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Review on the Mechanisms of Mycorrhizal Fungal Residues in Improving Soil Aggregate Structure and Their Effects on Crop Growth

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Abstract

Mycorrhizal fungi play a crucial role in promoting soil aggregate formation and stability. This paper reviews the regulatory mechanisms of mycorrhizal fungi and their live fungal residues on soil aggregate structure and their effects on crop growth. Mycorrhizal fungi enhance soil particle cohesion and improve soil structure through three primary mechanisms: physical entanglement, secretion of cementing substances, and microbial community regulation. These processes simultaneously promote nutrient absorption, enhance crop stress resistance, and reduce disease risks. Additionally, live fungal residues serve as organic soil amendments with promising applications in improving soil organic matter content and microbial activity. However, their application still faces challenges such as fungal species specificity, environmental dependency, and lack of standardized technology. Future research should integrate multi-omics approaches to elucidate mycorrhizal fungi-microbe-plant interactions and develop more adaptable fungal residue-based composite materials to promote the application of mycorrhizal technology in sustainable agriculture.

Keywords

Mycorrhizal fungi; Live fungal residues; Soil aggregates; Crop growth; Sustainable agriculture.

1. Introduction

Soil aggregates are the fundamental structural units of soil, and their stability plays a crucial role in agricultural production[1]. The formation and stability of aggregates directly affect soil properties such as water infiltration, nutrient cycling, erosion resistance, and plant growth potential[2] . In recent years, mycorrhizal fungi, as a type of soil microorganism, have gained widespread attention for their role in promoting the formation and stability of soil aggregates. Mycorrhizal fungi form complex networks through symbiotic relationships with plant roots, which not only improve soil structure but also enhance plants' nutrient absorption capabilities, boosting their stress resistance and growth potential[3-4] .

With growing attention to soil health and sustainable agriculture, the application of mycorrhizal fungi and their active fungal residues has been increasingly promoted. Active fungal residues, consisting of fungal metabolites and residual products, not only continue the functions of mycorrhizal fungi but also further improve soil structure and enhance crop growth. Through these mechanisms, the application of mycorrhizal fungi and their residues is considered an important direction for promoting sustainable agricultural development.

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This paper reviews the regulatory mechanisms of mycorrhizal fungi and their residues on soil aggregate structure and their effects on crop growth. The aim is to provide theoretical support for sustainable agricultural development, especially in improving soil health, promoting crop yield, and enhancing ecological environmental sustainability.

2. Mechanisms of Mycorrhizal Fungi in Improving Soil Aggregate Structure

2.1. Physical Effects: Hyphal Entanglement and Network Consolidation

Mycorrhizal fungal hyphae directly promote soil particle aggregation through wrapping. Hyphae come into direct contact with soil particles, forming a dense network structure that binds individual microaggregates (d < 250 μm) into larger aggregates (d > 250 μm). This process helps improve soil pore structure, enhancing water and air infiltration. For instance, arbuscular mycorrhizal (AM) fungi and ectomycorrhizal (ECM) fungi can wrap or penetrate soil microaggregates, combining them into more stable aggregates. This wrapping and bonding mechanism not only improves the physical properties of the soil but also enhances its erosion resistance.

In practical studies, the hyphal density of AM fungi has shown a significant positive correlation with the proportion of larger aggregates in the soil. Mycorrhizal fungi, through their hyphal physical actions, can effectively increase soil porosity, improving its aeration and water infiltration. This not only enhances the structural stability of the soil but also creates a better growing environment for crops. Mycorrhizal hyphae are resistant to tensile forces, with ECM hyphal elastic modulus effectively counteracting external forces like rainwater erosion, thereby increasing soil structural stability.

2.2. Biochemical Effects: Secretion of Cementing Substances

Mycorrhizal fungi enhance the bonding strength between soil particles by secreting a variety of binding substances, promoting the stability of soil aggregates. Studies show that mycorrhizal fungi secrete organic substances, the most important of which include glomalin-related soil proteins (GRSP), polysaccharides, and organic acids.

Role of GRSP: AM fungi secrete GRSP, which is a key binding substance. GRSP has strong hydrophobicity, which allows it to coat soil particles and slow down the wetting rate, reducing the risk of aggregate disintegration. The amount of GRSP is significantly positively correlated with the mean weight diameter (MWD) of large aggregates, so an increase in GRSP helps in the formation and stabilization of larger aggregates. **Polysaccharides and Organic Acids**: Mycorrhizal fungi secrete polysaccharides (such as chitin) and organic acids (such as oxalic acid), which can bind with soil minerals through hydrogen bonds and cation bridges, further promoting the conversion of microaggregates to larger aggregates. Additionally, organic acids can lower soil pH, promoting the dissolution of soil minerals and the release of nutrients, which enhances soil nutrient availability. **Other Metabolic Products**: Metabolites like ergosterol, extracellular enzymes (such as β-glucosidase), and others indirectly affect the formation of soil aggregates by regulating organic matter decomposition and the carbon-nitrogen cycle. Through the secretion of these metabolites, mycorrhizal fungi not only stabilize soil structure but also affect soil nutrient cycling, further improving the overall health of the soil.

2.3. Microbial Community Regulation

Mycorrhizal fungi not only improve soil structure through physical and biochemical actions but also indirectly promote soil aggregate formation by regulating the rhizosphere microbial community. Mycorrhizal fungi can influence the composition of the soil microbial community

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by interacting with rhizosphere microorganisms, which enhances soil biological activity and aggregate stability.

For example, AM fungi can recruit specific microorganisms, such as actinobacteria and nitrogen-fixing bacteria, by secreting specific chemical signals. Actinobacteria enhance soil particle binding through the secretion of extracellular polysaccharides (EPS), further promoting soil aggregate formation. Nitrogen-fixing bacteria improve soil fertility by providing nitrogen, thus benefiting plant growth.

Moreover, mycorrhizal fungi compete with pathogenic microbes for resources, suppressing their growth or inducing systemic resistance (ISR) in plants, reducing the incidence of soil-borne diseases, and further improving soil structure and plant growth.

3. Applications of Live Mycorrhizal Fungal Residues and Their Effects on Crop Growth

3.1. Definition and Functions of Live Fungal Residues

Active fungal residues refer to fungal hyphal remains, secretions, and unused organic materials produced during the metabolism of mycorrhizal fungi. These residues not only continue the functions of mycorrhizal fungi but also have important value in the recycling of agricultural waste. The functions of active fungal residues include:

Continuous Release of Binding Substances: GRSP, polysaccharides, and other binding substances in fungal residues can act on the soil for an extended period, slowing the degradation of aggregates and enhancing soil structural stability. **Provision of Carbon and Nutrients**: Fungal residues are rich in organic carbon and mineral elements (such as phosphorus and potassium), which serve as energy sources for microbial activity, promoting the accumulation of soil organic matter and improving soil fertility and microbial activity. **Regulation of Soil Microbial Activity**: The hyphal remains in fungal residues provide habitats for soil microorganisms, maintaining the diversity of rhizosphere microbes and contributing to the stability of the soil ecosystem.

3.2. Direct Mechanisms Promoting Crop Growth

Improved Nutrient Uptake: Mycorrhizal fungi expand the plant root's absorption range, significantly improving its ability to acquire phosphorus, nitrogen, and trace elements. For example, AM fungi secrete phosphatases to convert insoluble phosphorus in the soil into plant-available phosphorus and directly transport it to plant roots. **Enhanced Stress Resistance**: Mycorrhizal symbiosis can improve plant stress resistance. Studies have shown that mycorrhizal fungi can induce the production of heat shock proteins, antioxidant enzymes, and other substances, which help alleviate the effects of drought, salinity, and heavy metal stress on crops, promoting their growth and development. **Disease Suppression**: Mycorrhizal fungi suppress soil-borne diseases by competing with pathogens for ecological niches or inducing systemic resistance (ISR) in plants. For instance, AM fungi inoculation has shown a significant yield increase in maize grown in soil with high pathogen load, particularly in soils with severe pathogen contamination.

3.3. Indirect Effects: Soil Structural Improvement and Its Cascade Effects

Water Regulation: Stable aggregate structures increase soil water retention, reducing water stress during drought periods, allowing crops to better cope with water shortages. **Reduced Nutrient Loss**: The pore structure of large aggregates can adsorb nutrient ions, reducing nutrient leaching loss and improving fertilizer utilization, thereby promoting crop growth and increasing agricultural productivity. **Promotion of Root Development**: Mycorrhizal fungi improve the physical environment of the soil (e.g., reducing mechanical resistance and

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improving aeration), facilitating plant root expansion and branching, forming denser root networks, and enhancing plant growth.

4. Current Applications and Challenges

4.1. Practical Applications

Agricultural Waste Recycling: The combined use of fungal residues with straw and organic fertilizers can synergistically increase soil organic matter content and the stability of aggregates, thereby improving soil structure and increasing soil fertility. **Optimized Inoculation Techniques**: Optimizing the inoculation techniques for mycorrhizal fungi can significantly increase crop yields. For example, field trials in Switzerland have shown that inoculation with mycorrhizal fungi can increase maize yields by 40%, especially in severely contaminated soils. **Ecological Restoration**: In degraded soils (e.g., mining areas or erosion-prone lands), the application of fungal residues can accelerate soil structural recovery and vegetation restoration, aiding in ecological restoration and soil health improvement.

4.2. Existing Challenges

Fungal Strain Specificity: Different mycorrhizal fungi (e.g., AM vs. ECM) have varying effects on soil aggregate formation and crop growth, requiring the selection of suitable fungal strains based on crop types and soil conditions. **Environmental Dependence**: The effectiveness of mycorrhizal fungi is influenced by environmental factors such as soil pH, moisture, and nitrogen fertilizer application. For instance, high nitrogen environments may suppress fungal colonization, affecting their growth and impact. **Lack of Standardization**: The production, preservation, and application methods of fungal residues have not yet been standardized, limiting their large-scale use.

5. Future Research Directions

Multi-Omics Approaches: Integrating metagenomics and metabolomics to decode mycorrhizal fungi-microbe-plant interactions. Development of Fungal Residue-Based Composites: Exploring combinations with biochar and nanomaterials to enhance adaptability. Long-Term Field Trials: Assessing the lasting impact of fungal residues on soil health and crop yields. Policy and Promotion Strategies: Establishing subsidy policies for mycorrhizal technology to encourage adoption in organic farming and ecological restoration.

6. Conclusion

Mycorrhizal fungi and their live residues significantly improve soil aggregate structure through physical, biochemical, and microbial mechanisms while directly or indirectly enhancing crop growth. Despite their immense potential, challenges remain in species selection, environmental adaptation, and technological standardization. Future research should focus on interdisciplinary approaches and technological innovations to maximize the benefits of mycorrhizal technology in sustainable agriculture.

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