



ARBUSCULAR MYCORRHIZAL FUNGI - A NATURAL BIO-TOOL FOR SUSTAINABLE CROP PRODUCTION

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Introduction

Arbuscular mycorrhizal (AM) fungi form intimate associations with the roots of nearly 80-90% of agricultural plant species, including cereals, pulses, oilseeds, vegetables and plantation crops. These fungi function as a living bridge between plant roots and the soil environment by developing an extensive network of hyphae that extends far beyond the nutrient depletion zone surrounding the roots. Through this network, AM fungi explore a much larger soil volume than roots alone, allowing plants to access immobile nutrients, particularly phosphorus, zinc and copper, which are otherwise poorly available in most agricultural soils. From a physiological perspective, AM fungi fundamentally alter plant nutrient acquisition strategies. Instead of relying solely on root diffusion and mass flow, plants acquire nutrients through a highly efficient fungal transport system. Specialized structures called arbuscules formed inside root cells provide a large interface for nutrient exchange, where mineral nutrients are transferred from the fungus to the plant in exchange for carbon compounds. This process increases nutrient uptake efficiency while reducing the metabolic cost of root proliferation, enabling plants to allocate more energy towards growth, reproduction and stress tolerance. Beyond nutrient uptake, mycorrhizal fungi play a critical role in regulating soil physical, chemical and biological properties. The fungal hyphae bind soil particles into stable aggregates through the secretion of glomalin, a glycoprotein that enhances soil structure, porosity and water-

holding capacity. These changes improve root penetration, reduce erosion and increase the soil's ability to store both water and organic carbon. In this way, mycorrhizal fungi contribute not only to crop productivity but also to long-term soil carbon sequestration and climate change mitigation. At the biochemical level, mycorrhizal colonization activates multiple plant signaling pathways involved in stress tolerance and immunity. Mycorrhizal plants exhibit improved antioxidant activity, hormonal balance and expression of defense-related genes, making them more resilient to drought, salinity, nutrient deficiency and pathogen attack. This systemic enhancement of plant health allows crops to perform better under suboptimal and changing environmental conditions, which are becoming increasingly common under climate change. Thus, mycorrhizal fungi represent a central biological mechanism through which plants, soil and microorganisms interact to maintain ecosystem stability. Their integration into agricultural systems provides a scientifically proven approach to improving nutrient use efficiency, strengthening soil health, increasing crop resilience and reducing reliance on external chemical inputs. For these reasons, AM fungi are now regarded as indispensable components of sustainable and climate-smart crop production systems.

Types of Mycorrhizae

Mycorrhizal associations occur in several forms, but two major types are most important from an agricultural and ecological point of view:

Arbuscular Mycorrhizae (AM) and Ectomycorrhizae (ECM).

1. Arbuscular Mycorrhizae (AM)

AM fungi enter the root tissues and form highly specialized structures known as arbuscules and vesicles inside the root cells. These structures serve as sites for the exchange of nutrients between the fungus and the plant. The fungus supplies minerals and water to the plant, while the plant provides carbohydrates produced through photosynthesis. AM fungi are associated with most agricultural crops, including cereals, pulses, oilseeds, vegetables, fruits and many plantation crops. Because of their wide host range and strong influence on nutrient uptake, AM fungi are extremely important for crop production and soil fertility management.

2. Ectomycorrhizae (ECM)

Ectomycorrhizal fungi do not enter the root cells. Instead, they form a dense covering around the root tips and grow between the outer root tissues. These fungi are mainly found in trees and woody plants such as pine, eucalyptus, oak and other forest species. ECM fungi are especially important in forest ecosystems. They support tree growth, improve nutrient cycling and play a key role in reforestation and afforestation programmes. Although they are not commonly used in field crops, they are essential for maintaining healthy forest soil.

When to apply AM fungi

AM fungi should always be applied at the early stage of crop growth because they need young, actively growing roots to establish their symbiotic association. The most effective time for application is at sowing, during transplanting, or within a few days after seed germination. In direct-seeded crops such as pulses, cereals, millets and oilseeds, AM fungi are best applied at the time of sowing so that the fungal spores can germinate along with the seed and colonize the emerging roots. In transplanted crops like rice and vegetables, AM fungi can be introduced either in the nursery stage or at the time of transplanting, which allows seedlings to develop mycorrhizal associations before or immediately after they are moved to the main field. In fruit

crops and plantation crops, AM fungi are ideally applied during pit filling or at the time of planting so that the young roots can immediately come in contact with the beneficial fungi.

How to apply AM fungi

AM fungi can be applied through several practical methods in agriculture. One common method is seed treatment, where the fungal inoculum is coated onto seeds before sowing. When the seeds germinate, the fungi grow along with the roots and quickly establish a symbiotic relationship, enabling the plant to absorb nutrients more efficiently from the soil. Another effective method is soil application, in which the AM fungi are mixed with organic sources and incorporated into the soil before sowing or transplanting. This allows the fungal spores and hyphae to spread in the root zone and form a network that enhances nutrient and water uptake. In nursery-raised crops, AM fungi can be applied directly to nursery beds so that seedlings become colonized at an early stage and carry the beneficial fungi into the main field after transplanting. In transplanted crops, root dipping is also a useful method, where seedling roots are dipped in a suspension of AM fungi before planting, ensuring direct and rapid contact between roots and fungi.

Fertilizer and soil management for AM fungi

For best results, AM fungi should be used along with balanced fertilizer management and good soil organic matter. Excessive application of chemical fertilizers, especially phosphorus, should be avoided because high levels of available phosphorus can reduce the activity and colonization of AM fungi. Soils with good organic matter and proper moisture conditions favor the growth and spread of mycorrhizal fungi. It is also important to avoid soil-applied fungicides immediately after applying AM fungi, as these chemicals can harm the beneficial fungi and reduce their effectiveness.

Importance of proper application

When AM fungi are applied at the correct time and in the proper way, they form an extensive network of fine hyphae in the soil that acts as an extension of the plant root system.

This network greatly increases the ability of plants to absorb phosphorus, micronutrients and water from a much larger volume of soil. As a result, crops show improved root development, better nutrient uptake, higher tolerance to drought and soil stress and increased resistance to certain soil-borne diseases. Therefore, timely and proper application of AM fungi plays a crucial role in improving crop productivity and sustainability in modern agriculture.

Functions of AM fungi in agriculture

Mycorrhizal fungi play multiple interconnected roles in agricultural ecosystems. Their functions go far beyond simple nutrient uptake and extend to soil health, plant physiology, stress tolerance and ecosystem stability. Through physical, biochemical and biological mechanisms, mycorrhizae enhance the overall efficiency of crop production systems.

1. Enhanced nutrient acquisition

One of the most important functions of mycorrhizae is improving the availability and uptake of essential nutrients. Plant roots alone can absorb nutrients only from the soil volume that is in direct contact with them. However, nutrients such as phosphorus, zinc and copper move very slowly in soil and become rapidly depleted around the root surface. Mycorrhizal fungi overcome this limitation by developing an extensive hyphal network that spreads far beyond the root zone. These hyphae penetrate small soil pores that roots cannot enter, allowing access to nutrient reserves that are otherwise unavailable. Mycorrhizal fungi absorb nutrients from these distant soil regions and transport them directly to plant roots through specialized exchange structures. This system significantly increases nutrient use efficiency, particularly for phosphorus, which is often the most limiting nutrient in agricultural soils.

2. Solubilization and mobilization of soil nutrients

Many nutrients in soil exist in insoluble or chemically fixed forms. Mycorrhizal fungi release organic acids, protons and phosphatase enzymes that dissolve mineral-bound phosphorus and micronutrients. This biochemical

activity converts unavailable nutrients into plant-usable forms. In addition, mycorrhizal fungi stimulate beneficial soil microorganisms that further enhance nutrient mineralization and recycling. This creates a biologically active rhizosphere where nutrients are continuously released and made available to crops.

3. Improved nitrogen utilization

Although nitrogen is more mobile than phosphorus, mycorrhizal fungi still play an important role in nitrogen efficiency. They increase root absorption area and enhance uptake of nitrate and ammonium. In organic and low-input systems, mycorrhizae assist in the transfer of nitrogen released from decomposing organic matter to plant roots. This results in improved nitrogen use efficiency and reduced nitrogen losses from the soil.

4. Increased water uptake and drought tolerance

Mycorrhizal hyphae act as microscopic extensions of the root system. They explore larger volumes of soil and extract water from fine pores that roots cannot access. This significantly improves plant water availability, especially under dry conditions. Mycorrhizal plants also show improved regulation of stomatal opening, higher leaf water content and better root hydraulic conductivity. These physiological changes allow crops to maintain photosynthesis and growth during periods of drought stress.

5. Improvement of soil structure and stability

Mycorrhizal fungi play a key role in soil aggregation. Their hyphae physically bind soil particles, while the glomalin they produce acts as a natural glue that stabilizes soil aggregates. Well-aggregated soils have better aeration, higher water infiltration and greater resistance to erosion. Improved soil structure supports healthy root development and creates favourable conditions for beneficial soil organisms, leading to long-term soil fertility.

6. Enhancement of root growth and architecture

Mycorrhizal colonization stimulates root branching and increases the formation of fine roots.

This improves the plant's capacity to absorb nutrients and water. Better root architecture also enhances anchorage, allowing plants to withstand lodging and mechanical stress.

7. Disease suppression and plant protection

Mycorrhizal fungi reduce the incidence of soil-borne diseases through several mechanisms. They compete with harmful pathogens for space and nutrients, form a protective barrier around roots and activate plant defense systems. Mycorrhizal plants produce more defensive enzymes and antimicrobial compounds, making them more resistant to infections.

8. Increased tolerance to environmental stress

Mycorrhizae help plants cope with salinity, heavy metals, temperature extremes and nutrient deficiencies. They regulate ion balance, reduce toxic metal uptake and improve antioxidant activity in plants. This allows crops to grow better under adverse soil and climatic conditions.

9. Improved carbon cycling and soil organic matter

Mycorrhizal fungi transfer carbon from plants into the soil through their hyphae and secretions. This contributes to soil organic matter formation and long-term carbon storage. Increased soil carbon improves soil fertility and helps mitigate climate change.

Benefits of mycorrhizae in sustainable agriculture

1. Lower dependence on chemical fertilizers

Because mycorrhizae improve nutrient availability and efficiency, farmers can reduce the amount of chemical fertilizers applied to crops. This not only lowers production costs but also decreases nutrient runoff and environmental pollution.

2. Better crop quality

Mycorrhizal plants often contain higher levels of essential minerals and produce stronger roots, healthier foliage and better-quality grains, fruits or vegetables. Improved nutrient balance

leads to better taste, shelf life and nutritional value.

3. Improved soil health

By enhancing soil structure, microbial activity and organic matter accumulation, mycorrhizae contribute to long-term soil productivity. Healthy soils are more resilient, support higher yields and sustain farming systems over many years.

4. Environmental sustainability

Using mycorrhizal fungi supports environmentally friendly farming practices. Reduced fertilizer use, improved soil health and better water efficiency all help lower the ecological footprint of agriculture. These benefits are especially important in the context of climate change and resource conservation.

Conclusion

Mycorrhizal fungi are not just growth promoters but essential biological regulators of soil-plant interactions. Through advanced nutrient transport, stress protection, soil aggregation and disease suppression, they play a fundamental role in sustainable crop production. Integrating mycorrhizal technology into modern agriculture can significantly improve productivity while preserving soil health and environmental quality.

References

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