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Role of Mycorrhizal Fungi in Enhancing Soil Structure and Plant Nutrition

Riya Das

Bidhan Chandra Krishi Viswavidyalaya, Department of Agricultural Chemistry and Soil Science, Mohanpur, Nadia-741252, India

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*Corresponding Author

Riya Das*

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INTRODUCTION

Mycorrhizal fungi are symbiotic microorganisms with specialized functions that live in close association with roots of plants, leading to a symbiotic relationship. In this symbiosis, the host plant provides the fungi with carbohydrates and other photosynthetic-derived organic compounds, whereas the fungi respond by increasing the plant's water and nutrient uptake from the soil. This symbiosis is not limited to a few species of plants—it happens in all terrestrial ecosystems, from forests and grasslands to agricultural lands.

The contribution of mycorrhizal fungi goes well beyond enhancing plant growth. They have a massive impact on soil health by increasing aggregation, enhancing microbial richness, and making the soil more capable of holding water and nutrients. Over the past few years, growing concern regarding degradation of soil, soil nutrient loss, and the environmental effects of chemical inputs has sparked renewed interest in mycorrhizal fungi as natural partners in sustainable agriculture. Being able to enhance nutrient efficiency, facilitate physical improvement in soil structure, and enhance plant resistance to stresses, mycorrhizal fungi present an exciting strategy for sustainable crop production and sustainable soil fertility management.

2. Types of Mycorrhizal Fungi

Mycorrhizae are generally divided into various categories according to their structural features and the type of association of their host plants:

2.1 *Arbuscular Mycorrhizal* Fungi (AMF)

Arbuscular mycorrhizal fungi are the most universal group, infecting the roots of most herbaceous and woody plants. They produce characteristic intracellular structures called arbuscules tree-like, branched structures used for nutrient exchange and vesicles, storage organs within root cells. Some common genera are Glomus, Acaulospora, and Gigaspora. AMF are especially valuable in agricultural ecosystems because they are highly effective in phosphorus acquisition and are capable of flourishing in a variety of soil types.

2.2 Ectomycorrhizae

Ectomycorrhizal fungi develop an external sheath, or mantle, on roots of plants, and their hyphae penetrate into the soil as well as between cortical cells of roots but not penetrating them. These are mainly connected with forest trees, for example, pines, oaks, and birches. Examples include Pisolithus, Amanita, and Boletus. Such fungi play a significant role in poor, acidic forest soils, where they increase phosphorus and nitrogen uptake and are involved in long-term carbon storage in soil.

2.3 Ericoid Mycorrhizae

Ericoid mycorrhizae are fungi with specializations that infect members of the Ericaceae, including heathers, blueberries, and cranberries. They produce delicate intracellular coils within the root cells and are very effective in obtaining nutrients from acidic, high-organic-content soils in which regular nutrient availability is lacking.

2.4 Orchid Mycorrhizae

Orchid mycorrhizae are responsible for orchid germination and development, as their seeds are tiny and contain minimal nutrient stores. The fungi provide the germinating seeds with carbohydrates, minerals, and growth factors to support seedling development. Without this symbiosis, most orchid species would be unable to exist in nature.

3. Contribution to Soil Structure Improvements

3.1 Soil Aggregation

Mycorrhizal fungi contribute significantly towards improving soil aggregation by secreting a glycoprotein called glomalin. This substance is akin to natural glue, which holds individual soil particles together and forms stable aggregates. Such aggregates help form an adequately structured soil, enabling better porosity to allow roots to penetrate with ease. A well-aggregated soil also allows for enhanced aeration and increases water penetration, hence an even better environment for root growth as well as microbial activity. In the long term, the structural enhancement produces healthier soils with increased ability to resist physical degradation.

3.2 Control of Erosion

The large network of mycorrhizal hyphae mechanically entwines soil particles, hence providing a denser soil matrix and minimizing the likelihood of wind and water erosion. By binding the soil surface, these fungi reduce the detachment and transport of soil particles during heavy rain or strong winds. Further, the enhanced aggregation through glomalin production increases the resistance of the soil to compaction and surface crusting. This protection is especially vital in agricultural soils where tillage, irrigation, and heavy machinery usage can otherwise compromise soil stability.

3.3 Water Retention

Mycorrhizal fungi indirectly enhance the water-holding capacity of the soil through enhancing its structure and aggregate stability. A well-aggregated soil possesses more water-storing pore spaces that release water more slowly to plants for a longer duration of time during drought conditions. This advantage is particularly vital under drought or water-limited conditions, where plants associated with mycorrhiza can sustain higher water content and physiological activity than non-mycorrhizal plants. Increased water holding contributes not only to plant survival but also to the decrease in irrigation frequency and amount required, thereby conserving water for agricultural purposes.

4. Role in Increasing Nutrient Acquisition

4.1 Nutrient Acquisition

Perhaps one of the greatest impacts of mycorrhizal fungi is to increase the nutrient acquisition of plants. The hyphae of the fungus reach far beyond the root absorption zone into the environment, essentially expanding the amount of soil excavated for the absorption of nutrients. This large system enables the plant to access nutrients otherwise beyond its reach. Mycorrhizae are especially efficient in enhancing the uptake of phosphorus (P), which is quite immobile in the soil and tends to be a growth-limiting nutrient under many conditions. Along with phosphorus, mycorrhizal relationships also enhance the uptake of nitrogen (N), potassium (K), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and other growth-essential macro- and micronutrients, thereby providing plant nutrition on a balanced and healthy basis.

4.2 Phosphorus Solubilization

Phosphorus in most soils is limited because of its tendency to form insoluble complexes with calcium, iron, or aluminum. Mycorrhizal fungi alleviate this constraint by exuding organic acids, chelating compounds, and phosphatase enzymes that dissolve these bound phosphorus forms. This process not only enhances the short-term phosphorus availability to the host plant but also enhances the utilization of external phosphorus fertilizer applications, thus minimizing the requirements for excessive external amendments.

4.3 Increased Nitrogen Cycling

Nitrogen is a critical nutrient, but its availability tends to be reliant on microbial decomposition and transformation activities. Mycorrhizal fungi help improve nitrogen cycling by ensuring access of plants to organic forms of nitrogen through interactions with decomposer microbes. They also affect mineralization and immobilization processes within the rhizosphere, enabling improved acquisition of nitrogen by plants. Through enhanced nitrogen use efficiency, mycorrhizae enable greater crop productivity with minimized fertilizer loss into the environment.

5. Benefits of Plant Growth and Stress Tolerance

Enhanced Water Use Efficiency

Mycorrhizal fungi improve water uptake by the plant from deeper layers and by smaller pores not accessible to roots alone. This promotes better use of water, enabling plants to sustain physiological functions even under moisture deficiency.

Reduction in Salt Stress

Under saline conditions, mycorrhizal fungi assist in the alleviation of salt stress through an improvement in the ionic balance ability of the plant. They regulate the absorption of beneficial ions while limiting the intake of detrimental ions like sodium (Na^+) and chloride (Cl^-). This culminates in enhanced osmotic adjustment and prevention of salt-induced injury.

Heavy Metal Detoxification

In polluted soils, mycorrhizae immobilize pathogen/toxic heavy metals like cadmium, lead, and arsenic in the root zone, keeping their excess accumulation in plant tissues under check. This protective action helps protect plant metabolism and facilitates cultivation under moderately polluted conditions.

Disease Suppression

Mycorrhizal fungi can also serve as natural biocontrol agents through the induction of host plant systemic resistance. This type of induced defense renders plants more resistant to specific soil-borne pathogens like Fusarium, Pythium, and Phytophthora, thus minimizing disease occurrence and intensity without depending extensively on chemical pesticides.

6. Agricultural Applications

Biofertilizers

Mycorrhizal inoculants are becoming known as valuable biofertilizers and, as such, provide a sustainable, environment-friendly substitute for chemical fertilizers. Their application can serve to reduce chemical inputs while still maintaining or enhancing the yield of crops.

Sustainable Agriculture

In reducing the reliance on chemical pesticides and fertilizers, mycorrhizal fungi encourage environmentally sustainable farming practices. Their role in nutrient cycling and soil structure enhancement also enhances long-term soil fertility and productivity.

Reclamation of Degraded Lands

In eroded, nutrient-poor, or desertified areas, mycorrhizal fungi can be critical to restoring ecosystems. They assist in the re-vegetation cover through a promotion of nutrient content and an improvement in seedling survival against adverse conditions.

7. Challenges and Future Prospects

Challenges

The widespread adoption of mycorrhizal technology in farming is constrained by several factors. The performance of mycorrhizal fungi can be soil type-, crop-, climatic-, and microbial community-dependent. Commercial supply of good quality inoculants remains low in most countries, and there are no standard production and quality control protocols usually in place. There is also limited farmer awareness and inadequate extension outreach to facilitate adoption.

Future Prospects

The agronomic potential of mycorrhizal fungi can further be utilized with the production of crop- and region-specific mycorrhizal products that are formulated according to local conditions. Combination of mycorrhizae with other useful microorganisms, including nitrogen-fixing bacteria and plant growth-promoting rhizobacteria (PGPR), can lead to synergistic effects on plant growth and stress tolerance. With increasing interest in organic and regenerative production systems, mycorrhizal technology will increasingly find applications as components of integrated soil fertility and crop management programs.

8. CONCLUSION

Mycorrhizal fungi are invaluable partners in soil structure and plant nutrition improvement. Their function goes beyond mere provision of nutrients to plants; they help aggregate soil, enhance water holding capacity, relieve environmental stresses, and enhance plant health through inherent disease suppression. For sustainable agriculture, mycorrhizae provide an affordable and environmentally friendly method of conserving soil fertility and productivity while lessening reliance on chemical inputs. Strengthening research, raising farmer awareness, and enhancing inoculant availability will be major strides towards maximally utilizing the potential of mycorrhizal fungi in contemporary cropping systems.

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