

Mycorrhizal Fungi: A Key Biological Strategy for Rhizosphere Engineering

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Mycorrhizae are fungi that refer to the beneficial symbiotic relationships between the arbuscular mycorrhizal fungi (AMF) and the roots of numerous plants widespread in the soil. The interaction between the plant and the fungus is mutualistic, with both benefiting from the association. Many of these fungi are obligate symbionts, meaning they cannot survive for long periods without their plant host. More than 80% of land plants, including over 250,000 species, form symbiotic relationships with mycorrhizal fungi. Mycorrhizae are primarily classified into three main types: endomycorrhizae (mycorrhiza living within a plant), ectomycorrhizae (mycorrhiza living on the outside of a plant) and ectendomycorrhiza (act as both ectomycorrhiza and arbuscular mycorrhiza). Arbuscular mycorrhizal fungi (AMF) are among the most widespread types of mycorrhizal fungi, forming mutualistic associations with approximately 80% of terrestrial plant species and are present in nearly all ecosystems. These fungi inhibit the root cortex and rhizodermis with their extended hyphae into the near soil to acquire important nutrients for plant growth, such as phosphorus (P), nitrogen (N) and various micronutrients (e.g., Cu, Fe, Zn and Mn). In return for these nutrients and other benefits, the fungi receive carbon (C) assimilated by the plant; these symbiotic relationships help in water and nutrient uptake, reducing plant abiotic stress.

The rhizosphere is the narrow soil region directly impacted by root secretions, rhizodeposits and the associated soil microorganisms. This region differs from the bulk soil in factors like water potential, redox conditions and availability of carbon compounds, which shape the distribution and activity of diverse microbial populations within the rhizosphere. It functions as a hub for interaction, where symbiotic organisms and the nearby root engage with the plant. Additionally, the rhizosphere functions as a protective microbial interface, safeguarding the plant against pathogenic threats.

Rhizodeposits are the substances secreted by plant roots and their associated microorganisms into the rhizosphere. Interaction and Communication within the rhizosphere are initiated when recipient organisms detect the signaling properties of these rhizodeposits. The nature and composition of root exudates can affect the microorganism's diversity and activity in the soil, encouraging the growth of beneficial microbes that enhance productivity and plant health, while also inhibiting harmful microbes in some cases.

Mycorrhization is a unique rhizosphere engineering approach that enhances soil carbon sequestration by increasing the transfer of photosynthates belowground, promoting the production and accumulation of mycorrhizal biomass and necromass in the soil, and stimulating plant growth and productivity through nutrient delivery and the formation of soil aggregates. Within this framework, mycorrhizal fungi emerge as biofunctional agents capable of modifying rhizospheric nutrient fluxes, altering root exudate composition, and reinforcing beneficial plant-microbe interactions. Mycorrhizal fungi support plant growth through various mechanisms, including improved nutrient acquisition, alleviation of abiotic and biotic stresses, and the detoxification of heavy metals, which in turn increases root-derived carbon inputs into the soil. Rhizosphere engineering involves the release of nutrients and signaling compounds such as amino acids, sugars, organic acids, flavonoids, mucilage, and proteins, which selectively recruit and shape beneficial microbial communities capable of influencing plant phenotype and performance. Furthermore, it has been proposed that genetically engineered plants could release specific microbial gene inducers, which not only stimulate plant growth but also improve plant health and soil conditions, including through the remediation of pollutants.

By enhancing nutrient uptake—particularly of phosphorus, nitrogen, and micronutrients—these fungi contribute to better soil structure, water retention, and overall plant performance. The genetic regulation of these fungi's functions, including the production of compounds like **glomalin**, further enhances their role in improving soil health. As agricultural systems continue to face challenges related to soil degradation, nutrient depletion, and environmental stresses, mycorrhizal fungi represent a sustainable and cost-effective tool for optimizing plant growth and reducing the need for chemical fertilizers. Integrating these fungi into soil management practices through rhizosphere engineering can help create more resilient, productive, and sustainable agricultural systems.

The mycorrhizal fungi interact with plants, such as improved germination, enhanced root and shoot development, better morphogenesis, positive effects on flowering, increased photosynthetic rates, and higher yields. Mycorrhization is a distinctive rhizosphere engineering technique that promotes soil carbon (C) sequestration through both direct and indirect pathways. Directly, it enhances soil C by (i) increasing the allocation of

photosynthates to the roots and (ii) boosting the production and accumulation of mycorrhizal biomass and necromass in the soil. Indirectly, mycorrhization fosters plant growth by providing vital nutrients and aiding in soil aggregate formation. Particular focus is given to arbuscular mycorrhizal fungi (AMF) due to their widespread occurrence and proven roles in phosphorus solubilization, water-use efficiency, and abiotic stress mitigation.

Arbuscular mycorrhizal fungi (AMF) are vital components of ecosystems, playing a key role in plant nutrition by improving access to soil-derived nutrients. Plants commonly form a close, natural association with AMF, which helps enhance the uptake of available nutrients through their roots. While phosphorus (P) was historically considered the primary nutrient absorbed by plant roots, it is now understood that AMF also aid in the uptake of a broad range of other nutrients. The primary reason for AMF's impact on phosphorus uptake is that plants require large quantities of phosphorus, but its natural availability is limited. Beyond phosphorus, AMF also influence the uptake of various other

essential nutrients. The current and future benefits of using AMF include increased crop yields, protection from root pathogens, improved resilience to environmental stresses, and reduced reliance on agrochemicals. Recent advancements in biotechnology have highlighted the need for high-quality, plant species-specific AMF. AMF can alter the uptake of several key plant nutrients, such as phosphorus (P), zinc (Zn), ammonium (NH₄), nitrate (NO₃), copper (Cu), and potassium (K), with these nutrients classified as either mobile or immobile within the plant. AMF support the acquisition of both types of nutrients. Zinc, in particular, plays a crucial role in the uptake of other essential plant nutrients, and AMF significantly enhance this process.

Mycorrhizal fungi are central to rhizosphere engineering, enhancing nutrient acquisition, soil structure, carbon sequestration, and plant resilience through finely regulated plant-microbe interactions. Advancing molecular and biotechnological approaches to develop crop and site-specific mycorrhizal consortia will enable more precise, climate-resilient, and sustainable agricultural systems.
