROS and boost the activity of antioxidant enzymes, AM plants are better able to withstand oxidative stress brought on by drought or salinity [89]. AM root colonization, which can enhance root growth, architecture, and hydraulic features, can lead to the development of a highly effective root system for water and nutrient uptake. several mycorrhizal fungal strains, including *Glomus intraradices, Glomus mosseae*, and several *Glomus* sp., may withstand heavy metal stress are important fungi [90]. Heavy metals are mostly accumulated in fungal hyphae as well as in arbuscules. The ability of fungal hyphae to attach to metals results in the immobilization of numerous heavy metals. In addition to increasing Pi uptake by roots, AM fungi also have a buffering effect on the uptake of cadmium, which lessens the harmful effects of cadmium on plant growth [91].

Alleviation of Biotic Stresses Plants are attacked by various organisms ranging from fungi, bacteria, viruses and nematodes. The establishment of the arbuscular mycorrhizal (AM) symbiosis with plant host is able to reduce the attack of different insect pest and pathogen. It is well acknowledged that AM symbioses lessen the harm that soil-borne pathogens inflict. Several studies have shown a decrease in the frequency and/or severity of illnesses like root rot or wilting brought on by a variety of fungi, bacteria, and oomycetes like Aphanomyces Phytophthora, and Pythium as well as bacteria like Erwinia carotovora. Several mechanisms have been proposed to explain the protection extended by AMF to host plants against attack by pathogens. Several different types of mechanisms, such as increasing root thickenings and producing chemical changes, have been proposed to explain how mycorrhizal mediated biotic stress tolerance by host plants. According to Khan et al. (2009), AM plants have been discovered to have significant levels of amino acids, particularly arginine. Mycorrhizal symbiosis causes the host plant to go through amazing physiological changes.

Carbon Sequestration and AM Fungi In exchange for host photosynthetic carbon (C), AM fungi carry out a variety of ecological tasks that almost invariably improve the fitness of hosts at all scales, from the individual to the community [101]. A well-known method of AM fungi sequestering C in soil is by transferring photosynthates from the host plants to intraradical hyphae of the fungus and then to extraradical hyphae [102]. Glomalin may indirectly affect soil carbon storage by stabilising soil aggregates, as evidenced by the close association between the amount of glomalin in soil, hyphal length, and soil aggregate stability [59]. Also, it is increasingly clear that the AM symbiosis can promote the production of plant secondary metabolites that are crucial for enhancing a plant's resistance to biotic and abiotic stressors or advantageous to human health due to their antioxidant activity (Adolfsson et. al., 2017). Plants grown in the field were found to have up to 50% more Zn in shoots and fruits than mutant plants with reduced mycorrhizal colonisation (mc)[103].

Challenges of AMF application:

Mycorrhiza associations like AMF seems to have huge benefits such as increasing soil fertility, plant growth, crop yielding capacity, stress resistance etc. but sometimes they can beless beneficial than their actual potential. To find out the actual potential and benefits of mycorrhizal fungi, large scale field trials must be done and then suitable AM combinations for different plants should be chosen. 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 might occasionally take over and produce better effects than the new ones. Also, according on their geographic locations, the same mycorrhizal species may have varied results (Fierer et. al., 2007). To solve this problem, indigenous mycorrhizal strains should be isolated toproduce inoculum and then they should be reintroduced to the field in large scale (Kour et. al., 2020).

Conclusion and future prospective

There is no doubt that arbuscular mycorrhizal fungi are one of the most important soil organisms. AMFs assist plants in absorbing water, consuming nutrients, and fending off biotic and abiotic stresses. Our finding of the underlying mechanisms is still limited, despite the fact that the importance of AMF in enhance soil fertility has long been recognized. Many studies have simultaneously looked at how AMF impacts the physical, chemical, and biological properties of the soil. In order to comprehend the role of AMF symbiotic interactions with crops in enhancing the physical, chemical, and biological features of the soil, the current review gives a complete explanation of the existing data. The synthesis of glomalin, which encourages the storage and flow of soil carbon and heightens soil stability, is one of the mechanisms we highlighted for how AMF influences soil fertility. AMF's advantageous interactions with other soil microbes, such Phosphate Solubilizing Bacteria, which produce phosphatase enzyme and mineralize organic Phosphate, were also highlighted. In the future, researchers should examine some aspects of this relationship that affect how AMF performs in soil. Future studies should use molecular methods, such as transcriptomic, gnomonic, and the creation of fungal mutants, to examine the regulation of N and its uptake from the soil during AMF symbiosis. The role of glomalin in enhancing carbon sequestration efficiency from a variety of climatic conditions and soil types needs to be further investigated in order to hasten its application in addressing soil degradation issues made worse by current climate disturbances. It is crucial to evaluate the accumulation and longevity of glomalin in soil fertility indices under various climatic, agrarian, and management situations. The effects of AMF on soil basal respiration are also being explored. It is difficult to understand how AMFs function in soil due to their obligate biotrophic nature. Hence, more field studies on how plant biodiversity affects

AMF diversity and operation are required. All these research topics should be based on new approaches, such as recent methodological advances in physiology, molecular biotechnology, and agroecology integrated into both laboratory and field conditions. Such actions are crucial for our ability to launch a fresh "green revolution" that is in line with the conditions needed to achieve a sustainable development that is rooted in agricultural production.

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Authors' contributions

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References

1. Philippot L, Raaijmakers JM, Lemanceau P, Van Der Putten WH. Going back to the roots: the microbial ecology of the rhizosphere. Nature Reviews Microbiology. 2013;11(11):789-99. https://doi.org/10.1038/nrmicro3109
2. Velten S, Leventon J, Jager N, Newig J. What Is Sustainable Agriculture? A Systematic Review.Sustainability. 2015; 7(6):7833 -7865. https://doi.org/10.3390/su7067833
3. Abbasi M, Maleki A, Mirzaeiheydari M, Rostaminiya M. 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. GesundePflanzen. 2022;7:1-2. https://doi.org/10.1007/s10343-022-00640-3
4. Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M. The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnology advances. 2014;32(2):429-48. https://doi.org/10.1016/j.biotechadv.2013.12.005
5. Ortas I, Ustuner O. The effects of single species, dual species and indigenous mycorrhiza inoculation on citrus growth and nutrient uptake. European Journal of Soil Biology. 2014;63:64-9. https://doi.org/10.1016/j.ejsobi.2014.05.007
6. SCHÜßLER A, Schwarzott D, Walker C. A new fungal phylum, the Glomeromycota: phylogeny and evolution. Mycological research. 2001;105(12):1413-21. https://doi.org/10.1017/S0953756201005196
7. Prasad R, Bhola D, Akdi K, Cruz C, KVSS S, Tuteja N, Varma A. Introduction to mycorrhiza: historical development. Mycorrhiza-function, diversity, state of the Art. 2017:1-7.
8. Brundrett MC. 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. 2009;320:37-77.
9. Saxena J, Chandra S, Nain L. Synergistic effect of phosphate solubilizing rhizobacteria and arbuscular mycorrhiza on growth and yield of wheat plants. Journal of soil science and plant nutrition. 2013;13(2):511-25.
10. Augé RM, Toler HD, Saxton AM. Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: a meta-analysis. Mycorrhiza. 2015;25(1):13-24. https://doi.org/10.1007/s00572-014-0585-4
11. Quiroga G, Erice G, Aroca R, Chaumont F, Ruiz-Lozano JM. 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. 2017;8:1056. https://doi.org/10.3389/fpls.2017.01056
12. Amirnia R, Ghiyasi M, Siavash Moghaddam S, Rahimi A, Damalas CA, Heydarzadeh S. 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. 2019;19:592-602. https://doi.org/10.1007/s42729-019-00058-3
13. Chitarra W, Pagliarani C, Maserti B, Lumini E, Siciliano I, Cascone P, Schubert A, Gambino G, Balestrini R, Guerrieri E. Insights on the impact of arbuscular mycorrhizal symbiosis on tomato tolerance to water stress. Plant Physiology. 2016;171(2):1009-23. https://doi.org/10.1104/pp.16.00307
14. Mirshad PP, Puthur JT. Arbuscular mycorrhizal association enhances drought tolerance potential of promising bioenergy grass *(Saccharum arundinaceumretz.).* Environmental Monitoring and Assessment. 2016;188:1-20. https://doi.org/10.1007/s10661-016-5428-7
15. Fiorilli V, Vannini C, Ortolani F, Garcia-Seco D, Chiapello M, Novero M, Domingo G, Terzi V, Morcia C, Bagnaresi P, Moulin L. Omics approaches revealed how arbuscular mycorrhizal symbiosis enhances yield and resistance to leaf pathogen in wheat. Scientific Reports. 2018;8(1):1-8. https://doi.org/10.1038/s41598-018-27622-8
16. Bernaola L, Stout MJ. The effect of mycorrhizal seed treatments on rice growth, yield, and tolerance to insect herbivores. Journal of Pest Science. 2021 Mar;94(2):375-92. https://doi.org/10.1007/s10340-020-01279-7
17. Sadhana B. Arbuscular Mycorrhizal Fungi (AMF) as a biofertilizer -a review. Int. J. Curr. Microbiol. App. Sci. 2014;3(4):384-400.
18. Jamiołkowska A, Księżniak A, Gałązka A, Hetman B, Kopacki M, Skwaryło-Bednarz B. Impact of abiotic factors on development of the community of arbuscular mycorrhizal fungi in the soil: a review. International Agrophysics. 2018;32(1).
19. Parihar M, Rakshit A, Meena VS, Gupta VK, Rana K, Choudhary M, Tiwari G, Mishra PK, Pattanayak A, Bisht JK, Jatav SS. The potential of arbuscular mycorrhizal fungi in C cycling: a review. Archives of Microbiology. 2020;202:1581-96. https://doi.org/10.1007/s00203-020-01915-x
20. Siddiqui ZA, Pichtel J. Mycorrhizae: an overview. Mycorrhizae: sustainable agriculture and forestry. 2008:1-35.
21. Zancarini A, Lépinay C, Burstin J, Duc G, Lemanceau P, Moreau D, Munier-Jolain N, Pivato B, Rigaud T, Salon C, Mougel C. 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. 2013;1:69-86. https://doi.org/10.1002/9781118297674.ch7

22. Spatafora JW, Chang Y, Benny GL, Lazarus K, Smith ME, Berbee ML, Bonito G, Corradi N, Grigoriev I, Gryganskyi A, James TY. A phylum-level phylogenetic classification of zygomycete fungi based on genome-scale data. Mycologia. 2016;108(5):1028-46. https://doi.org/10.3852/16-042

23. Smith SE, Read DJ. Mycorrhizal symbiosis. Academic press; 2010.

24. Dal Cortivo C, Ferrari M, Visioli G, Lauro M, Fornasier F, Barion G, Panozzo A, Vamerali T. Effects of seed-applied biofertilizers on rhizosphere biodiversity and growth of common wheat (*Triticum aestivum* L.) in the field. Frontiers in Plant Science. 2020;11:72. https://doi.org/10.3389/fpls.2020.00072

25. Dowarah B, Gill SS, Agarwala N. Arbuscular mycorrhizal fungi in conferring tolerance to biotic stresses in plants. Journal of Plant Growth Regulation. 202;1-6. https://doi.org/10.1007/s00344-021-10392-5

26. Zhu Y, Lv GC, Chen YL, Gong XF, Peng YN, Wang ZY, Ren AT, Xiong YC. Inoculation of arbuscular mycorrhizal fungi with plastic mulching in rainfed wheat: A promising farming strategy. Field Crops Research. 2017;204:229-41. https://doi.org/10.1016/j.fcr.2016.11.005

27. Espidkar Z, Yarnia M, Ansari MH, Mirshekari B, Asadi Rahmani H. 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. 2017;15(4):195-216.

28. Suri VK, Choudhary AK. 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. 2013;44(17):2587-604. https://doi.org/10.1080/00103624.2013.803569

29. Erman M, Demir S, Ocak E, Tüfenkçi Ş, Oğuz F, Akköprü A. 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. 2011;122(1):14-24. https://doi.org/10.1016/j.fcr.2011.02.002

30. Sharma V, Sharma S, Sharma S, Kumar V. Synergistic effect of bio-inoculants on yield, nodulation and nutrient uptake of chickpea (*Cicer arietinum* L) under rainfed conditions. Journal of Plant Nutrition. 2019;42(4):374-83. https://doi.org/10.1080/01904167.2018.1555850

31. Rezaei-Chiyaneh E, Jalilian J, Seyyedi SM, Barin M, Ebrahimian E, Afshar RK. Isabgol (*Plantago ovata*) and lentil (*Lens culinaris*) intercrop responses to arbuscular mycorrhizal fungi inoculation. Biological Agriculture & Horticulture. 2021;37(2):125-40. https://doi.org/10.1080/01448765.2021.1903556

32. Trewin, N.H. & C.M. Rice (eds.): The Rhynie hot-spring system: geology, biota and mineralisation. – Trans. Roy. Soc. Edinburgh, Earth Sci. 2004;94: 285–521.

33. PIROZYNSKI KA, DALPE Y. Geological history of the Glomaceae with particular reference to mycorrhizal symbiosis. Symbiosis. 1989.

34. Redecker D. Specific PCR primers to identify arbuscular mycorrhizal fungi within colonized roots. Mycorrhiza. 2000;10(2):73-80. https://doi.org/10.1007/s005720000061

35. Brundrett MC. Coevolution of roots and mycorrhizas of land plants. New phytologist. 2002;154(2):275-304. https://doi.org/10.1046/j.1469-8137.2002.00397.x

36. Raven JA, Andrews M. Evolution of tree nutrition. Tree Physiology. 2010;30(9):1050-71. https://doi.org/10.1093/treephys/tpq056

37. Li X, Zhang J, Gai J, Cai X, Christie P, Li X. Contribution of arbuscular mycorrhizal fungi of sedges to soil aggregation along an altitudinal alpine grassland gradient on the T ibetan P lateau. Environmental microbiology. 2015;17(8):2841-57. https://doi.org/10.1111/1462-2920.12792

38. Zanne AE, Tank DC, Cornwell WK, Eastman JM, Smith SA, FitzJohn RG, McGlinn DJ, O'Meara BC, Moles AT, Reich PB, Royer DL. Three keys to the radiation of angiosperms into freezing environments. Nature. 2014;506(7486):89-92. https://doi.org/10.1038/nature12872

39. Smith, S.E.; Smith, F.A. Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *Biol. Annu. Rev. Plant* **2011**, *62*, 227–250. https://doi.org/10.1146/annurev-arplant-042110-103846

40. Brundrett MC. Global diversity and importance of mycorrhizal and nonmycorrhizal plants. Biogeography of mycorrhizal symbiosis. 2017:533-56.

41. Swaty R, Michael HM, Deckert R, Gehring CA. Mapping the potential mycorrhizal associations of the conterminous United States of America. Fungal Ecology. 2016;24:139-47. https://doi.org/10.1016/j.funeco.2016.05.005

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

43. Freudenstein JV, Broe MB, Feldenkris ER. Phylogenetic relationships at the base of Ericaceae: implications for vegetative and mycorrhizal evolution. Taxon. 2016;65(4):794-804. https://doi.org/10.12705/654.7

44. Szabó K, Böll S, Erős-Honti ZS. Applying artificial mycorrhizae in planting urban trees. Applied ecology and environmental research. 2014;12(4):835-53.

45. van Der Heijden MG, Martin FM, Selosse MA, Sanders IR. Mycorrhizal ecology and evolution: the past, the present, and the future. New phytologist. 2015;205(4):1406-23. https://doi.org/10.1111/nph.13288

46. Pellegrino E, Bedini S. Enhancing ecosystem services in sustainable agriculture: biofertilization and biofortification of chickpea (*Cicer arietinum* L.) by arbuscular mycorrhizal fungi. Soil Biology and biochemistry. 2014;68:429-39. https://doi.org/10.1016/j.soilbio.2013.09.030

47. Prasad R, Bhola D, Akdi K, Cruz C, KVSS S, Tuteja N, Varma A. Introduction to mycorrhiza: historical development. Mycorrhiza-function, diversity, state of the Art. 2017:1-7.

48. Cervantes-Gámez RG, Bueno-Ibarra MA, Cruz-Mendívil A, Calderón-Vázquez CL, Ramírez-Douriet CM, Maldonado-Mendoza IE, Villalobos-López MÁ, Valdez-Ortíz Á, López-Meyer M. Arbuscular mycorrhizal symbiosis-induced expression changes in *Solanum lycopersicum* leaves revealed by RNA-seq analysis. Plant Molecular Biology Reporter. 2016;34:89-102. https://doi.org/10.1007/s11105-015-0903-9

49. Castellanos-Morales V, Villegas J, Wendelin S, Vierheilig H, Eder R, Cárdenas-Navarro R. 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. 2010;90(11):1774-82. https://doi.org/10.1002/jsfa.3998

50. Lingua G, Bona E, Manassero P, Marsano F, Todeschini V, Cantamessa S, Copetta A, D'Agostino G, Gamalero E, Berta G. 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. 2013;14(8):16207-25. https://doi.org/10.3390/ijms140816207

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

52. Baslam M, Qaddoury A, Goicoechea N. Role of native and exotic mycorrhizal symbiosis to develop morphological, physiological and biochemical responses coping with water drought of date palm, *Phoenix dactylifera*. Trees. 2014;28:161-72.
53. da Silva IR, de Mello CM, Neto RA, da Silva DK, de Melo AL, Oehl F, Maia LC. Diversity of arbuscular mycorrhizal fungi along an environmental gradient in the Brazilian semiarid. Applied Soil Ecology. 2014;84:166-75. https://doi.org/10.1016/j.apsoil.2014.07.008
54. Eftekhari M, Alizadeh M, Mashayekhi K, Asghari HR. *In vitro* propagation of four Iranian grape varieties: influence of genotype and pretreatment with arbuscular mycorrhiza. Vitis. 2012;51(4):175-82.
55. Dave S, Tarafdar JC. Stimulatory synthesis of saponin by mycorrhizal fungi in safed musli (*Chlorophytum borivilianum*) tubers. Int Res J Agric Sci Soil Sci. 2011;1:137-41.
56. Geneva MP, Stancheva IV, Boychinova MM, Mincheva NH, Yonova PA. 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. 2010;90(4):696-702. https://doi.org/10.1002/jsfa.3871
57. Garg N, Bharti A. Salicylic acid improves arbuscular mycorrhizal symbiosis, and chickpea growth and yield by modulating carbohydrate metabolism under salt stress. Mycorrhiza. 2018;28(8):727-46.
58. Karagiannidis N, Thomidis T, Lazari D, Panou-Filotheou E, Karagiannidou C. Effect of three Greek arbuscular mycorrhizal fungi in improving the growth, nutrient concentration, and production of essential oils of oregano and mint plants. Scientia horticulturae. 2011;129(2):329-34. https://doi.org/10.1016/j.scienta.2011.03.043
59. Cosme M, Fernández I, Declerck S, van der Heijden MG, Pieterse CM. A coumarin exudation pathway mitigates arbuscular mycorrhizal incompatibility in Arabidopsis thaliana. Plant molecular biology. 2021;106:319-34.
60. Rasouli-Sadaghiani M, Hassani A, Barin M, Danesh YR, Sefidkon F. Effects of arbuscular mycorrhizal (AM) fungi on growth, essential oil production and nutrients uptake in basil. J Med Plants Res. 2010;4(21):2222-8. https://doi.org/10.5897/JMPR10.337
61. Mishra V, Gupta A, Kaur P, Singh S, Singh N, Gehlot P, Singh J. Synergistic effects of Arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria in bioremediation of iron contaminated soils. International journal of phytoremediation. 2016;18(7):697-703. https://doi.org/10.1080/15226514.2015.1131231
62. Ratti N, Verma HN, Gautam SP. Effect of Glomus species on physiology and biochemistry of *Catharanthus roseus*. Indian Journal of Microbiology. 2010;50:355-60.
63. Giovannetti M, Volpe V, Salvioli A, Bonfante P. Fungal and plant tools for the uptake of nutrients in arbuscular mycorrhizas: a molecular view. InMycorrhizal mediation of soil 2017;107-128. https://doi.org/10.1016/B978-0-12-804312-7.00007-3
64. Mandal S, Evelin H, Giri B, Singh VP, Kapoor R. Arbuscular mycorrhiza enhances the production of stevioside and rebaudioside-A in Stevia rebaudiana via nutritional and non-nutritional mechanisms. Applied soil ecology. 2013;72:187-94. https://doi.org/10.1016/j.apsoil.2013.07.003
65. Nell M, Wawrosch C, Steinkellner S, Vierheilig H, Kopp B, Lössl A, Franz C, Novak J, Zitterl-Eglseer K. Root colonization by symbiotic arbuscular mycorrhizal fungi increases sesquiterpenic acid concentrations in *Valeriana officinalis* L. Planta Medica. 2009;80:393-8. https://doi.org/10.1055/s-0029-1186180
66. Miura C, Yamaguchi K, Miyahara R, Yamamoto T, Fuji M, Yagame T, Imaizumi-Anraku H, Yamato M, Shigenobu S, Kaminaka H. The mycoheterotrophic symbiosis between orchids and mycorrhizal fungi possesses major components shared with mutualistic plant-mycorrhizal symbioses. Molecular Plant-Microbe Interactions. 2018;31(10):1032-47. https://doi.org/10.1094/MPMI-01-18-0029-R
67. Qin Z, Zhang H, Feng G, Christie P, Zhang J, Li X, Gai J. Soil phosphorus availability modifies the relationship between AM fungal diversity and mycorrhizal benefits to maize in an agricultural soil. Soil Biology and Biochemistry. 2020;144:107790. https://doi.org/10.1016/j.soilbio.2020.107790
68. Chen S, Zhao H, Zou C, Li Y, Chen Y, Wang Z, Jiang Y, Liu A, Zhao P, Wang M, Ahammed GJ. Combined inoculation with multiple arbuscular mycorrhizal fungi improves growth, nutrient uptake and photosynthesis in cucumber seedlings. Frontiers in Microbiology. 2017;8:2516. https://doi.org/10.3389/fmicb.2017.02516
69. Shen SK, Wang YH. 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. 2011;59(5):460-7. https://doi.org/10.1071/BT11002
70. Rodrigues MÂ, Piroli LB, Forcelini D, Raimundo S, da Silva Domingues L, Cassol LC, Correia CM, Arrobas M. Use of commercial mycorrhizal fungi in stress-free growing conditions of potted olive cuttings. Scientia Horticulturae. 2021;275:109712. https://doi.org/10.1016/j.scienta.2020.109712
71. Zaidi A, Khan MS. Stimulatory effects of dual inoculation with phosphate solubilising microorganisms and arbuscular mycorrhizal fungus on chickpea. Australian Journal of Experimental Agriculture. 2007;47(8):1016-22. https://doi.org/10.1071/EA06046
72. Zhang H, Liu Z, Chen H, Tang M. Symbiosis of arbuscular mycorrhizal fungi and *Robinia pseudoacacia* L. improves root tensile strength and soil aggregate stability. Plos one. 2016;11(4):e0153378. https://doi.org/10.1371/journal.pone.0153378
73. Nizar KM, Tan CC, Masya ME. Psychological Effects of Arbuscular Mychorrhiza Fungi Reducing Chemical Fertilizer on The Growth of Oil Palm Seedling. InIOP Conference Series: Earth and Environmental Science 2023; 1167(1):012017. https://doi.org/10.1088/1755-1315/1167/1/012017
74. Kalayu G. Phosphate solubilizing microorganisms: promising approach as biofertilizers. International Journal of Agronomy. 2019;2019:1-7. https://doi.org/10.1155/2019/4917256
75. Faghihinia M, Jansa J, Halverson LJ, Staddon PL. Hyphosphere microbiome of arbuscular mycorrhizal fungi: a realm of unknowns. Biology and Fertility of Soils. 2023;59(1):17-34. https://doi.org/10.1007/s00374-022-01683-4
76. Parihar M, Chitara M, Khati P, Kumari A, Mishra PK, Rakshit A, Rana K, Meena VS, Singh AK, Choudhary M, Bisht JK. Arbuscular mycorrhizal fungi: Abundance, interaction with plants and potential biological applications. Advances in Plant Microbiome and Sustainable Agriculture: Diversity and Biotechnological Applications. 2020:105-43.
77. Hashem A, Kumar A, Al-Dbass AM, Alqarawi AA, Al-Arjani AB, Singh G, Farooq M, Abd_Allah EF. Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. Saudi journal of biological sciences. 2019;26(3):614-24. https://doi.org/10.1016/j.sjbs.2018.11.005
78. Alimi AA, Ezeokoli OT, Adeleke R, Moteetee A. Arbuscular mycorrhizal fungal communities colonising the roots of indigenous legumes of South Africa as revealed by high-throughput DNA metabarcoding. Rhizosphere. 2021;19:100405. https://doi.org/10.1016/j.rhisph.2021.100405
79. Larimer AL, Clay K, Bever JD. Synergism and context dependency of interactions between arbuscular mycorrhizal fungi and rhizobia with a prairie legume. Ecology. 2014;95(4):1045-54. https://doi.org/10.1890/13-0025.1

80. Agarwal AN, Singh JA, Singh AP. Arbuscular mycorrhizal fungi and its role in sequestration of heavy metals. Trends Biosci. 2017;10(21):4068-77.

81. López-Pedrosa A, González-Guerrero M, Valderas A, Azcón-Aguilar C, Ferrol N. GintAMT1 encodes a functional high-affinity ammonium transporter that is expressed in the extraradical mycelium of *Glomus intraradices*. Fungal Genetics and Biology. 2006;43(2):102-10. https://doi.org/10.1016/j.fgb.2005.10.005

82. Bedini S, Avio L, Sbrana C, Turrini A, Migliorini P, Vazzana C, Giovannetti M. Mycorrhizal activity and diversity in a long-term organic Mediterranean agroecosystem. Biology and Fertility of Soils. 2013;49:781-90.

83. Blanco-Canqui H, Lal R. Crop residue management and soil carbon dynamics. Soil carbon sequestration and the greenhouse effect. 2009;57:291-309. https://doi.org/10.2136/sssaspecpub57.2ed.c17

84. Khalvati M, Bartha B, Dupigny A, Schröder P. Arbuscular mycorrhizal association is beneficial for growth and detoxification of xenobiotics of barley under drought stress. Journal of Soils and Sediments. 2010;10:54-64. https://doi.org/10.1007/s11368-009-0119-4

85. Lucas WJ, Groover A, Lichtenberger R, Furuta K, Yadav SR, Helariutta Y, He XQ, Fukuda H, Kang J, Brady SM, Patrick JW. The plant vascular system: evolution, development and functions f. Journal of integrative plant biology. 2013;55(4):294-388. https://doi.org/10.1111/jipb.12041

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

87. Gherbi H, Markmann K, Svistoonoff S, Estevan J, Autran D, Giczey G, Auguy F, Péret B, Laplaze L, Franche C, Parniske M. 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. 2008;105(12):4928-32. https://doi.org/10.1073/pnas.0710618105

88. Seeram NP. Berry fruits: compositional elements, biochemical activities, and the impact of their intake on human health, performance, and disease. Journal of agricultural and food chemistry. 2008;56(3):627-9. https://doi.org/10.1021/jf071988k

89. Cavagnaro TR, Barrios-Masias FH, Jackson LE. Arbuscular mycorrhizas and their role in plant growth, nitrogen interception and soil gas efflux in an organic production system. Plant and soil. 2012;353:181-94. https://doi.org/10.1007/s11104-011-1021-6

90. García A, Labidi J, Belgacem MN, Bras J. The nanocellulose biorefinery: woody versus herbaceous agricultural wastes for NCC production. Cellulose. 2017;24:693-704. https://doi.org/10.1007/s10570-016-1144-2

91. Colombo RP, Ibarra JG, Bidondo LF, Silvani VA, Bompadre MJ, Pergola M, Lopez NI, Godeas AM. Arbuscular mycorrhizal fungal association in genetically modified drought-tolerant corn. Journal of environmental quality. 2017;46(1):227-31. https://doi.org/10.2134/jeq2016.04.0125

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

93. Shaul O, Galili S, Volpin H, Ginzberg I, Elad Y, Chet I, Kapulnik Y. Mycorrhiza-induced changes in disease severity and PR protein expression in tobacco leaves. Molecular Plant-Microbe Interactions. 1999;12(11):1000-7. https://doi.org/10.1094/MPMI.1999.12.11.1000

94. Zhang HS, Qin FF, Qin P, Pan SM. 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. 2014;24:383-95. https://doi.org/10.1007/s00572-013-0546-3

95. Ozgonen H, Erkilic A. Growth enhancement and Phytophthora blight (*Phytophthora capsici* Leonian) control by arbuscular mycorrhizal fungal inoculation in pepper. Crop Protection. 2007;26(11):1682-8. https://doi.org/10.1016/j.cropro.2007.02.010

96. Siddiqui ZA, Sayeed Akhtar M. 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. 2009;75:144-53. https://doi.org/10.1007/s10327-009-0154-4

97. Pozo MJ, Azcón-Aguilar C. Unraveling mycorrhiza-induced resistance. Current opinion in plant biology. 2007;10(4):393-8. https://doi.org/10.1016/j.pbi.2007.05.004

98. Pradhan M, Baldwin IT, Pandey SP. Argonaute7 (AGO7) optimizes arbuscular mycorrhizal fungal associations and enhances competitive growth in *Nicotiana attenuata*. New Phytologist. 2023;240(1):382-98. https://doi.org/10.1111/nph.19155

99. Bordoloi A, Nath PC, Shukla AK. Distribution of arbuscular mycorrhizal fungi associated with different land use systems of Arunachal Pradesh of Eastern Himalayan region. World Journal of Microbiology and Biotechnology. 2015;31:1587-93. https://doi.org/10.1007/s11274-015-1909-z

100. García-Garrido JM, Ocampo JA, García-Romera I. Enzymes in the arbuscular mycorrhizal symbiosis. Marcel Dekker, New York; 2002 Jan 29.

101. Sundram S, Othman R, Idris AS, Angel LP, Meon S. Improved Growth Performance of *Elaeis guineensis* Jacq. Through the Applications of Arbuscular Mycorrhizal (AM) Fungi and Endophytic Bacteria. Current Microbiology. 2022;79(5):155. https://doi.org/10.1007/s00284-022-02842-4

102. Chen S, Zhao H, Zou C, Li Y, Chen Y, Wang Z, Jiang Y, Liu A, Zhao P, Wang M, Ahammed GJ. Combined inoculation with multiple arbuscular mycorrhizal fungi improves growth, nutrient uptake and photosynthesis in cucumber seedlings. Frontiers in Microbiology. 2017;8:2516. https://doi.org/10.3389/fmicb.2017.02516

103. Khaosaad T, Staehelin C, Steinkellner S, Hage-Ahmed K, Ocampo JA, Garcia-Garrido JM, Vierheilig H. The Rhizobium sp. strain NGR234 systemically suppresses arbuscular mycorrhizal root colonization in a split-root system of barley (*Hordeum vulgare*). Physiologia plantarum. 2010;140(3):238-45. https://doi.org/10.1111/j.1399-3054.2010.01396.x