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Biofertilizer Induces Soil Disease Suppression by Activating Pathogen Suppressive Protist Taxa

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INTRODUCTION

Soil-borne diseases continue to pose a serious threat to global crop production by reducing yield quality and economic returns across a wide range of agricultural systems. Pathogens such as fungi, oomycetes, bacteria and soil-dwelling parasites persist in soil for extended periods and are often difficult to control using conventional approaches. Chemical-based disease management has historically been effective in reducing pathogen pressure, but its long-term application has led to negative consequences, including environmental pollution, degradation of soil structure, disruption of beneficial microbial communities and development of resistant pathogen strains. These challenges have intensified the search for sustainable alternatives that maintain productivity while preserving soil ecological integrity.

Biofertilizers have emerged as an important component of sustainable agriculture due to their capacity to enhance nutrient availability, improve plant growth and promote soil biological activity. Traditionally, biofertilizers were viewed primarily as inoculants supplying beneficial bacteria or fungi that directly stimulate plant nutrition. However, advances in soil microbial ecology have revealed that biofertilizers exert broader ecological effects by reshaping soil microbial networks and trophic interactions. These indirect effects are increasingly recognised as central to their role in disease suppression.

Among soil microbial groups, protists occupy a pivotal yet often overlooked position. Protists include amoebae, flagellates, ciliates and other microbial eukaryotes that are abundant and functionally diverse in soil ecosystems. They regulate microbial populations through selective grazing, influence nutrient mineralisation and mediate energy flow between trophic levels. Importantly, protists can preferentially prey on plant pathogenic microbes or stimulate beneficial microbial taxa through top-down control mechanisms.

Recent studies suggest that biofertilizer application can activate specific protist taxa that contribute to pathogen suppression. By altering resource availability, microbial community composition and soil physicochemical properties, biofertilizers create favourable conditions for pathogen-suppressive protists. These protists indirectly suppress disease by reducing pathogen abundance, enhancing antagonistic bacteria and fungi and promoting plant-induced resistance.

Understanding the mechanisms by which biofertilizers influence protist-mediated disease suppression is critical for optimising their use in sustainable agriculture. This article aims to synthesise current research on biofertilizer-induced activation of pathogen-suppressive protist taxa and their role in soil disease suppression. The review integrates ecological theory, experimental evidence and applied perspectives to provide a comprehensive framework for future research and agricultural practice.

Soil-Borne Diseases and the Concept of Disease-Suppressive Soils

Disease suppressive soils are defined as soils in which disease incidence remains low despite the presence of a virulent pathogen and a susceptible host. Suppressiveness can arise from abiotic factors such as soil texture, pH and nutrient status or from biotic factors related to microbial activity. Biotic suppressiveness is often attributed to the collective action of soil microorganisms that inhibit pathogen establishment, survival, or virulence.

Microbial-mediated disease suppression involves complex interactions among bacteria, fungi, protists and soil fauna. Beneficial bacteria may produce antibiotics, compete for nutrients or induce plant defence responses. Fungi may parasitise pathogens or occupy infection sites. Protists contribute by regulating microbial population structure and promoting functional diversity within the soil food web. Biofertilizers can enhance soil suppressiveness by stimulating these biological processes. Rather than acting as direct pesticides, biofertilizers promote a resilient soil ecosystem capable of resisting pathogen invasion through multiple complementary mechanisms.

Biofertilizers Types and Modes of Action

Biofertilizers encompass a wide range of biological products containing living microorganisms or biologically derived compounds that improve soil fertility and plant health. Common categories include nitrogen-fixing bacteria phosphate phosphate-solubilising microorganisms, potassium mobilizers, arbuscular mycorrhizal fungi and organic-based microbial amendments.

The primary modes of action of biofertilizers include enhancement of nutrient availability, stimulation of root growth, improvement of soil structure and modulation of microbial community composition. Through these mechanisms, biofertilizers indirectly influence higher trophic levels, including protists and microfauna. Biofertilizer application reshapes the rhizosphere microbiome by stimulating beneficial microbes and pathogen-suppressive protist taxa, leading to enhanced soil disease suppression Figure 1.

Organic biofertilizers such as compost-based inoculants and microbial-enriched organic amendments are particularly effective in shaping soil food webs due to their complex nutrient profiles and sustained resource release. These inputs often promote diverse microbial communities that support protist proliferation and functional specialisation.

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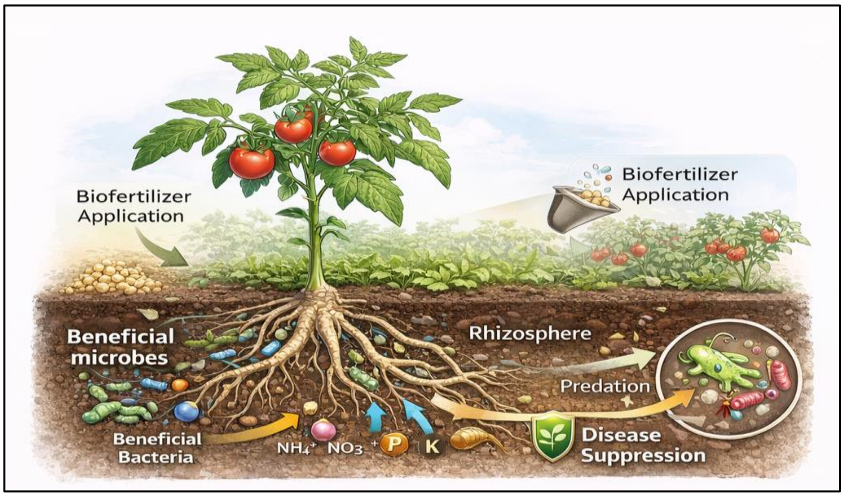

Figure 1. Conceptual illustration showing biofertilizer-induced activation of soil protists and their role in suppressing plant pathogens through soil food web interactions.

Soil Protists Diversity and Ecological Functions

Protists are ubiquitous in soils and represent one of the most diverse groups of microbial eukaryotes. They occupy multiple trophic roles, including bacterivores, fungivores, omnivores and predators of other protists. Through selective grazing, protists regulate microbial biomass composition and activity. Protist grazing stimulates microbial turnover, leading to enhanced nutrient mineralisation, particularly nitrogen and phosphorus. This process increases nutrient availability for plants and beneficial microbes. In addition, protist-mediated predation can suppress pathogenic microorganisms directly or indirectly by favouring competitive antagonists.

Protists also contribute to soil aggregation and carbon cycling through their interactions with bacteria and fungi. Their sensitivity to environmental changes makes them responsive indicators of soil management practices, including biofertilizer application.

Activation of Pathogen Suppressive Protist Taxa by Biofertilizers

Biofertilizers influence protist communities by modifying resource availability, habitat structure and microbial prey composition. Increased bacterial biomass following biofertilizer application provides abundant food resources for bacterivorous protists, leading to their proliferation. Certain protist taxa exhibit preferential feeding on pathogenic bacteria and fungi, thereby reducing pathogen populations.

Studies have identified specific protist groups, such as cercozoan amoebae and ciliates, that are associated with disease-suppressive soils. These taxa often increase in abundance following application of organic biofertilizers and microbial inoculants. Biofertilizers may also enhance protist diversity and functional redundancy, which contributes to ecosystem stability. Diverse protist communities are better able to adapt to environmental fluctuations and maintain suppressive functions under varying conditions.

Mechanisms of Protist-Mediated Disease Suppression

Protist-mediated disease suppression operates through several interconnected mechanisms. Direct predation reduces pathogen abundance and disrupts infection cycles. Selective grazing alters microbial community structure, favouring beneficial antagonists that further suppress pathogens.

Protists can stimulate microbial secondary metabolite production by imposing grazing pressure. This induces bacteria and fungi to produce antibiotics, enzymes and other bioactive compounds that inhibit pathogens. Protist activity also enhances nutrient cycling, which improves plant vigour and resistance to disease. Healthier plants are better able to activate defence responses and tolerate pathogen attack.

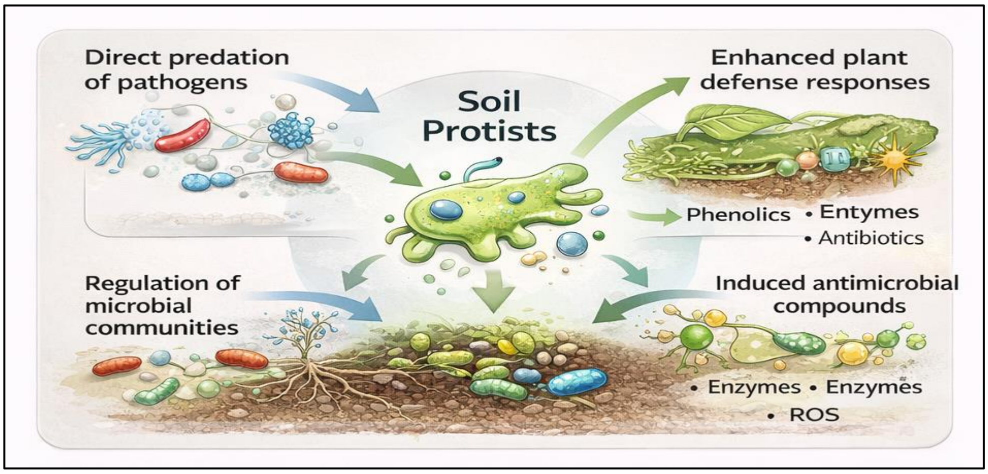

Figure 2. Mechanisms by which soil protists contribute to biofertilizer-induced soil disease suppression, including pathogen predation, microbial regulation and stimulation.

Interactions Between Protists, Bacteria and Fungi

Soil disease suppression emerges from complex multitrophic interactions rather than single-organism effects. Protists influence bacterial and fungal communities, which in turn affect plant health and pathogen dynamics.

Biofertilizers promote beneficial bacteria that serve as prey for protists, creating positive feedback loops that enhance microbial activity. Mycorrhizal fungi benefit indirectly from protist-mediated nutrient release and reduced pathogen pressure.

These interactions highlight the importance of considering the entire soil food web when designing biofertilizer-based disease management strategies.

Table 1 Major Protist Groups Involved in Soil Disease Suppression

Protist group	Feeding behaviour	Contribution to disease suppression
Amoebae	Bacterivory fungivory	Direct pathogen reduction nutrient mineralisation
Cercozoa	Selective grazing	Regulation of pathogenic bacteria
Ciliates	Rapid bacterivory	Enhanced microbial turnover
Flagellates	Bacterivory	Promotion of beneficial microbes

Biofertilizer Formulation and Application Strategies

The effectiveness of biofertilizers in activating pathogen suppressive protists depends on formulation composition, application timing and soil conditions. Liquid formulations provide rapid microbial establishment while solid organic carriers support long-term microbial activity.

Application methods include soil incorporation, seed treatment and fertigation. Combining biofertilizers with organic amendments enhances protist response by providing sustained nutrient inputs and habitat complexity.

Repeated applications may be necessary to establish stable suppressive communities, particularly in degraded soils.

Table 2: Effects of Biofertilizer Application on Soil Biological Parameters

Biofertilizer type	Observed effect	Impact on protists
Bacterial inoculant	Increased microbial biomass	Enhanced protist abundance
Organic biofertilizer	Improved soil structure	Greater protist diversity
Mycorrhizal formulation	Enhanced root colonisation	Indirect stimulation of protists

Implications for Sustainable Agriculture

Biofertilizer-induced activation of pathogen-suppressive protists offers a promising pathway toward sustainable disease management. This approach reduces dependence on chemical pesticides, improves soil health and enhances ecosystem resilience.

By leveraging natural soil food web dynamics, farmers can achieve durable disease suppression that is less prone to resistance development. Integration of biofertilizers into holistic soil management programs supports long-term productivity and environmental sustainability.

Challenges and Future Research Directions

Despite growing evidence, challenges remain in translating protist-based disease suppression into practical applications. Soil protist communities are highly context-dependent and influenced by climate, crop type and management practices.

Future research should focus on identifying key protist indicators of suppressive soils, understanding functional traits and developing biofertilizer formulations that consistently promote beneficial protist taxa. Advances in molecular ecology and imaging techniques will facilitate these efforts.

CONCLUSION

Biofertilizers play a critical role in inducing soil disease suppression by activating pathogen suppressive protist taxa and reshaping soil microbial food webs. Through direct predation regulation of microbial communities and enhancement of nutrient cycling, protists contribute to a resilient soil ecosystem capable of suppressing plant pathogens. Integrating biofertilizers that promote beneficial protist activity represents a sustainable and ecologically sound strategy for disease management in modern agriculture. Continued research and field validation will further refine this approach and expand its adoption across diverse cropping systems.

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