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Short communication

Mycorrhizae: Functional Diversity, Ecological Significance, and Molecular Basis of Plant–Fungal Symbiosis

Leena Kumar
National Institute of Botanical Research, Hyderabad, India
E-mail: leena.kuApr@nibr.ac.in

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ABSTRACT

Mycorrhizae represent one of the most widespread and evolutionarily significant symbiotic associations between plants and fungi. These interactions enhance plant nutrient acquisition, improve soil structure, and increase resilience to environmental stress. Mycorrhizal fungi colonize plant roots and extend their hyphal networks into the surrounding soil, thereby increasing the effective surface area for nutrient and water absorption. The partnership contributes to improved uptake of phosphorus, nitrogen, and essential micronutrients. At the molecular level, the symbiosis is regulated by a complex exchange of signaling molecules that initiate root colonization and maintain functional compatibility. Mycorrhizae also influence ecosystem processes such as carbon cycling and soil fertility. Recent research highlights their potential applications in sustainable agriculture, ecological restoration, and climate resilience. This paper provides an overview of mycorrhizal diversity, functional roles, molecular mechanisms, and ecological significance, emphasizing their importance in enhancing plant health and promoting long-term soil sustainability.

Keywords: Mycorrhizae, Plant–Fungal Symbiosis, Arbuscular Mycorrhiza, Ectomycorrhiza, Nutrient Uptake, Phosphorus Acquisition, Soil Ecology, Hyphae, Root Colonization, Signaling Molecules, Plant Growth, Stress Tolerance.

INTRODUCTION

Mycorrhizae are mutualistic associations between plant roots and fungi that play a foundational role in terrestrial ecosystems. These symbiotic relationships, formed by nearly 90% of plant species, have existed for more than 400 million years and were essential for the initial colonization of land by early plants (Turk et al., 2006). Mycorrhizal fungi enhance nutrient and water acquisition while receiving carbohydrates produced through photosynthesis, creating a reciprocal exchange vital to both partners.

There are two major types of mycorrhizae: arbuscular mycorrhizae (AM) and ectomycorrhizae (ECM). Arbuscular mycorrhizae are the most widespread, forming intricate structures called arbuscules within root cortical cells. These structures facilitate efficient nutrient exchange between the fungus and the plant.

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Ectomycorrhizae, in contrast, form dense fungal sheaths around the roots and a Hartig net between root cells. Each type plays unique ecological roles and is associated with different plant groups, ranging from grasses to forest trees.

One of the most important contributions of mycorrhizae is improved nutrient uptake. Fungal hyphae extend far beyond the root zone, accessing phosphorus, nitrogen, potassium, and various micronutrients unavailable to roots alone. Phosphorus, often immobile in soil, becomes more accessible through fungal enzymes and organic acid production (Allen, 1991). This enhanced nutrition leads to increased plant growth, better seedling establishment, and greater ecosystem productivity.

The molecular signaling underlying mycorrhizal formation involves several steps. Plants release signaling molecules such as strigolactones, which stimulate fungal germination and growth toward the root. In response, fungi produce Myc factors that activate plant receptors, triggering changes in calcium signaling, transcription, and root cell structure. These coordinated processes allow successful colonization and formation of functional symbiotic organs. Understanding these molecular interactions is crucial for optimizing symbiosis in agricultural systems (Dighton, 2009).

Mycorrhizae are not only beneficial for plant nutrition but also improve plant resilience to various stresses. Under drought conditions, fungal hyphae enhance water uptake and regulate plant hormonal responses. Mycorrhizal colonization can also reduce heavy metal toxicity by immobilizing metals in fungal tissues or the rhizosphere. Furthermore, mycorrhizae strengthen plant resistance to pathogens by inducing systemic defense responses and competing with harmful microbes in the soil.

Beyond individual plant benefits, mycorrhizae play vital roles in ecosystem stability. They contribute to soil aggregation through the production of glomalin, a fungal protein that promotes soil structure. Mycorrhizal networks also facilitate nutrient sharing and communication between plants, influencing community dynamics and forest regeneration (Boyno & Demir, 2022). By enhancing carbon sequestration, mycorrhizae contribute to long-term soil fertility and global carbon cycling.

Mycorrhizal associations represent one of the most successful evolutionary strategies in the plant kingdom, profoundly shaping the structure and function of terrestrial ecosystems. Their importance stems not only from their global abundance but also from the intricate biological processes that allow plants and fungi to function almost as a single integrated system. This intimate relationship is rooted in a long evolutionary history, with fossil evidence indicating that early land plants relied heavily on ancient mycorrhizal fungi for nutrient acquisition in nutrient-poor substrates. As plants diversified, mycorrhizal fungi coevolved, giving rise to specialized forms that respond to specific environmental constraints and plant needs. Today, these symbioses continue to drive ecosystem productivity, influence species distributions, and regulate the biogeochemical cycles essential for sustaining life on Earth.

Central to the functioning of mycorrhizae is their remarkable capacity to modify and enhance the physical environment in which plant roots operate. Fungal hyphae, which are far finer than the smallest root hairs, penetrate micro-pores in the soil that roots cannot reach. In doing so, they create extensive networks that act as extensions of the root system, dramatically increasing the soil volume explored for nutrients and water. These networks interact with soil minerals, decomposing organic matter and mobilizing nutrients that would otherwise remain unavailable. This microbial mediation of nutrient cycling is particularly important in ecosystems with nutrient limitations, such as phosphorus-poor tropical soils or nitrogen-deficient temperate forests (Figueiredo et al., 2021).

The influence of mycorrhizae extends beyond the individual plant to the broader biological community. Networks of interconnected fungal hyphae can link multiple plants, forming what researchers call “common mycorrhizal networks” (CMNs). Through these networks, plants can exchange resources, signaling molecules, and even chemical cues that regulate competition and cooperation. Seedlings growing in shaded environments may receive carbon from mature trees through CMNs, giving them a better chance of survival (Siddiqui & Pichtel, 2008). Conversely, plants under attack by pathogens or herbivores may send warning signals via hyphal connections, activating defense responses in neighboring plants. These remarkable interactions highlight the role of mycorrhizae as information highways in natural ecosystems.

CONCLUSION

Mycorrhizae are essential components of plant health, soil ecology, and ecosystem functioning. Their ability to enhance nutrient uptake, increase stress tolerance, and improve soil structure highlights their importance in both natural and agricultural systems. Advances in understanding the molecular and ecological aspects of mycorrhizal symbiosis offer promising avenues for developing sustainable farming practices, restoring degraded landscapes, and strengthening plant resilience in a changing climate. Continued research on mycorrhizae will provide deeper insights into their potential to support global food security and environmental sustainability.

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