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REVIEW ARTICLE

Mycorrhizal Fungi in Sustainable Agriculture: Enhancing Crop Yields and Soil Health

Prakash Pralhad Sarwade, Kavita Narayan Gaisamudre (Sarwade)[1] and Rajesh S. Gaikwad[2]

Department of Botany, Shikshan Maharshi Guruvarya R. G. Shinde Mahavidyalaya, Paranda Dist. Dharashiv 413 502, (M.S.), India.
[1]Department of Botany, Shriman Bhausaheb Zadbuke Mahavidyalaya Barshi Tal. Barshi, Dist- Solapur 413 401. (M.S.), India.
[2]Department of Botany, Swami Vivekanand Senior College, Mantha Tq. Mantha Dist. Jalna -431504 (M.S), India.

**Corresponding Author*: ppsarwade@gmail.com

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ABSTRACT

Mycorrhizal fungi, beneficial soil microorganisms, offer potential for sustainable agriculture. This literature review explores their ability to enhance crop production and soil quality by forming symbiotic relationships with plant roots, expanding root networks, and improving nutrient absorption, particularly phosphorus, nitrogen, and micronutrients. They also enhance drought resistance and water efficiency. Research indicates significant yield increases with appropriate mycorrhizal fungi strains in various agricultural systems. Beyond yield, these fungi improve soil health by enhancing structure, aggregation, water retention, fertility, and nutrient cycling, and by breaking down organic matter and sequestering carbon. These benefits arise from complex plant-fungal symbioses involving signaling pathways, molecular mechanisms, and gene expression changes. Integrating mycorrhizal fungi into sustainable farming includes various inoculation methods and reducing chemical fertilizers. Challenges include efficient mass production and quality control. Future research should focus on these issues and the long-term sustainability impacts. Utilizing plant-fungal symbioses can develop sustainable agricultural practices, addressing global food security with minimal environmental impact.

Keywords: Mycorrhizal fungi, Sustainable agriculture, Crop yields, Soil health.

INTRODUCTION

Sustainable agriculture and soil health have become increasingly important in addressing global food security challenges and environmental concerns associated with conventional agricultural practices (Semida *et al.*, 2019). As the world population continues to grow and climate change threatens agricultural productivity, there is an urgent need for innovative approaches to enhance crop yields while maintaining ecological balance. Arbuscular mycorrhizal fungi (AMF) have been widely studied for their symbiotic relationships with plants and agricultural benefits. These soil microorganisms create networks within plant roots, enhancing nutrient uptake and plant health.

Numerous researchers in India, such as Muthukumar *et al.*, (2006), Bhale *et al.*, (2010), Sarwade *et al.*, 2011;2012), Sawant *et al.*, (2011) and Sandhya *et al.*, (2013;2016) have documented AMF in various plant species of medicinal plants (Sarwade *et al.*, 2024) include species such as *Cinnamomum zeylanicum* (Kumar *et al.*, 2024), *Moringa oleifera* (Otia *et al.*, 2024), and *Allium sativum* L. (Mishra *et al.*, 2024). Recent studies by Sandhya *et al.*, (2013; 2016) and Prakash *et al.*, (2021) have expanded knowledge on AMF distribution and diversity in different plants across the country.

Interest in AMF is growing due to their potential to transform sustainable agriculture. These fungi can significantly increase crop yields and improve soil health (Slimani *et al.*, 2024). By forming symbiotic associations with plant roots, AMF enhance nutrient absorption, particularly phosphorus and nitrogen. They also improve soil structure, water retention, and plant resistance to biotic and abiotic stresses.

Thus, integrating AMF into agricultural systems is a critical area of research, with potential benefits for food security, reduced chemical fertilizer use, and environmentally friendly farming practices. This literature review aims to synthesize existing research on mycorrhizal fungi in agriculture and explore their implications for sustainable agricultural practices (Fig.1).

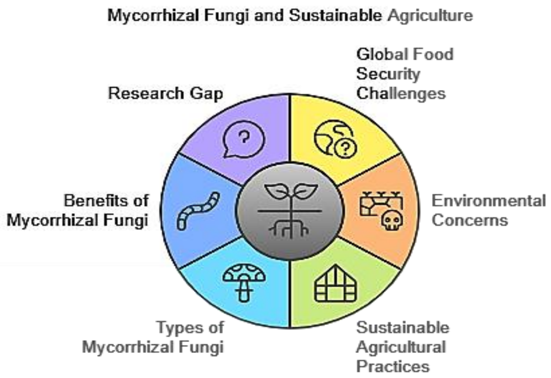

Figure 1

Mycorrhizal Fungi and Crop Yields

Research has demonstrated that mycorrhizal fungi can significantly enhance crop yields through various mechanisms (fig.2). One of the primary benefits is improved nutrient uptake and utilization, particularly for essential elements such as phosphorus, nitrogen, and micronutrients like zinc and copper (Kaur *et al.*, 2014). This enhanced nutrient acquisition leads to improved plant growth and development, including modifications to root system architecture and increased photosynthetic efficiency (Chen *et al.*, 2017).

The symbiotic relationship between mycorrhizal fungi and plant roots creates an extensive network of fungal hyphae that effectively extends the plant's root system. This expanded network allows plants to access nutrients from a larger soil volume, significantly improving their nutrient acquisition capabilities (Ramírez-Flores *et al.*, 2019). For example, studies have shown that mycorrhizal associations can increase phosphorus uptake by up to 100% in some crop species, leading to improved growth and yield (Bagyaraj *et al.*, 2015).

Studies have also shown that mycorrhizal fungi contribute to increased drought tolerance and water use efficiency in crops. This is achieved through improved water uptake mechanisms and osmotic adjustment in plants. The fungal hyphae can access water in soil pores that are too small for plant roots to penetrate, thereby enhancing the plant's ability to withstand water stress. Additionally, mycorrhizal fungi have been found to induce changes in plant physiology, such as increased production of osmolytes and antioxidants, which further contribute to drought resistance (Fernández-Lizarazo & Moreno-Fonseca, 2016).

Case studies have demonstrated enhanced crop yields in various agricultural systems, including cereal crops, legumes, horticultural crops, and perennial crops in agroforestry systems (Li *et al.*, 2008). For instance, field trials with wheat have shown yield increases of up to 30% when inoculated with appropriate mycorrhizal fungi strains. Similarly, studies on tomatoes and other vegetable crops have reported significant improvements in fruit quality and quantity when grown in association with mycorrhizal fungi (Giovannetti *et al.*, 2011).

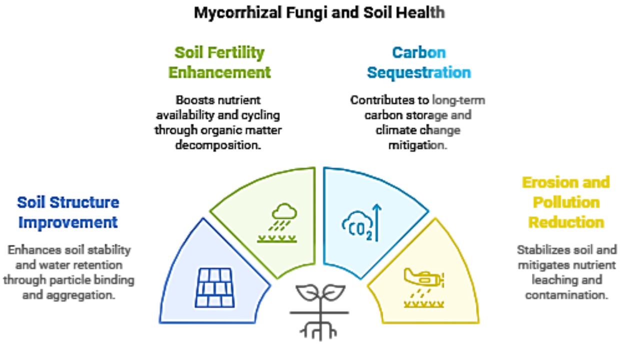

Figure 2

Mycorrhizal Fungi and Soil Health

In addition to their direct effects on crop yields, mycorrhizal fungi play a crucial role in improving soil health. They contribute to soil structure and aggregation by binding soil particles and forming stable aggregates, which in turn improves soil porosity and water retention (Bitterlich, Sandmann, *et al.*, 2018). The extensive network of fungal hyphae acts as a biological "glue," helping to create and maintain soil structure (Krishnakumar *et al.*, 2013). This improved soil structure enhances water infiltration, reduces soil erosion, and provides a better environment for root growth and development.

These fungi also enhance soil fertility and nutrient cycling through their involvement in organic matter decomposition and nutrient mobilization (Martin & Van Der Heijden, 2024). Mycorrhizal fungi produce enzymes that can break down complex organic compounds, releasing nutrients that would otherwise be unavailable to plants. This process not only benefits the host plant but also contributes to the overall nutrient cycling in the soil ecosystem (Simard *et al.*, 2003).

Furthermore, mycorrhizal fungi have been shown to increase soil organic matter content and contribute to carbon sequestration, offering potential benefits for climate change mitigation (Vishwakarma, 2024). The fungal biomass itself represents a significant carbon pool in the soil, and the improved plant growth facilitated by mycorrhizal associations leads to increased carbon inputs through root exudates and plant residues (Basiru & Hijri, 2024).

Their extensive hyphal networks help reduce soil erosion and pollution by stabilizing soil and mitigating nutrient leaching and runoff (Ranganathswamy *et al.*, 2019). This is particularly important in agricultural systems where excessive fertilizer use can lead to environmental pollution. Mycorrhizal fungi can help retain nutrients in the soil-plant system, reducing the need for chemical fertilizers and minimizing nutrient losses to the environment (Vosátka & Albrechtová, 2009).

Mechanisms of Mycorrhizal Fungal Benefits

The beneficial effects of mycorrhizal fungi are underpinned by complex plant-fungal symbiotic relationships. These interactions involve intricate signaling pathways, molecular mechanisms, and changes in gene expression in both plants and fungi (Gianinazzi-Pearson *et al.*, 2007). The establishment of the symbiosis begins with a molecular dialogue between the plant and fungus, involving the exchange of signaling molecules that trigger specific developmental processes in both organisms (Lambais, 2006).

Nutrient exchange and mobilization occur through specialized transport systems, while the fungi also modulate the soil microbiome and influence rhizosphere microbial communities (Duponnois *et al.*, 2008). The fungal partner develops specialized structures within plant roots, such as arbuscules in arbuscular mycorrhizal fungi, which serve as the primary site of nutrient exchange. These structures are characterized by a highly branched fungal network surrounded by the plant cell membrane, creating an extensive interface for nutrient transfer (Roth *et al.*, 2018).

Recent advances in genomics and transcriptomics have provided insights into the molecular mechanisms underlying these symbiotic interactions (Serrano *et al.*, 2024). For example, studies have identified specific plant genes that are upregulated during mycorrhizal colonization, including those involved in nutrient transport, stress response, and hormone signaling. Similarly, fungal genes related to nutrient acquisition and carbon metabolism are differentially expressed during symbiosis establishment (Gao *et al.*, 2023).

Applications in Sustainable Agriculture

The integration of mycorrhizal fungi into sustainable agricultural practices involves various inoculation methods and techniques (Herath *et al.*, 2024). These include spore-based inoculation, the use of mycorrhizal root fragments, and commercial formulations. The choice of inoculation method depends on factors such as crop type, soil conditions, and the scale of application (Fig.3).

Mycorrhizal fungi-based biofertilizers and bio stimulants have been developed and can be integrated with conventional fertilization practices (Sharma *et al.*, 2024). These products often contain a mixture of different mycorrhizal fungal species, along with other beneficial microorganisms and organic compounds that support their establishment and function (Passamani *et al.*, 2024). When used in combination with reduced chemical fertilizer inputs, these biofertilizers can maintain or even improve crop yields while reducing the environmental impact of agriculture (Giovannini *et al.*, 2020).

Mycorrhizal fungi also show promise in integrated pest management strategies, contributing to disease suppression and enhanced pest resistance in crops (Da Silva Folli-Pereira *et al.*, 2020). The mechanisms behind this enhanced resistance include improved plant nutrition, induced systemic resistance, and changes in root exudation patterns that influence soil microbial communities (Monther & Kamaruzaman, 2012). For example, studies have shown that mycorrhizal colonization can reduce the incidence and severity of soil-borne pathogens such as Fusarium and Phytophthora species (WANG *et al.*, 2023).

Successful implementation of mycorrhizal fungi in agriculture has been demonstrated through large-scale field trials, organic farming systems, and the restoration of degraded agricultural lands. In organic farming, where synthetic fertilizers and pesticides are not used, mycorrhizal fungi play a crucial role in maintaining soil fertility and plant health (Al-Yahya'ei *et al.*, 2020). Similarly, in the restoration of degraded lands, inoculation with mycorrhizal fungi has been shown to accelerate plant establishment and improve soil quality (Shuab *et al.*, 2019).

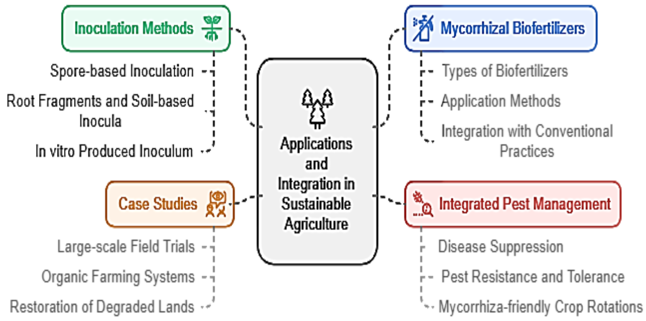

Figure 3

Challenges and Future Directions

Despite the potential benefits, scaling up mycorrhizal fungi production and application presents challenges (Benami *et al.*, 2020). These include developing efficient mass production techniques, ensuring quality control and standardization, and addressing economic feasibility concerns. The production of high-quality inoculum in large quantities remains a significant hurdle, as many mycorrhizal fungi species are obligate symbionts that cannot be cultured independently of their plant hosts.

Future research should focus on overcoming these challenges and further exploring the long-term effects of mycorrhizal fungi on agricultural sustainability (Hagh-Doust *et al.*, 2022). This includes:

1. Developing improved inoculation techniques that ensure successful establishment of mycorrhizal symbiosis under various field conditions.

2. Investigating the interactions between mycorrhizal fungi and other beneficial soil microorganisms to develop more effective microbial consortia for sustainable agriculture.

3. Exploring the potential of mycorrhizal fungi in enhancing crop resilience to climate change, including tolerance to extreme temperatures, salinity, and heavy metal stress.

4. Conducting long-term field studies to assess the impact of mycorrhizal fungi on soil health, carbon sequestration, and ecosystem services in different agricultural systems.

5. Integrating mycorrhizal fungi into breeding programs to develop crop varieties that form more efficient symbiotic associations.

6. Investigating the role of mycorrhizal fungi in improving the nutritional quality of crops, including micronutrient content and biofortification.

7. Developing molecular tools for rapid and accurate identification of mycorrhizal fungal species and assessment of their colonization levels in field conditions.

8. Exploring the potential of mycorrhizal fungi in urban agriculture and controlled environment systems, such as vertical farming and hydroponics.

CONCLUSION

The symbiotic relationships between plants and these beneficial fungi, sustainable agricultural practices can be developed to address global food security challenges while minimizing environmental impacts. The multifaceted benefits of mycorrhizal fungi, including improved nutrient uptake, enhanced stress tolerance, and contributions to soil health.

The integration of mycorrhizal fungi into farming systems offers a promising approach to reduce dependency on chemical inputs, improve resource use efficiency, and enhance ecosystem services provided by agricultural landscapes. However, realizing the full potential of mycorrhizal fungi in sustainable agriculture will require continued research, development of practical applications, and collaboration between scientists, farmers, and policymakers.

By fostering a deeper understanding of the complex interactions between plants, mycorrhizal fungi, and the soil ecosystem, we can develop more holistic and sustainable approaches to agriculture that not only meet the growing global demand for food but also preserve and enhance the health of our planet's ecosystems for future generations.

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