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Mycorrhizae: A Rhizolive Symbiotic Fungi in Organic Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Mycorrhizae, a symbiotic association between fungal hyphae and plant roots, play a crucial role in achieving sustainable development goals in natural farming by enhancing soil structure, nutrient uptake, and plant growth. Arbuscular Mycorrhizae (AM) and Ectomycorrhizae are often encouraged

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in no-tillage systems and conservation agriculture. Mycorrhizal fungi, particularly within the rhizolive consortium, are shown to improve soil fertility, water retention, heavy metal degradation, and disease resistance. They assist in nutrient cycling, especially phosphorus, and contribute to soil aggregation through the secretion of Glomalin-Related Soil Proteins (GRSP). The use of AM fungi in pest and disease management, land rehabilitation, and bioremediation is highlighted, emphasizing their potential in sustainable agriculture. The paper also outlines methods for the mass production of Arbuscular Mycorrhiza Fungi as biofertilizers, including soil-less culture, carrier-based inoculum, and hairy root culture techniques. Certain agronomic practices and modifications in the existing land management practices by multiple cropping systems rather than mono-cropping to deliberately improve the resource use efficiency and soil organic carbon dynamics through this symbiotic relationship in enhancing soil health, plant productivity, and ecological balance in farming systems.

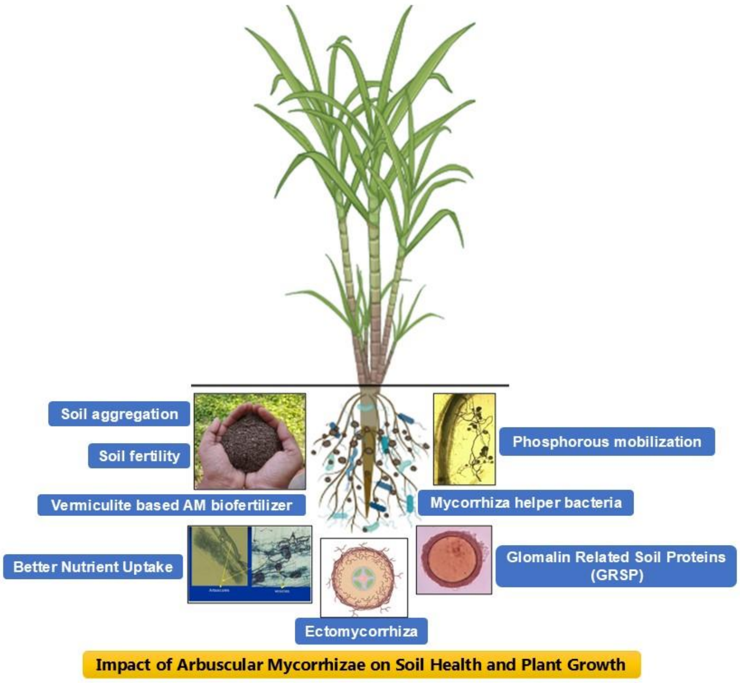

Fig. 1. Impact of arbuscular mycorrhizae on soil health and plant growth

Keywords: Mycorrhizae; soil fertility; nutrient uptake; AMF biofertilizer; sustainability.

1. INTRODUCTION

"Mycorrhizae (fungus-root) is the association between fungal hyphae and underground plant parts of Bryophytes or Pteridophytes or roots of seed plants. Frank, a German pathologist used the term mycorrhiza meaning 'Fungus roots' in 1885 It plays a vital role as a crucial link between plants and soil Mycorrhiza is a type of endophytic, biotrophic, mutualistic, tri-trophic obligatory fungi prevalent in many cultivated and natural ecosystems" [1].

These fungi extend into the plant roots, significantly expanding the root system, sometimes by thousands of times. The various structures created by the root tip, hairs, and fungal hyphae are characteristic of different mycorrhizal associations. These fungi form a symbiotic relationship with plants, aiding in converting complex substrates into simpler forms. Miles of fungal filaments can be present in a single ounce of healthy soil. Arbuscular Mycorrhizae (AM) are among the most prevalent fungi in agricultural soils, comprising 5-50% of the microbial biomass. These fungi form extensive networks, with 10-100 meters of mycelium per centimeter of root. Nearly all tropical crops form associations with AM, and many are highly responsive to Arbuscular Mycorrhizal Fungi (AMF). The benefits of these

Table 1. Types of mycorrhizae based on anatomical and morphological structures

S.No.	Types of Mycorrhizae	Examples
1.	Ectomycorrhizae	*Amanita muscaria*, *Boletus*, *Scleroderma citrinum*
2.	Endomycorrhizae or Arbuscular Mycorrhizal Fungi (AMF)	*Acaulospora, Endogone, Glomus mosseae, G. etunicatum, G. clarum, G. caledonium*, *Gigaspora, Glaziella*
3.	Ectendomycorrhizae	*Wilcoxina*
4.	Arbutoid mycorrhizae	*Boletus*, *Scleroderma*
5.	Monotropoid mycorrhizae	*Monotropa hypopitys*
6.	Ericoid mycorrhizae	*Rhizoscyphus*, *Sebacina*
7.	Orchidaceous mycorrhizae	*Sesbania, Russula*

associations include enhanced uptake of immobile nutrients, particularly phosphorus, and various micronutrients, promotion of plant growth through a three-way interaction between roots and the rhizosphere microbiome, protection against pathogens, mitigation of aluminum and heavy metal toxicity, improved water relations under nutrient-limited conditions, and contribution to soil structure through the accumulation of GRSP [2].

Natural farming involves the propagation of mycorrhizae by incorporating specific inputs during the plant's nutritive cycle. A key indicator of organically managed natural fields is well-structured soil with a high percentage of water-stable aggregates [3,4]. The Indigenous mycorrhizal fungi, known as the 'Rhizolive consortium', along with plant growth-promoting rhizobacteria (PGPR), play a vital role in enhancing plant growth and development. "Mycorrhizal interaction offers plants, soil, and sustainable agriculture several advantages and helps to improve soil structure by creating humic compounds and organic glues that help improve soil porosity and aggregate formation, and that's how plant growth increases due to improved aeration, water movement, root growth" [5-8]. Ectomycorrhizae and endomycorrhizae are important in agriculture and forestry. But, endomycorrhizae (Arbuscular Mycorrhizae) are the most abundant and widespread vascular flowering plants in natural and agricultural ecosystems, undisturbed forest ecosystems where soil is undisturbed [9].

2. MYCORRHIZAL GLOMALINS FOR SOIL AGGREGATION

Mycorrhizal Glomalin-Related Soil Proteins (GRSP) include various glycoproteins secreted into the soil by the hyphae and spore walls of arbuscular mycorrhizal fungi (AMF). These proteins, such as the hydrophobic and heat-resistant glomalin, are released from AMF spores and through the degradation of hyphae. GRSP plays a crucial role in binding and safeguarding soil organic matter and particles by forming a water-repellent layer, which enhances soil aggregation [10]. Alongside GRSP, soil organic matter and organic carbon serve as binding agents that contribute to soil aggregation and interact with soil properties at different depths in lead-zinc contaminated areas [11]. AMF promotes the stability of soil aggregates by affecting plant root exudation [12]. Glomalin recognized as a potential soil conditioner, is vital for soil aggregation and influences soil-water dynamics [13,14]. Studies have demonstrated that GRSP production and the induction of certain soil enzymes by AMF are significant indicators of soil fertility. The amount of these compounds in soils changes depending on the phosphorus levels present in the soil [15].

3. MYCORRHIZAL ASSOCIATION IN THE NATURAL AND ORGANIC FARMING SYSTEM

Mycorrhizae in the soil boost carbon accumulation by depositing glomalin, which strengthens soil structure by binding organic matter to mineral particles. Mycorrhizal association helps in improving the soil structure by producing humic compounds and organic glues as well which help in improving the soil porosity and formation of aggregates and that's how plant growth increased because of improved aeration, water movement, growth of roots, *etc*., Wahdan et al. [16] described the relationship between higher plant roots and AM fungi for plant growth promotion and improved nutrient uptake in plants. Soil and crop management practices like tillage frequency, use of pesticides or fungicides, fertilizer application, and cropping intensity and rotation play a crucial role in AM colonization and differ completely between conventional farming and organic farming. A study by Sale et al. [17] demonstrated that reduced tillage in organic farming significantly enhanced the density and diversity of AMF topsoil spores compared to conventional tillage. In reduced tillage plots, spore densities ranged from 42.7 to 48.9 spores per gram, whereas conventional tillage plots had lower densities, around 29.5 to 29.8 spores per gram. Additionally, species richness was higher in reduced tillage plots, with up to 32 species identified, in contrast to fewer species in conventional plots. Although AMF diversity and abundance tended to decrease with soil depth, reduced tillage sustained greater AMF diversity in deeper layers than conventional tillage. Moreover, the study identified several AMF indicator species linked to specific land use and tillage practices, highlighting the sensitivity of AMF communities to different agricultural approaches.

Soti et al. [18] indicated that the community dynamics of AMF are highly influenced by agronomic practices, the use of cover crops promotes the abundance, diversity, and sporulation efficiency of AMF in tested crops such as vegetable crops *Capsicum annuum* and *Allium fistulosum* at Texas. Furthermore, the cover crops like Sorghum, Cowpea, and Sunn hemp in fallow conditions augmented the relative abundance of AM spores in the rhizosphere. Mycorrhizal interactions have many benefits for plants, soils, and sustainable agriculture. Mycorrhizal associations help improve soil structure by producing humus substances and organic adhesives that improve soil porosity and aggregate formation, enhancing plant growth through improved aeration, water movement, and root growth.

Azhar et al. [19] experimented with coffee farms in Indonesia, to explore the differences in AM colonization in conventional and organic farming at two different sites. It was found that the number and diversity of *Glomus* spores were abundant in coffee roots of organic farming systems. In Germany, the research findings by Wahdan et al. [20] speculated future climate scenarios and farming methods that affect AMF in wheat roots. It compares conventional and organic farming practices under both current and projected climate conditions. The findings reveal that both climate and farming practices have a substantial impact on AMF community composition. Conventional farming tends to lower AMF diversity, whereas organic farming increases AMF richness, particularly in the Gigasporaceae family. Increased AMF richness was associated with better nutrient levels in wheat grains, suggesting that organic farming could be crucial for sustaining soil health and crop productivity as climate change progresses.

Chen et al. [21] analyzed the operational taxonomic units of Maize cultivated soil arbuscular mycorrhizal fungal community in poor-quality farming situations in China. It was found that in conventional farming lands *Glomus, Septoglomus, Funneliformis,* and *Kamienskia* were predominantly present, whereas, *Paraglomus*, *Glomus,* and *Ambispora* were prevalent in organic farming situations. The colonization efficiency and the taxonomic diversity of AM fungi were relatively higher in conventional farming systems rather than in organic farms. AMF are soil fungi that form a symbiotic relationship with the roots of host plants. In this study, sugarcane rhizospheric soil samples were collected from six different locations in Tamil Nadu. Both the rhizospheric soil and roots were analyzed to determine the relative abundance of AMF. Through morphological and taxonomic characterization, *G. intraradices* was identified as the most predominant AM fungus in the sugarcane rhizosphere. The colonization potential and spore propagation capacity of this fungus in maize (*Zea mays* L.) using the open pot culture method were 65% and 121%, respectively. To test the germination of *G. intraradices* spores, four different substrates - Modified Strullu and Romand (MSR) medium, Murashige and Skoog (MS) medium, White's medium, and 0.75% water agar were used. Among these, the MSR medium showed the highest spore germination rate (80%) and the longest germ tube elongation (63 mm) after 30 days of incubation at 27°C in darkness. These naturally surviving, efficient AM spores can be used for monoxenic *In-vitro* inoculum production [22].

4. MYCORRHIZA HELPER BACTERIA

When the diversity of AMF is relatively high, very well-structured and biologically active enriched soil is widespread. Master quality of soil structure is the outcome of the sum of biological activities in the soil of any natural environment. AM fungi form a symbiotic relationship with 80% of terrestrial plants, improve plant growth, and nutrient accumulation, enhance drought stress tolerance, and maintain soil structure, AM fungi increase the biomass, N, and P content in shoots and roots of plants. AM fungi via extensive extraradical hyphae interacting with indigenous microbial communities play crucial roles in plant growth in natural habitats. AM fungi regulate plant growth, and they are positively affected by cooperating with indigenous microorganisms Furthermore, AM fungi mycelium can transfer the photosynthetic carbohydrates from the host plants to the soil, which recruits soil microorganisms [23].

“Mycorrhizae works in synergy with beneficial microorganisms, such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and plant-growth-promoting rhizobacteria. The combination of AM fungi and specific bacteria could promote plant growth by minimizing drought-related stress effects. AM fungi and phosphorus-solubilizing bacteria enhance plant nutrient absorption. Additionally, plant growth-promoting rhizobacteria can support the activity and establishment of mycorrhizal fungi. AM fungi play important roles in improving plant growth and nutrient absorption. However, AM fungi inevitably interact with indigenous microorganisms in the vegetation restoration of the degraded ecosystem” [2].

5. ECTOMYCORRHIZAL ASSOCIATION IN TREE CROPS

It is evidenced that ectomycorrhizal interactions between tree roots help to fix nitrogen in Orchids, Ericales, and forest trees. Most vascular plants possess both mycorrhizae and N-fixing symbiotic interactive organelles. The non-legumes with ectotrophic or endotrophic actinorhizal nodules are the best examples of it. The bacterial community living in the rhizosphere or proximity to plant roots is called mycorrhizosphere. N-fixing bacteria are even found inside the fungal mantle of ectomycorrhizae. Nutrient fluxes and dynamics between soil and trees, vascular plant roots are mediated by ectomycorrhiza act as an interface linking the transfer of low-availability nutrients from the soil to the host trees and receive below-ground carbon allocation especially carbohydrates from root exudates in return from plants. Mycorrhiza increases the growth of plants by producing certain hormones like cytokinins and gibberellins. AMF expands the root surface area for absorption, thereby extending root longevity, enhancing the uptake of scarce nutrients, improving nutrient storage, reducing interactions with soil colloids, and boosting nodulation and nitrogen fixation. The crop yield improved by mycorrhizal association specifically in infertile soils by providing P in the soil which is not readily available to plants for growth. Plant growth increases because mycorrhizal association helps in the uptake of nutrients especially phosphorous, carbon, nitrogen, and other micronutrients specifically zinc and copper [24].

6. AMF IN INSECT PEST AND DISEASE MANAGEMENT

AMFs are important because of their role in pest management and the presence of mantle which acts as a physical barrier against soil-borne pests, nematodes, and pathogens. The mycorrhizal association also helps to control the weeds in the safest way as compared to chemicals used to control the growth of weeds. Mycorrhizal association also helps in land rehabilitation. Because mycorrhizal association helps in the uptake of nutrients under water stress conditions, that’s how plants develop resistance against drought stress. This association allowed plants to grow in saline, nutrient-deficient, degraded, and eroded soils, as well as in areas affected by coal waste. AMF plays a crucial role in improving and preserving soil structural quality in natural soils. Glomalin secretion from the extraradical hyphae of AMF is a major factor in soil structure formation, helping to bind the soil.

AMF are essential elements of the rhizosphere in most plants and significantly contribute to reducing plant diseases caused by pathogens like *Phytophthora, Rhizoctonia, Pythium, Aphanomyces, Verticillium, Fusarium, Macrophomina*, as well as other soil-borne diseases. Ectomycorrhizal fungi such as *Paxillus involutus* and *Pisolithus tinctorius* control the root rot-causing disease caused by saprophytic fungi like *Fusarium moniliforme*, *Fusarium oxysporum* and *Phytophthora cinnamomi* in *red pines (Pinus resinosa)* and in sand pine respectively [25].

AMF negatively suppresses the pathogens by identifying them through chitin-related compounds, such as chito-oligosaccharides and lipo-chito-oligosaccharides. In turn, the receptor complex (LysM-RLK) of host plants produces microbe-specific molecular patterns in combination with other proteins. Kalamulla et al. [26] indicated elaborately that “the survival of both plants and fungi is required in mycorrhizal symbiosis. The plant roots formed an association with the AMF which is very common in nature and agricultural ecosystems. Mycorrhizal association increases the root absorptive area from 10 to 1000 times for uptake of soil nutrients most importantly phosphorous and all other major 15 macro and micronutrients. It also controls the diseases and drought stress in host plants. Various types of research have now proved the importance of AMF in agricultural systems because of their ability to interact with soil components, improving soil structure, and other soil microbial interactions and maintaining the structure of plant communities. AM fungi are considered as the intermediate between the host plant and the nutrient and that's why considered very important as a regulator for nutrient uptake but if there is already enough amount of P present in the soil or because of the application of fertilizers the presence of AMF reduced in the soil. In organic farming it is highly appreciated to use biological regulators for providing nutrients to the plants instead of forced-fed readily soluble inorganic nutrients by application of fertilizers and organic farming can increase the AMF inoculum in the soil. The role of mycorrhizal association was understood in the ecosystem due to the advanced research in this field. This advancement in mycorrhizal research has increased its applicability in different fields like agriculture, horticulture, and forestry. In organic farming, techniques such as crop rotation, intercropping, and manuring are implemented to boost soil fertility, ultimately leading to the growth of healthy crops. That's why the soil managed organically has a larger number of AMF spores, colonization of roots, and inoculum potential than the conventionally managed soil but it is not always the same that low input practices will lead to an increase in biodiversity. The population of AMF can be influenced by the use of fertility building crops, cash crops, avoid using chemicals for weeds and fungicides. Citrus, Coffee, Oil palm, Rubber, Tea, are important trees that have mycorrhizal associations".

The AMF plays a key role in nutrient uptake, decreasing diseases, and helpful in pathogen control in organic farming. A study was conducted to assess bio-agent effectiveness in managing fungal diseases in sesame, such as leaf blight and root rot, which can affect the crop at all growth stages. The study found that treating sesame seeds with *Bacillus subtilis* (TNAU-Bs1) at 20 ml/kg of seed, combined with soil application of AMF at 50 kg/ha at 15 days after sowing (DAS). A foliar spray of a liquid formulation of *Bacillus amyloliquefaciens* (TNAU-PP-CC-B-0171) at 0.75% on 45 DAS, significantly reduced disease incidence. In the rabi season, this treatment led to a 62.58% reduction in leaf blight (with a PDI of 18.12) and a 90.39% reduction in root rot incidence (at 4.24%) compared to the control. Similar results were observed in the kharif season, with a 64.55% reduction in root rot (6.92% incidence) and an 85.05% reduction in leaf blight (14.98 PDI) compared to the control [27]. The study evaluated the effectiveness of *G. intraradices*, an AM species, in promoting root colonization when applied through seed coating. Using a cellulosic polymer, the AM spores adhered well to maize seeds, achieving a coating efficiency of 83% and mean root colonization of 57%. Among various seed treatments, Imidacloprid at 5 mL/kg seed caused a minimal reduction in AM root colonization, while fungicides like Thiram and Carbendazim had detrimental effects. In pot culture, seeds coated with *G. intraradices* showed the highest root colonization at 62.7%. Even when combined with Imidacloprid, root colonization remained high at 55%, outperforming conventional vermiculite-based soil inoculation, which achieved 52%. Overall, the ROC-developed AM fungi were more effective in enhancing plant growth through improved root colonization [28]. Organic farming is emerging as a uniform group of farming practices that work based on the International Federation of Organic Agricultural Movements. The general rule of this is replacing the biocides and fertilizers with organic regulators and crop rotation. Because of the restriction of using readily soluble fertilizers, there is a limited amount of P in the soil. To overcome the pathogenic fungi, biocontrol agents are also used, which do not harm the AMF. The only macronutrient that is not available for plants is P and because of hyphae formed by mycorrhizal fungi, this major nutrient along with N is available for plants thus the farmers no longer depend on the fertilizers to meet the plant's demand for Phosphorous. Mycorrhizal association is very important for legume plants for its requirement of P for maximum growth and also for nitrogen fixation and nodulation. Enhanced nitrogen fixation by Rhizobium and increased phosphorus uptake by AMF reduce the need for chemical fertilizers, thereby controlling water and air pollution associated with their use.

7. RHIZOLIVE CONSORTIUM AND ITS ROLE IN SOIL FERTILITY

Mycorrhizal fungi enable plants to absorb more nutrients and water from soils. They also improve plant tolerance to various environmental conditions. Moreover, these fungi play a significant role in soil aggregation and boost soil microbial activity. Xie et al. [29] have evidenced the role of nitrogen fixation by arbuscular mycorrhizal fungi.

1. Mycorrhizal fungi convert insoluble phosphorus in the soil into a soluble form, making it more accessible to plants.
2. Microelements such as manganese, sulphur, iron, zinc, molybdenum, nickel, cobalt, and others are made more easily available to plants by supplying them in soluble form.
3. This fungus also improves the performance of nitrogen-fixing bacteria such as *Rhizobium* and *Azotobacter*.
4. Mycorrhizal fungi release hydrogen cyanide around plant roots, which kills pathogenic fungi, bacteria, nematodes, and other organisms in the soil.
5. Plants show resistance to diseases and pests as a result of mycorrhizal fungi.
6. It enhances water availability in non-irrigated locations where crops are rain-fed and increases drought resistance in plants.
7. Mycorrhizal benefits may include increased production, nutrient accumulation, and reproductive success.
8. Mycorrhizal fungi help reduce agricultural losses by directly and indirectly boosting plant resilience against pests like nematodes and diseases, while also promoting plant growth, yield, and profitability.
9. Mycorrhizal fungi may protect their plant partners from excessive salt concentrations in salty soil.
10. The external surfaces of the filaments secrete adhesive substances that cause fine soil particles to aggregate, thereby forming soil structure and reducing the risk of erosion.
11. Mycorrhizal fungi are extremely beneficial in agriculture because they act to boost the absorption of phosphorus and other nutrients. Plants gain non-nutritional advantages from changes in water relations, phytohormone levels, carbon absorption, and so on. Some ectomycorrhizae and ericoid fungi may break down phenolic substances in soils, which can interfere with nutrient absorption.
12. Mycorrhizae improve seed germination and seedling establishment due to the breakdown of seed dormancy by avoiding environmental stresses and it increases the photosynthesis rate, N, P, and K content, and finally enhances the seedlings' resistance to environmental stresses, including pathogens.
13. Mycorrhiza colonization of plant roots reduces the translocation of heavy metals (bioremediation) to shoots by binding the heavy metals to the cell walls of the fungal hyphae in roots. In this way, Mycorrhiza can help higher plants to adapt and survive in contaminated habitats. Mycorrhizal fungi may also directly or indirectly help to the stabilization of soil carbon in addition to promoting plant growth development by fixing additional carbon in the vegetation. First, fungus filaments contain a component that is rich in carbon and may stay in the soil for a very long time. It also offers the initial stage in the process of turning plant waste into stable soil carbon for other soil fungi. Increase plant survival and establishment when sowing or transplanting. Mycorrhizal fungi increase blooming and fruiting also.
14. Mycorrhizal fungus optimizes fertilizer use, particularly phosphorus, and also contributes to the maintenance of soil quality and nutrient cycling. A single treatment can last the entire life of the plant. It minimizes fertilizer use, watering costs, and plantation management costs.

8. HEAVY METAL TOLERANCE IN PLANTS

Heavy metal pollution hampers microbial activity and reduces soil microorganism populations. The high toxicity of heavy metals to these microorganisms and their processes has lasting impacts on the soil, making it a critical issue [30,31]. AMFs are helpful in the upgradation of soil structure, aiding plants in their water relations, and reducing heavy metal phytotoxicity in contaminated soils through the influence of arbuscular mycorrhizal fungi [32,33,34]. Reports indicate that AMF has developed strategies to mitigate heavy metal risks, such as immobilizing metallic compounds, precipitating phosphate particles in the soil, and adsorbing chitin within the fungal cell wall. Additionally, AMF can chelate heavy metals within its structure [35]. Nair et al. [36] proposed that AM hyphae might act as metal filters within the plant by trapping potentially harmful substances in polyphosphate granules. Metal toxicity can impact various AM fungal strains, making them vulnerable to metal poisoning. The colonization of a plant by AMF can affect the plant's resistance to death, as the extensive network of external hyphae produced by the fungus may capture metals and protect the plant. This protective effect depends on the ecological changes induced by AMF in response to the presence of toxic metals. The mycorrhizal fungus *Glomus caledonium* appears to be a promising option for the bioremediation of soils contaminated with heavy metals [37,38].

9. MASS PRODUCTION OF AMF BIOFERTILIZER

The basic principle is to grow them in live crops in the roots for infection into the host roots and the root bits along with the carrier material are used as AMF biofertilizers. The common methods of AMF production are

1. Soilless culture method
2. Carrier-based inoculum method
3. Hairy root culture method

9.1 Soilless Culture Method

Step 1: Construct a brick tank 1m (b) X 2m (l) X 0.30 m (h).
Step 2: Fill with 150Kg of vermiculite up to 20cm height of the tank and add 200g pure AMF inoculum + 2g of urea + 4g superphosphate at the time of sowing the host seeds namely maize or sorghum.
Step 3: Sow surface sterilized seeds of 50g of Maize.
Step 4: Maintain for 45 days, Collect the roots and note the infection (%).
Step 5: Remove the shoot portion and mix the roots with vermiculite (composted coir pith can also be used for large scale.
Step 6: Final product store din gummy bags (Shelf life is 6 months).

9.2 Carrier-based Inoculum Method

The host crop is grown in the sterilized soil with the introduced inoculum for 90 days and is used for bulk inoculum. For the preparation of sterilized soil, the inert material (Calcined montmorillonite clay is used for AMF). *Glomus* sp. shows 90% infection in maize roots after 45 days of crop growth.

9.3 Hairy Root or Root Organ Culture: Hairy Root Induction from Carrot (*Daucus carota*)

The root organ culture of *Daucus carota* was produced through *Agrobacterium rhizogenes* 532 transformed Ri T-DNA hairy roots in MS medium and genetically confirmed (340 bp agropine synthase gene) through a polymerase chain reaction. The cultural parameters for the regeneration of the transformed roots were standardized as MSR medium at pH 5.5, sucrose 1.0 percent amended with gellan gum 0.3 percent in 24 h dark incubation at 27°C. The monoxenic culture of AM Fungus, *G. intraradices* was successfully established using *in-vitro* cultivation systems in transformed roots of carrots [39].

10. CONCLUSION

Mycorrhizae, as a symbiotic association between fungi and plant roots, are vital for sustainable agriculture due to their multifaceted roles in enhancing soil fertility, nutrient uptake, and plant health. the various types of mycorrhizae, including am and ectomycorrhizae, offer significant benefits by improving soil structure, facilitating nutrient cycling, and resisting environmental stresses and diseases. particularly, the rhizolive consortium exemplifies the potential of mycorrhizal fungi in improving soil fertility and plant growth through mechanisms like GRSP secretion, which aids in soil aggregation and stability. the application of mycorrhizal fungi in farming systems, whether organic or conventional, underscores their importance in promoting plant growth and resilience. techniques such as soil-less culture, carrier-based inoculum, and hairy root culture for the mass production of VAM biofertilizers are essential for harnessing these benefits on a large scale. in conclusion, mycorrhizae are crucial for sustainable agricultural practices, offering a natural means to reduce dependency on chemical fertilizers and promote ecological balance in farming systems. their integration into agricultural practices is beneficial and essential for the future of farming and environmental stewardship. Certain agronomic practices and modifications in the existing land management practices by multiple cropping systems rather than monocropping to deliberately improve the resource use efficiency and soil organic carbon dynamics through this symbiotic relationship in enhancing soil health, plant productivity, and ecological balance in farming systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Tawaha AR, Khanum S, Al Tawaha AR, Thangadurai D, Sangeetha J, Rauf A, Khalid S, Saranraj P, Safari ZS, Zahid NA, Qazizadah AZ. Use of mycorrhiza in organic farming. In IOP Conference Series: Earth and Environmental Science. 2021;788(1):012167. IOP Publishing. DOI:10.1088/1755-1315/788/1/012167.
2. Cibichakravarthy B, Kumutha K, Balachandar D. Arbuscular mycorrhizal fungal diversity in phosphorus-deficient Alfisols of a dry North-western agro-ecosystem of Tamil Nadu, India. Annals of Microbiology. 2015;65:143-53. DOI:10.1007/s13213-014-0845-8.
3. Boutaj H, Chakhchar A, Meddich A, Wahbi S, El Alaoui-Talibi Z, Douira A, Filali-Maltouf A, El Modafar C. Mycorrhizal autochthonous consortium induced defense-related mechanisms of olive trees against Verticillium dahliae. Journal of Plant Diseases and Protection. 2021;128: 225-37.
4. Boutaj H, Chakhchar A, Meddich A, Wahbi S, El Alaoui-Talibi Z, Douira A, Filali-Maltouf A, El Modafar C. Bioprotection of olive tree from Verticillium wilt by autochthonous endomycorrhizal fungi. Journal of Plant Diseases and Protection. 2020;127:349-57.
5. Rahou YA, Boutaj HA, Boutasknit AB, Douira AL, Benkirane RA, El Modafar CH, Meddich AB. Colonization of tomato roots with arbuscular mycorrhizal fungi changes antioxidative activity and improves tolerance to Verticillium dahliae. Plant Cell Biotechnol. Mol. Biol. 2021, Sep 17;22:65-81.
6. Boutaj H, Meddich A, Wahbi S, Moukhli A, El Alaoui-Talibi Z, Douira A, Filali-Maltouf A, El Modafar C. Effect of arbuscular mycorrhizal fungi on verticillium wilt development of olive trees caused by Verticillium dahliae. Research Journal of Biotechnology. 2019, Jul; 14(8).
7. Ait Rahou Y, Ait-El-Mokhtar M, Anli M, Boutasknit A, Ben-Laouane R, Douira A, Benkirane R, El Modafar C, Meddich A. Use of mycorrhizal fungi and compost for improving the growth and yield of tomato and its resistance to *Verticillium dahliae*. Archives of Phytopathology and Plant Protection. 2021, Aug 27;54(13-14):665-90.
8. Villani A, Tommasi F, Paciolla C. The arbuscular mycorrhizal fungus *Glomus viscosum* improves the tolerance to verticillium wilt in artichokes by modulating the antioxidant defense systems. Cells. 2021 Jul 30;10(8):1944.
9. George NP, Ray JG. The inevitability of arbuscular mycorrhiza for sustainability in organic agriculture - A critical review. Frontiers in Sustainable Food Systems. 2023 Feb 24;7:1124688. Doi: 10.3389/fsufs.2023.1124688.
10. Irving TB, Alptekin B, Kleven B, Ane JM. A critical review of 25 years of glomalin research: a better mechanical understanding and robust quantification techniques are required. New Phytologist. 2021;232(4):1572-81. DOI: 10.1111/nph.17713.
11. Yang Y, He C, Huang L, Ban Y, Tang M. The effects of arbuscular mycorrhizal fungi on glomalin-related soil protein distribution, aggregate stability, and their relationships with soil properties at different soil depths in lead-zinc contaminated areas. Plos One. 2017;12(8):e0182264. DOI: 10.1371/journal.pone.0182264.
12. Lu, LH, Zou YN, Wu QS. Mycorrhizas mitigate soil replant disease of peach through regulating root exudates, soil microbial population, and soil aggregate stability. Communications in Soil Science and Plant Analysis. 2019, Apr 12;50(7): 909-21. DOI: 10.1080/00103624.2019.1594882
13. Zhang Z, Mallik A, Zhang J, Huang Y, Zhou L. Effects of arbuscular mycorrhizal fungi on inoculated seedling growth and rhizosphere soil aggregates. Soil and Tillage Research. 2019;194:104340. DOI: 10.1016/j.still.2019.104340.
14. Jadrane I, Dounas H, Kouisni L, Aziz F, Ouahmane L. Inoculation with selected

indigenous mycorrhizal complex improves *Ceratonia siliqua's* growth and response to drought stress. Saudi Journal of Biological Sciences. 2021;28(1):825-32. DOI: 10.1016/j.sjbs.2020.11.018.
15. Wu QS, Li Y, Zou YN, He XH. Arbuscular mycorrhiza mediates glomalin-related soil protein production and soil enzyme activities in the rhizosphere of trifoliate orange grown under different P levels. Mycorrhiza. 2015;25:121-30. DOI: 10.1007/s00572-014-0594-3.
16. Wahdan SF, Asran AG, Abdellatef M, Atia MA, Ji L. Arbuscular Mycorrhizal Fungi in Organic Versus Conventional Farming. In Arbuscular Mycorrhizal Fungi and Higher Plants: Fundamentals and Applications. Singapore: Springer Nature Singapore. 2024;259-286. Available:https://doi.org/10.1007/978-981-99-8220-2-12.
17. Sale V, Aguilera P, Laczko E, Mäder P, Berner A, Zihlmann U, van der Heijden MG, Oehl F. Impact of conservation tillage and organic farming on the diversity of arbuscular mycorrhizal fungi. Soil Biology and Biochemistry. 2015, May 1;84:38-52. DOI: 10.1016/j.soilbio.2015.02.005.
18. Soti P, Kariyat R, Racelis A. Effective farm management promotes native AMF and benefits organic farming systems. Agriculture, Ecosystems & Environment. 2023;342:108240. Available:https://doi.org/10.1016/j.agee.2022.108240.
19. Azhar A, Merdekawati E, Pramudia A, Ehara H, Trisia MA, Dahliani L. Observation of arbuscular mycorrhizal fungi (AMF) spores in organic and conventional coffee farms. InE3S Web of Conferences 2023;454:02001. EDP Sciences. DOI:10.1051/e3sconf/202345402001.
20. Wahdan SF, Reitz T, Heintz-Buschart A, Schädler M, Roscher C, Breitkreuz C, Schnabel B, Purahong W, Buscot F. Organic agricultural practice enhances arbuscular mycorrhizal symbiosis in correspondence to soil warming and altered precipitation patterns. Environmental Microbiology. 2021, Oct;23(10):6163-76. DOI: 10.1111/1462-2920.15492.
21. Chen J, Li J, Yang Y, Wang Y, Zhang Y, Wang P. Effects of conventional and organic agriculture on soil arbuscular mycorrhizal fungal community in low-quality farmland. Frontiers in Microbiology. 2022;13:914627. DOI: 10.3389/fmicb.2022.914627.
22. Srinivasan M, Kumar K, Kumutha K. Isolation and selection of efficient AM fungi spores from sugarcane rhizosphere for *In vitro* AM inoculum production. Biochemical and Cellular Archives. 2014;14(1):89-93.
23. Kalamulla R, Karunarathna SC, Tibpromma S, Galappaththi MC, Suwannarach N, Stephenson SL, Asad S, Salem ZS, Yapa N. Arbuscular mycorrhizal fungi in sustainable agriculture. Sustainability. 2022, Sep 27;14(19):12250. DOI: 10.3390/su141912250.
24. Pena R, Bluhm SL, Ammerschubert S, Agui-Gonzalez P, Rizzoli SO, Scheu S, Polle A. Mycorrhizal C/N ratio determines plant-derived carbon and nitrogen allocation to symbiosis. Communications Biology. 2023;6(1):1230. DOI: 10.1038/s42003-023-05591-7.
25. Larbi-Koranteng S, Kankam F, Adomako J, Abdulai M. Role of Mycorrhizae in Crop Protection. In Arbuscular Mycorrhizal Fungi in Agriculture-New Insights. Ed. Rodrigo Nogueira de Sousa. IntechOpen. 2022; 272. DOI:10.5772/intechopen.109020.
26. Kalamulla R, Karunarathna SC, Tibpromma S, Galappaththi MC, Suwannarach N, Stephenson SL, Asad S, Salem ZS, Yapa N. Arbuscular mycorrhizal fungi in sustainable agriculture. Sustainability. 2022;14(19):12250. Available:https://doi.org/10.3390/su141912250.
27. Sangeetha A, Gayathry G, Baskaran R. Exploration of bacillus species and AMF in the management of sesame root rot (*Macrophomina phseaolina*) and leaf blight (*Alternaria sesame*). Journal of Oilseeds Research. 2022;39(3):219-24. Available:https://doi.org/10.56739/jor.v39i3and4.144271.
28. Vinu Radha R, Marimuthu P, Kumutha K. Improved performance of seed coating of AM spore inoculum developed through root organ culture. Asian Journal of Microbiology Biotechnology and Environmental Science. 2019;21(3):183 – 191.
29. Xie K, Ren Y, Chen A, Yang C, Zheng Q, Chen J, Wang D, Li Y, Hu S, Xu G. Plant nitrogen nutrition: The roles of arbuscular mycorrhizal fungi. Journal of Plant Physiology. 2022;269:153591.

DOI:10.1016/j.jplph.2021.153591.

30. Tang J, Zhang J, Ren L, Zhou Y, Gao J, Luo L, Yang Y, Peng Q, Huang H, Chen A. Diagnosis of soil contamination using microbiological indices: A review on heavy metal pollution. Journal of Environmental Management. 2019;242:121-30. DOI: 10.1016/j.jenvman.2019.04.061.
31. Rajendran S, Priya TA, Khoo KS, Hoang TK, Ng HS, Munawaroh HS, Karaman C, Orooji Y, Show PL. A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. Chemosphere. 2022; 287:132369. DOI:10.1016/j.chemosphere.2021.132369.
32. Zhang Z, Mallik A, Zhang J, Huang Y, Zhou L. Effects of arbuscular mycorrhizal fungi on inoculated seedling growth and rhizosphere soil aggregates. Soil and Tillage Research. 2019;194: 104340. DOI: 10.1016/j.still.2019.104340.
33. Jadrane I, Dounas H, Kouisni L, Aziz F, Ouahmane L. Inoculation with selected indigenous mycorrhizal complex improves Ceratonia siliqua's growth and response to drought stress. Saudi Journal of Biological Sciences. 2021;28(1):825-32. DOI: 10.1016/j.sjbs.2020.11.018.
34. Riaz M, Kamran M, Fang Y, Wang Q, Cao H, Yang G, Deng L, Wang Y, Zhou Y, Anastopoulos I, Wang X. Arbuscular mycorrhizal fungi-induced mitigation of heavy metal phytotoxicity in metal contaminated soils: A critical review. Journal of Hazardous Materials. 2021;402: 123919. DOI: 10.1016/j.jhazmat.2020.123919.
35. Chen J, Guo J, Li Z, Liang X, You Y, Li M, He Y, Zhan F. Effects of an arbuscular mycorrhizal fungus on the growth of and cadmium uptake in maize grown on polluted wasteland, farmland and slopeland soils in a lead-zinc mining area. Toxics. 2022;10(7):359. DOI: 10.3390/toxics10070359.
36. Nair A, Rao AS, Bhanu L, More VS, Anantharaju KS, More SS. Arbuscular mycorrhizae, a treasured symbiont to agriculture. In New and Future Developments in Microbial Biotechnology and Bioengineering. Elsevier. 2022; 45-62. DOI: 10.1016/B978-0-323-85163-3.00011-9.
37. Manale A, Hyberg S. A Guide to understanding the fundamental principles of environmental management: It ain't magic: Everything goes somewhere; IWA Publishing: London, UK; 2021. DOI: 10.2166/9781789060997.
38. Huang G, Ren H, Wang A, Wan X, Wu Z, Zhong X. iTRAQ-based proteomic analysis reveals the molecule mechanism of reducing higher alcohols in Chinese rice wine by nitrogen compensation. Annals of Microbiology. 2021;71:1-3. DOI: 10.1186/s13213-020-01611-7.
39. Vinu Radha R. Evaluation of seed coating of arbuscular mycorrhizal spore inoculum developed through root organ culture. Ph.D thesis. Doctor of Philosophy in Agricultural Microbiology. Tamil Nadu Agricultural University, Coimbatore. 2014; 278. Available:http://krishikosh.egranth.ac.in/handle/1/5810066373

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