The genus Bacillus as a promising biological control agent for sustainable crop protection

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INTRODUCTION

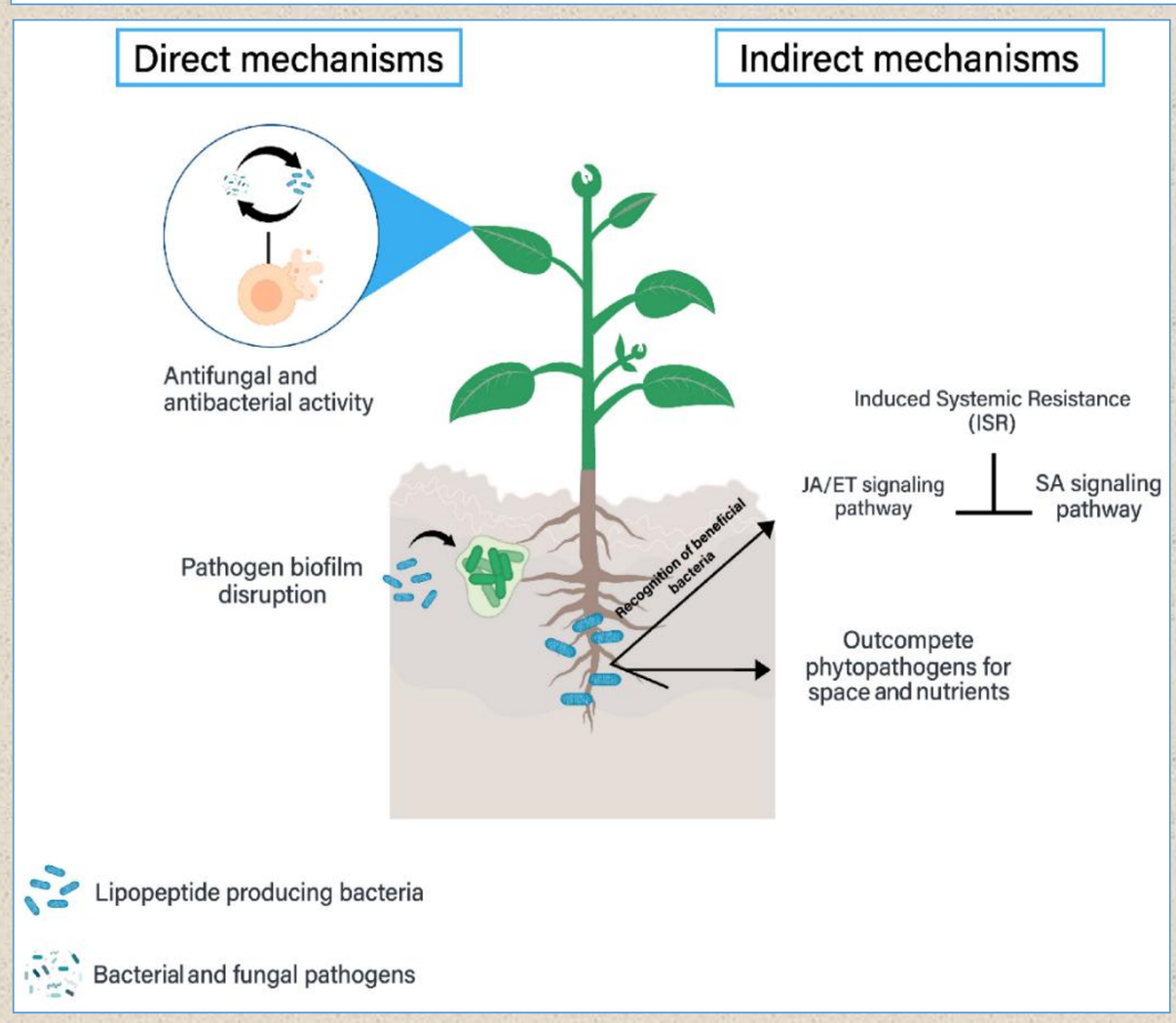
The agricultural sector presently meets 80% of the world's food demand, which is expected to quadruple by 2050 due to population growth and the effects of climate change. However, plant diseases brought on by bacteria, viruses, nematodes, and fungi are among the factors that restrict output and account for 20–40% of losses in agricultural productivity. Plant growth-promoting microorganisms (PGPM) and biological control agents (BCA) have been studied and used more frequently in recent decades due to the growing interest in controlling diseases of agricultural interest. They are also used in the formulation of biopesticides that are part of Integrated Pest and Disease Management (IPDM). Traditionally, chemical pesticides are used to control plant diseases and pests, which increases environmental problems and uses a lot of resources.

THE BACILLUS GENUS – CLASSIFICATION, CHARACTERISTICS AND ECOLOGY

The genus currently contains over 336 species that can be categorized into several groups due to their genetic similarity. The most significant of these groups are: a) the pathogenicity-related group of Bacillus cereus, which includes Bacillus cereus anthracis-thuringiensis; b) the environmental bacilli, which are characteristically present in various habitats, such as the group of Bacillus subtilis, which is made up of Bacillus subtilis-licheniformispumilus; c) the group of Bacillus clausii-halodurans; and d) the group that includes Bacillus sp. NRRLB-14911-coahuilensis.

The Bacillus genus is characterized by a variety of traits, including its ability to grow either aerobically or anaerobically, its Gram-positive status, its bacillary morphology, its flagellar motility, and its variable size (0.5 to 10 μm). Its optimal growth occurs at a pH of neutral, with a wide range of growth temperatures, although the majority of species are mesophilic (temperature between 30 and 45 °C). Its metabolic diversity is linked to the promotion of plant growth and pathogen control.

Morphological characteristics of *Bacillus* spp. A) *Bacillus* spp., Gram positive; B) endospores (green) and bacillary cells (red); and C) macroscopic morphology of *Bacillus* spp.



MAIN MECHANISMS OF BIOLOGICAL CONTROL OF THE BACILLUS GENUS

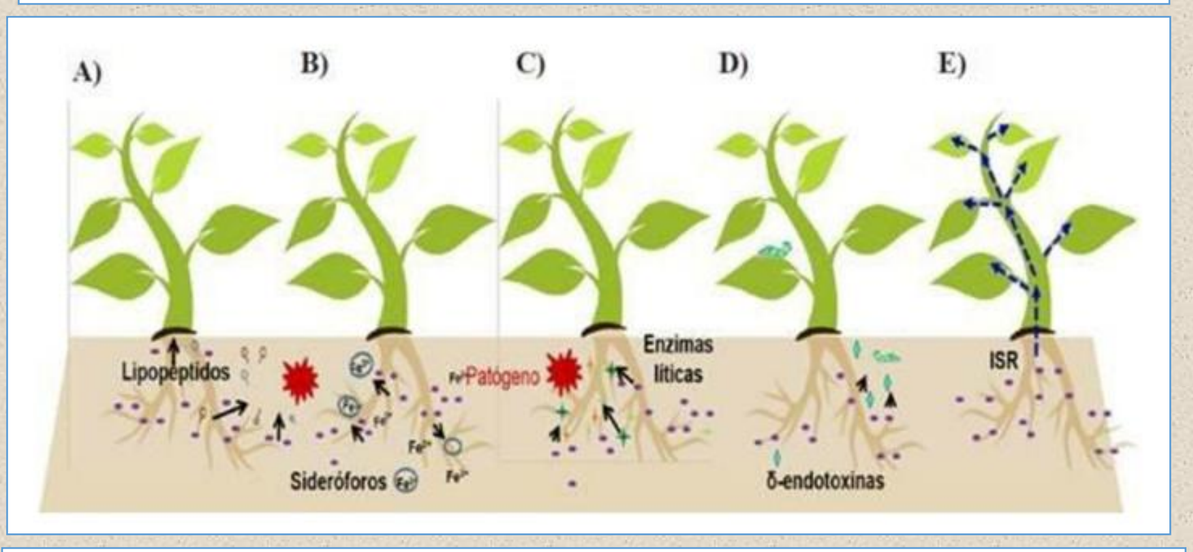
Production of lipopeptides- Lipopeptides have been suggested as the most effective metabolites for this biological activity due to their ecological role and antimicrobial capability

Production of lytic enzymes- One of the most extensively documented biological control methods, especially against infections of fungal origin, is the synthesis of enzymes that aid in the breakdown of the cell wall of phytopathogenic agents.

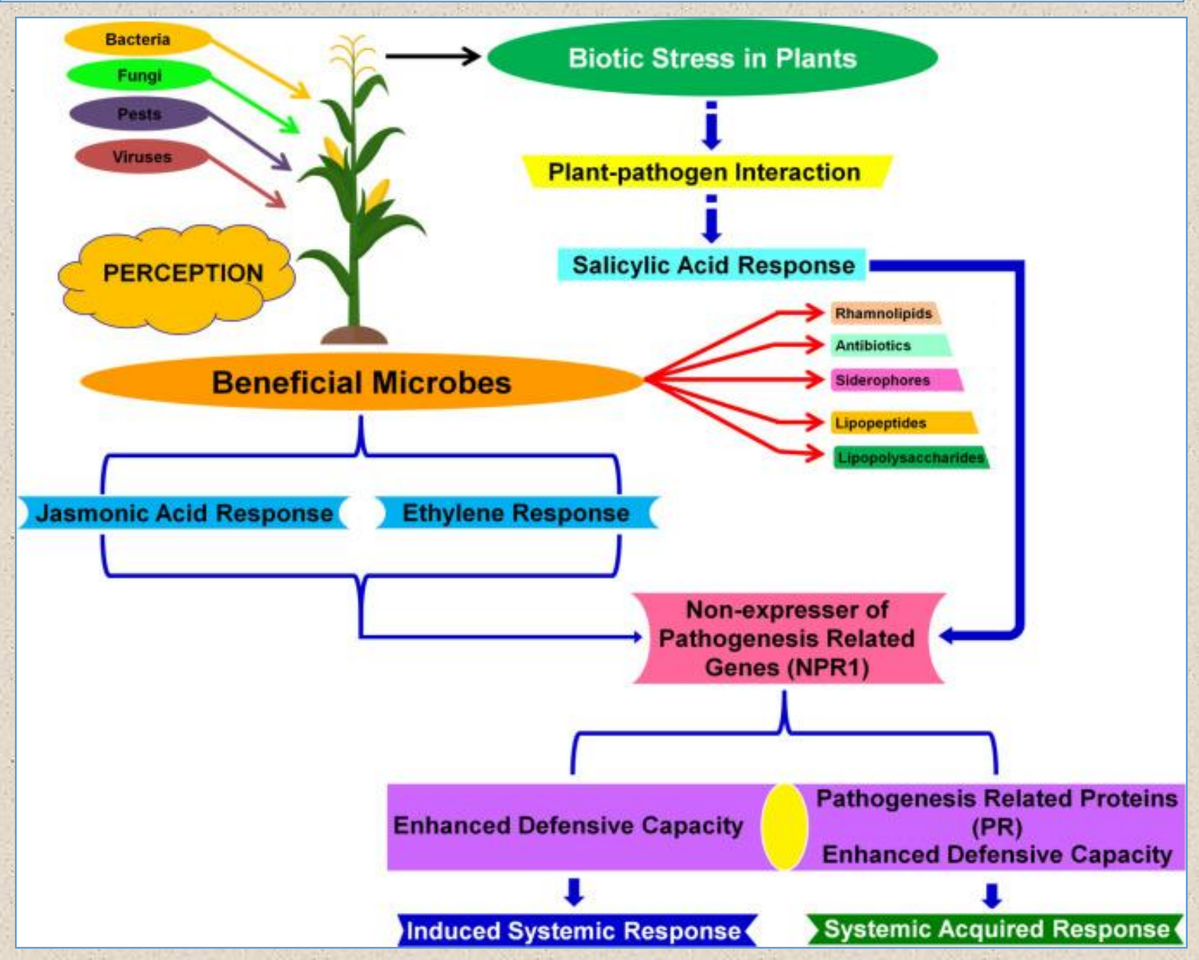
Production of siderophores- Since pathogenic microorganisms rely heavily on iron for growth, a wide range of strains of the Bacillus genus with the capacity for biological control have demonstrated the ability to synthesize siderophores, which regulate the concentration of iron in the medium through its chelation (Fe3+-siderophore) and make the metal unavailable to them.

Production of δ-endotoxins- Bacillus thuringiensis (Bt) is the primary producer of δ-endotoxins. The Cyt (cytolitic) protein has been linked to toxic effects on a wide range of insects, especially diptera.

Induced systemic response- chemical signals (elicitors) generated by helpful microbes can cause the systemic response in plants. Numerous eliciting chemicals, such as lipopeptides, phytohormones, and volatile compounds are produced by Bacillus and cause a systemic reaction in plants.



Main biological control mechanisms of the genus Bacillus: the production of lipopeptides (A), siderophores (B), lytic enzymes (C) and δ-endotoxins (D), and the induction of the systemic response (E).



Biotic stress and induction of induced systemic response.

Lipopeptide's role in the biological control of phytopathogens is divided into direct (including the two main bioactivities for pathogen inhibition) and indirect mechanisms (including induced systemic resistance and competition mechanisms).

CONCLUSION

The *Bacillus* has emerged as a powerful ally in sustainable agriculture, offering natural protection against plant diseases while strengthening crop resilience. Its ability to thrive in diverse environments and deliver stable, spore-based products makes it a practical tool for farmers seeking pesticide-free solutions. Yet, challenges in field performance, regulation, and farmer awareness must be overcome to unlock its full potential. With innovation, collaboration, and education, *Bacillus* can move from niche bioproducts to a cornerstone of global food security and ecological balance.

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