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Short Communication

Tracking milestone advances in exploiting Rhizobia in biocontrol of plant diseases

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Abstract: Rhizobia, long recognized for symbiotic nitrogen fixation, have recently emerged as promising biocontrol agents against a broad spectrum of soil-borne plant pathogens. This concise review summarizes milestone advances demonstrating how rhizobia suppress fungal, oomycete and nematode diseases in both legume and non-legume crops. Disease suppression is mediated through direct mechanisms such as siderophore-mediated iron competition, antibiosis and secretion of cell wall-degrading enzymes, as well as indirect mechanisms involving induced systemic resistance and modulation of plant defense signaling pathways. Emphasis is placed on molecular interactions, phytoalexin induction and quorum sensing as central processes underlying rhizobial biocontrol. Key challenges and future research priorities for integrating rhizobia into sustainable plant disease management strategies are highlighted.

Keywords: Rhizobium; biocontrol, induced systemic resistance, siderophores, antibiosis, phytoalexins

1. Introduction

The increasing demand for sustainable and environmentally benign alternatives to chemical pesticides has intensified interest in microbial-based plant disease management strategies. Among plant growth-promoting rhizobacteria (PGPR), rhizobia are distinctive due to their well-established symbiotic association with legumes and their emerging role in plant disease suppression. Beyond biological nitrogen fixation, rhizobia contribute to plant health by modulating rhizosphere microbial communities, enhancing nutrient acquisition and activating host defence responses (Bhattacharyya & Jha, 2012; Lugtenberg & Kamilova, 2009).

Recent bibliometric and experimental studies highlight a sharp rise in research focusing on PGPR-mediated biocontrol, including rhizobia, as eco-friendly alternatives to synthetic fungicides (Espinosa-Palomeque et al., 2025). Advances in molecular ecology and plant–microbe interaction studies have further expanded the functional scope of rhizobia, positioning them as multifunctional agents capable of promoting growth while simultaneously limiting pathogen establishment in both legume and non-legume crops (Rasool et al., 2025).

2. Direct biocontrol mechanisms

Rhizobia directly suppress phytopathogens through the synthesis and release of bioactive metabolites that restrict pathogen growth and survival in the rhizosphere.

2.1. Siderophore-mediated iron competition

Iron is a critical micronutrient that strongly influences microbial competition in soil ecosystems. Many rhizobial strains produce high-affinity siderophores that efficiently chelate ferric iron, thereby reducing its availability to competing phytopathogens. (Neilands, 1995). This iron deprivation limits pathogen proliferation and contributes to disease suppression, particularly under iron-limiting soil conditions. Recent studies confirm that rhizobial and PGPR-derived siderophores play a pivotal role in suppressing soil-borne fungal pathogens under iron-limiting conditions, contributing significantly to disease reduction in crop plants (Venkataramana & Ndakidemi, 2024).

2.2. Antibiosis and enzymatic degradation

Several rhizobial isolates produce antimicrobial compounds, including bacteriocins and peptide-based antibiotics, that directly inhibit pathogen growth. In addition, the secretion of hydrolytic enzymes such as chitinases and β-1,3-glucanases disrupts pathogen cell wall integrity, leading to reduced virulence or pathogen death. These mechanisms collectively enhance rhizobial antagonistic potential in the rhizosphere. Experimental evidence from recent rhizobial–pathogen interaction studies further support the role of antibiosis and enzymatic degradation in suppressing root rot and wilt pathogens in leguminous crops (Balti et al., 2025).

3. Indirect biocontrol via induced resistance

In addition to direct antagonism, rhizobia induce systemic resistance in host plants, resulting in enhanced tolerance to a broad spectrum of pathogens. This induced resistance is commonly associated with elevated synthesis of phytoalexins, pathogenesis-related proteins and defence-related enzymes (Hammerschmidt, 1999; Heil & Bostock, 2002). The process is predominantly mediated through jasmonic acid and ethylene signalling pathways, enabling plants to mount faster and stronger defence responses upon pathogen challenge (Kloepper et al., 2004).

Recent experimental evidence demonstrates that PGPR-mediated ISR significantly reduces disease severity in economically important crops such as tomato and chickpea by priming host defence pathways rather than exerting direct toxicity on pathogens (Mazuecos-Aguilera et al., 2025; Balti et al., 2025). Moreover, interactions between introduced rhizobia and resident soil microbial communities have been shown to modulate the magnitude and consistency of ISR responses, emphasizing the ecological complexity of rhizobia-mediated disease suppression under field conditions (Rasool et al., 2025).

4. Conclusion and future perspectives

Rhizobia employ multifaceted biocontrol mechanisms integrating direct antagonism (siderophores, antibiotics, enzymes) with host defense modulation (ISR, SAR). Recent research highlights the expanding role of PGPR in sustainable agriculture through enhanced plant resilience, stress tolerance, and reduced reliance on chemical inputs. Continued research into rhizobial signaling and host responses will further unlock their biocontrol potential in diverse agroecosystems (bibliometric trends show strong growth in this field)

Field-based studies demonstrate that rhizobial inoculation can significantly reduce disease severity while simultaneously improving plant growth and yield (Ganesan et al., 2007; Hahn et al., 2016). Recent multi-location evaluations confirm that Rhizobium and Bradyrhizobium species exhibit promising biocontrol potential against root rot and wilt pathogens, particularly when integrated with sustainable agronomic practices (Venkataramana & Ndakidemi, 2024).

Future research should prioritize elucidation of molecular signalling networks governing rhizobia–plant–pathogen interactions, optimization of inoculant formulations and delivery systems, and assessment of rhizobial performance across diverse soil microbiomes (Espinosa-Palomeque et al., 2025; Rasool et al., 2025). Integration of rhizobia with compatible microbial consortia represents a promising strategy to enhance reliability, scalability and resilience of biological disease management under changing climatic and edaphic condition

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