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

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## Abstract

Plant diseases caused by fungi, bacteria, nematodes, and viruses continue to be one of the greatest challenges for global food production, threatening food security and economic stability by generating yield losses estimated between 20% and 40%. Conventional management relies heavily on chemical pesticides, which, although effective in the short term, have raised significant concerns due to the development of resistant pathogen strains, accumulation of toxic residues in soil and water, and negative impacts on non-target organisms and human health. These challenges have fostered the search for sustainable and eco-friendly alternatives, among which microbial biocontrol agents (BCA) are increasingly recognized as essential tools in integrated pest and disease management programs.

Within this framework, the genus *Bacillus* has emerged as one of the most versatile and effective groups of beneficial microorganisms in agriculture. Species such as *Bacillus subtilis*, *B. amyloliquefaciens*, *B. pumilus*, and *B. thuringiensis* are widely studied for their ability to form endospores that confer environmental resilience, and for their metabolic versatility in producing antibiotics, lipopeptides, siderophores, and volatile organic compounds with broad-spectrum antimicrobial activity. These species exhibit multiple mechanisms of action, ranging from antibiosis, hyperparasitism, and enzymatic degradation of pathogen cell walls, to indirect processes such as induction of systemic resistance in plants, nutrient competition, and growth promotion. The combined effects of these mechanisms not only suppress phytopathogens but also enhance plant vigor and resilience under biotic and abiotic stress. These traits enable their application as biopesticides, biofertilizers, and plant growth-promoting rhizobacteria.

However, despite these successes, challenges remain regarding strain selection, biosafety assurance, ecological compatibility, and consistency of performance under field conditions. Advances in genomics, metabolomics, and microbial ecology are shedding light on the genetic determinants of biocontrol activity and host–microbe interactions, offering opportunities to design next-generation biopesticides with improved efficacy and specificity. Furthermore, the integration

of *Bacillus*-based products with cultural practices and other biological inputs could reinforce their role as keystone organisms in sustainable farming systems.

Overall, the genus *Bacillus* represents a cornerstone in the transition toward pesticide-free agriculture. Continued interdisciplinary research and field-based validation will be crucial to unlock its full potential, ensuring both crop protection and ecological balance in the face of global food security challenges.

**Keywords:** *Bacillus*, biological control, biopesticides, sustainable agriculture, plant–microbe interactions, biosecurity