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Eco-Friendly Pest Management: Exploring the Biocontrol Power of Bacillus Species

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ABSTRACT

Bacillus species are widely recognized as effective biological control agents due to their multifaceted mechanisms for suppressing plant pathogens and promoting plant growth. These mechanisms include the formation of resistant endospores, high adaptability to environmental stresses, and the production of antimicrobial compounds such as lipopeptides, volatile organic compounds, and hydrolytic enzymes. In addition, Bacillus spp. can induce systemic resistance in plants, contribute to nutrient solubilization, and modulate the rhizosphere microbiome, making them key components of sustainable and organic agriculture. Despite these advantages, several challenges limit the consistent performance of Bacillus-based products under field conditions. Environmental factors such as ultraviolet radiation, soil pH, temperature, and moisture can reduce bacterial survival and bioactivity. Moreover, certain strains, including *B. velezensis*, may exhibit phytopathogenic potential under specific conditions, highlighting the need for careful strain selection and strict regulatory oversight. Recent advances in genomics, bioinformatics, and synthetic biology have facilitated the identification and manipulation of biosynthetic gene clusters, enabling improvements in strain performance. These developments support the design of optimized formulations and more targeted delivery strategies. Furthermore, combining Bacillus-based products with other biological agents or organic amendments can enhance their efficacy. Incorporation of Bacillus into Integrated Pest Management and Integrated Crop Management programs may further increase their effectiveness and sustainability.

Keywords: Pesticides, Antimicrobial Compounds, Lipopeptides, bacteria

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Introduction

Excessive use of pesticides causes chemical contamination of agricultural lands and wastewater, creating a serious environmental problem. It also leads to the loss of non-target species such as beneficial insects, birds, aquatic organisms, and soil invertebrates (Wu and Chen, 2004, Tazunoki et al., 2022). Furthermore, the accumulation of pesticide residues in the food chain at elevated concentrations can cause severe health problems (Sharma et al., 2024), such as acute poisoning, cancer, neurological impairments, and endocrine disruptions (Bhatia et al., 2024, Zhou et al., 2025). Infants and children are particularly susceptible to these adverse effects due to their greater physiological vulnerability.

To reduce the adverse impacts of pesticide, use and foster sustainable agricultural practices, alternative strategies such as organic farming and biological control have been developed. Among these, the application of biological control agents (particularly beneficial microorganisms such as bacteria and fungi) plays a pivotal role in pest management and plant health without causing environmental harm (Manzar et al., 2022). In recent years, biological control products, especially those based on *Bacillus* species, have gained considerable attention as effective and environmentally safe alternatives to chemical pesticides. Their effectiveness stems from their strong ability to colonize the plant rhizosphere, enhance tolerance to environmental stresses, and produce a wide range of antimicrobial compounds (Pirttilä et al., 2021, Hussaini, 2014, Mongkolthanaruk, 2012). Moreover, these bacteria generate heat- and drought-resistant spores, which provide remarkable stability and persistence under natural conditions, thereby contributing significantly to reducing pesticide dependence and improving crop productivity (Mongkolthanaruk, 2012).

Biological and Physiological Characteristics of *Bacillus*

Bacillus species are Gram-positive, rod-shaped microorganisms that are aerobic or facultatively anaerobic and capable of forming endospores. Most members of this genus are saprophytic, contributing significantly to the decomposition of organic matter (Muthulakshmi et al., 2023, Soltani and Ringø, 2024). Owing to their distinct physiological traits, *Bacillus* species can colonize diverse ecological niches, including freshwater and saline environments, marine sediments, desert sands, hot springs, and even polar soils (Soltani and Ringø, 2024).

Many *Bacillus* species possess the ability to degrade a wide range of organic compounds derived from plant and animal sources, such as cellulose, starch, proteins, agar, and hydrocarbons. In addition, several species are recognized for their functional roles as antibiotic producers, heterotrophic nitrifiers, denitrifiers, nitrogen fixers, iron precipitators, selenium oxidizers, manganese reducers, and acidophilic or alkaliphilic microorganisms (Soltani and Ringø, 2024).

Beyond their metabolic versatility, *Bacillus* species establish interactions with plants both in the rhizosphere and within internal tissues (as endophytes), thereby influencing the expression of key genes and promoting plant growth and health (Muthulakshmi et al., 2023). These bacteria synthesize a broad spectrum of secondary metabolites with diverse structures and biological functions, which substantially enhance their potential as biological control agents (Aqel et al., 2024, Chaabouni et al., 2012). Their remarkable adaptability to fluctuating environmental conditions (including elevated temperatures, wide pH ranges, variable oxygen levels, and their inherent metabolic and genetic plasticity) further underscores their role as effective microbial agents under adverse environmental conditions (Aqel et al., 2024).

Biocontrol Mechanisms of *Bacillus* Spp.

Bacillus species play a vital role in the biological control of plant pathogens through diverse mechanisms. One of the most prominent strategies is the production of antimicrobial compounds, including lipopeptides such as iturin, surfactin, and fengycin, which exhibit strong antifungal and antibacterial activities (Chaabouni et al., 2012, Zeriouh et al., 2014, Dimkić et al., 2022). Additionally, the synthesis of secondary metabolites like subtilosin A, bacilysin, and bacillomycin contributes significantly to the direct suppression of plant pathogens (Ji et al., 2023).

Volatile organic compounds (VOCs) produced by Bacillus not only inhibit pathogen growth but also enhance plant defense against biotic stress through the induction of systemic resistance (ISR) (Dimkić et al., 2022, Ji et al., 2023, Zhang et al., 2020). These bacteria also compete with pathogens for nutrients and space, thereby preventing their growth and colonization (Dimkić et al., 2022, Miljaković et al., 2020). Moreover, *Bacillus* forms stable biofilms around plant roots, enabling the sustained release of antimicrobial substances (Ganchev, 2021).

Another notable feature of *Bacillus* is its ability to activate induced systemic resistance in plants via jasmonic acid (JA) and salicylic acid (SA) signaling pathways, leading to the expression of pathogenesis-related (PR) proteins and other defense-related proteins (Dimkić et al., 2022, Miljaković et al., 2020). Furthermore, Bacillus disrupts the quorum sensing systems of pathogens, interfering with processes such as biofilm formation, sporulation, and the expression of virulence factors (Miljaković et al., 2020, Bais et al., 2004).

Additional Roles of Bacillus in Soil Microbiota and Plant Health

Another prominent role of *Bacillus* species is their impact on soil microbiota. These bacteria modify the microbial community composition, creating favorable conditions for the growth of beneficial (Zhang et al., 2023). Moreover, Bacillus enhances plant growth and development by solubilizing and making nutrients (such as phosphate) more bioavailable (Hashem et al., 2019, Miljaković et al., 2020), and by producing plant growth hormones like auxin and gibberellic acid (Hashem et al., 2019, Muthulakshmi et al., 2023). In addition, the production of antibiotics (Nowocień and Sokołowska, 2022) and hydrolytic enzymes such as chitinases and proteases (Dobrzyński et al., 2023) contributes to the degradation of pathogen cell walls and suppression of their growth.

Antimicrobial Compounds

One of the most important strategies employed by Bacillus species in the biological control of plant pathogens is the production of diverse antimicrobial compounds. These include lipopeptides, secondary metabolites, and volatile organic compounds (VOCs), which exhibit significant antifungal, antibacterial, and antiviral activities (Al-Mutar et al., 2023, Cawoy et al., 2015). The antimicrobial agents produced by Bacillus play a key role in suppressing the growth of pathogens, enhancing plant immunity, and improving soil health.

Diversity of Antimicrobial Metabolites Produced by *Bacillus* Spp.

Bacillus spp. is recognized for producing an exceptionally wide array of antimicrobial metabolites, including lipopeptides, ribosomal peptides (bacteriocins), non-ribosomal peptides, polyketides, and volatile organic compounds (VOCs), which play important roles in the inhibition of plant pathogens, as summarized in Figure 1. According to a review by Tran et al., (2022), more than 47 antimicrobial compounds with distinct mechanisms have been identified from different *Bacillus* spp., mainly targeting vital pathways of microbial cells, including the cell wall, membrane, intracellular processes, and emerging molecular pathways (Tran et al., 2022). Lantibiotics such as subtilin, mersacidin, clausin, and haloduracin bind to cell wall precursors (lipid II), thereby disrupting peptidoglycan synthesis and ultimately causing cell death (Tran et al., 2022).

On the other hand, lipopeptides such as iturin, surfactin, and fengycin exhibit potent antifungal and antibacterial activities by disrupting the cell membranes of fungi and bacteria, while bacteriocins and bacteriocin-like inhibitory substances (BLISs) inhibit a wide range of pathogens, particularly species of *Listeria*, *Staphylococcus*, and *Pseudomonas* (Stoica et al., 2019). In addition, recent studies have reported that more than 89 antimicrobial peptides produced by *Bacillus* spp. have been identified, which are capable of targeting the DNA, membrane, and cell wall of pathogens and can also enhance plant immune responses (Zhang et al., 2025).

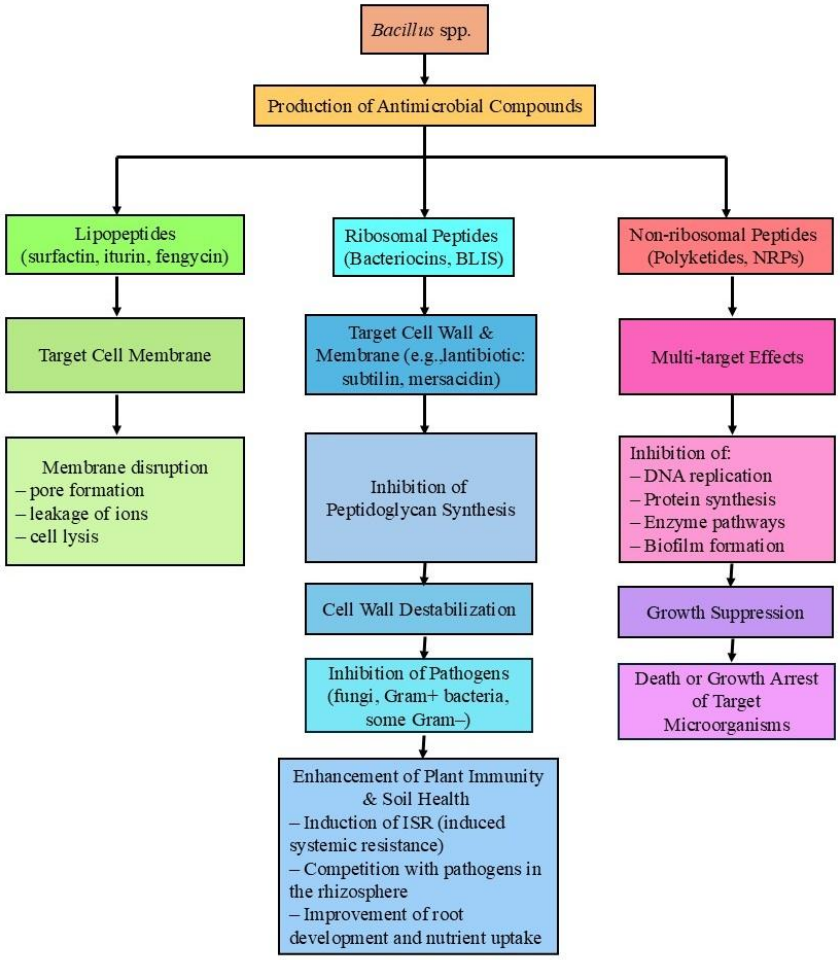

Figure 1: Schematic overview of the major classes of antimicrobial compounds produced by *Bacillus* spp. and their mechanisms of action in suppressing plant pathogens and enhancing plant health.

Biofilm Formation

Certain epiphytic microorganisms possess the ability to form biofilms by aggregating and adhering to surfaces. A biofilm is defined as a structured community of microorganisms embedded within an extracellular matrix and attached to living or non-living surfaces (Fig. 2). Many bacteria are capable of forming biofilms under various environmental conditions, including on the surface of stems, leaves, the plant rhizosphere, soil particles, fungi, and organic compost (Pandin et al., 2017).

It has been shown that root exudates can stimulate biofilm formation by biocontrol agents (Pandin et al., 2017). Biofilm formation is closely linked to the efficiency of rhizosphere colonization (in rhizobacteria) or plant tissue colonization (in endophytes). Effective colonization enhances nutrient accessibility and strengthens biocontrol performance. However, factors such as pH, temperature, moisture, oxygen concentration, and the presence of metal ions in the rhizosphere or plant tissues can significantly influence the formation and stability of biofilms (Dobrzyński et al., 2023).

Biofilms enhance the ability of *Bacillus* spp to suppress plant pathogens. *B. velezensis* PG12, for instance, forms biofilms that improve its colonization on apple fruits and enhance its biocontrol efficacy against apple ring rot disease (Zhang et al., 2025). Similarly, *Bacillus amyloliquefaciens* WS-10 forms biofilms that help suppress *Ralstonia solanacearum*, the causative agent of bacterial wilt in tobacco (Ahmed et al., 2022).

Biofilm formation is often associated with the production of antimicrobial compounds. For example, *B. subtilis* ASAG 010 produces surfactin within its biofilm, enhancing its antifungal activity against *Fusarium graminearum* (Jia et al., 2025).

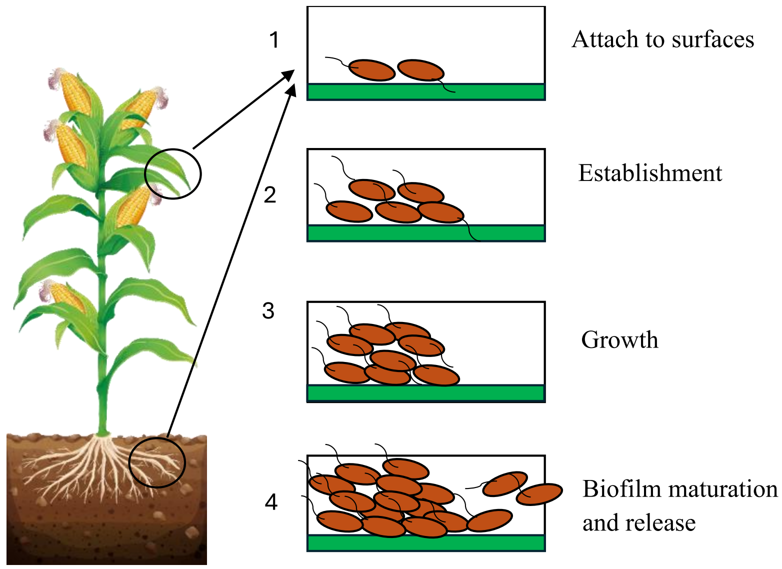

Figure 2: Schematic model of bacterial biofilm development on plant surfaces

Induced Systemic Resistance Triggered by *Bacillus* Spp.

Induced Systemic Resistance (ISR) is an enhanced physiological state in plants that is activated in response to specific environmental stimuli. In this state, the plant's innate defense mechanisms are strengthened against future biotic stresses. Bacillus species can induce long-lasting systemic resistance in plants through interactions with the root system (Dobrzyński et al., 2023). A key feature of ISR is its persistence, providing continuous protection against pathogens (Dobrzyński et al., 2023, Choudhary and Johri, 2009). This process is mediated by signaling pathways such as jasmonic acid and salicylic acid, which lead to the expression of a suite of defense-related genes in the plant (Choudhary and Johri, 2009)

Key Bacillus Spp. Used in Biocontrol

Several Bacillus species are widely utilized in the development of biocontrol products due to their ability to produce diverse bioactive compounds, their high adaptability to various environmental conditions, and their multifunctional role in promoting plant health (Table 1).

Table 1: Effectiveness of Bacillus Species in Plant Disease Management and Their Role as Eco-Friendly Alternatives to Chemical Pesticides

Species	Application	Example Product(s)	Mode of Action	Reference(s)
B. thuringiensis	Biopesticide	Dipel®, Xentari®	Cry proteins, antibiosis	(Balderas-Ruíz et al., 2021, Sena da Silva et al., 2021, Turanli et al., 2012)
B. subtilis	Biocontrol, plant growth promotion	Serenade	Antimicrobial compounds, antibiosis, biofilm formation, ISR	(Rahman, 2017)
B. amyloliquefaciens	Biocontrol, plant growth promotion	Various formulations	Lipopeptides, antibiosis, systemic resistance	(Zheng et al., 2013, Jin et al., 2018)
B. velezensis	Fungal disease control	Fungifree AB™	Antibiosis, systemic resistance	(Balderas-Ruíz et al., 2021)
B. cereus	Plant disease control	Various formulations	Antimicrobial compounds	(Seo et al., 2012)

Below is an overview of the most important species within this genus:

B. thuringiensis (Bt)

This species is one of the most well-known biological control agents with insecticidal properties. Bt produces crystalline proteins known as δ-endotoxins or Cry proteins, which interact with specific receptors in the insect gut, leading to feeding disruption, paralysis, and ultimately death (Sanchis and Bourguet, 2009, Sanchis, 2011). Bt-based products occupy a significant portion of the biopesticide market (Berini et al., 2024).

B. subtilis

A soil-dwelling bacterium with strong capabilities in protecting plants and promoting their growth. B. subtilis plays a significant role in sustainable agriculture through mechanisms such as the production of diverse antimicrobial compounds, biofilm formation, induction of systemic resistance in plants, and secretion of hydrolytic enzymes (Sidorova et al., 2018, Ganchev, 2021, Blake et al., 2021).

B. velezensis

This species is recognized as an effective biological control agent due to its ability to suppress a wide range of plant pathogens, including fungi, bacteria, and nematodes. *B. velezensis* produces cyclic lipopeptides, polyketides, and enzymes such as protease and chitosanase, which degrade fungal cell walls. It also exhibits strong biofilm formation and induces systemic resistance in plants (Rabbee et al., 2019, Han et al., 2024, Li et al., 2024).

B. amyloliquefaciens

This species plays a key role in plant growth and development by enhancing soil nutrient availability, modifying the rhizosphere microbial community, secreting plant growth hormones and volatile organic compounds (VOCs), and inducing resistance against both biotic and abiotic stresses (Zhang et al., 2017, Ilyas et al., 2024, Kröber et al., 2016).

B. cereus

B. cereus is capable of forming biofilms that enhance plant resistance to environmental stresses and pathogens through the secretion of metabolites, surfactants, and enzymes (Majed et al., 2016). Additionally, by producing growth-promoting compounds such as indole-3-acetic acid (IAA), ACC deaminase, and siderophores, it improves seed germination, seedling growth, and overall plant health (Zhou et al., 2021).

Main Pests Targeted by *Bacillus* spp.

Bacillus species, especially *B. Thuringiensis* and *Bacillus subtilis*, are widely used as biological control agents against different agricultural pests. These bacteria have shown effectiveness against several important insect pests and plant pathogens, as reported in many scientific studies.

B. Thuringiensis is mainly applied for the control of insect pests. It is particularly effective against lepidopteran species such as *Helicoverpa armigera*, where *B. Thuringiensis* strains have demonstrated strong insecticidal activity and significant larval mortality (Pinheiro and Valicente, 2021). Similarly, high mortality rates have been reported for *Spodoptera litura* following treatment with *B. Thuringiensis* and *B. subtilis* fusants (Revathi et al., 2014). *B. Thuringiensis* toxins are also commonly used to manage *Plutella xylostella* (diamondback moth), a major pest of cruciferous crops (Sayyed et al., 2008). *B. Thuringiensis* strains have also shown activity against coleopteran pests. Notable examples include *Anthonomus grandis* (cotton boll weevil), which causes major economic losses in cotton production (Sauka et al., 2024), and *Diabrotica virgifera virgifera* (western corn rootworm), for which *B. Thuringiensis* maize has been widely adopted, although resistance has been reported in some cases (Gassmann et al., 2020). In addition, *B. Thuringiensis* strains have demonstrated toxicity toward hemipteran pests such as *Bemisia tabaci* (whitefly), suggesting their potential use in integrated pest management programs (Cabra and Fernandez, 2019, Mensah and Young, 2017).

Bacillus subtilis is mainly recognized for its biocontrol activity against plant pathogens. Several studies have shown that *B. subtilis* strains are effective in controlling fungal pathogens such as *Fusarium oxysporum*, the causal agent of Fusarium wilt (Boulahouat et al., 2023), and *Rhizoctonia solani*, where high biocontrol efficacy has been reported, particularly in tomato plants (Ma et al., 2015). In addition to fungi, *B. subtilis* has shown antagonistic effects against bacterial pathogens, including *Ralstonia solanacearum*, which causes bacterial wilt in a wide range of crops (Kadhim and Matloob, 2025). Moreover, *B. subtilis* strains have been reported to cause high mortality in certain insect pests such as *Pieris brassicae*, a pest of brassica crops, and *Dendroctonus micans*, an important forest pest (Usta et al., 2025).

Limitations of Bacillus-Based Biological Control

Although Bacillus-based biocontrol agents often perform successfully under laboratory or controlled conditions, they frequently fail to demonstrate the same level of efficacy in field environments (Serrão et al., 2024). This discrepancy can be attributed to various environmental factors; for instance, exposure to ultraviolet (UV) radiation may reduce the viability of bacterial cells or the stability of their active compounds (Idris et al., 2024). Additionally, harsh climatic conditions or unfavorable physicochemical properties of the soil (such as unsuitable pH or poor texture) can diminish the effectiveness of these agents (Mahapatra et al., 2022).

Moreover, certain *Bacillus* strains, have been associated with disease outbreaks in specific crops. For example, *B. velezensis* has been reported as the causal agent of bulb rot in onion and soft rot in potato (Rabbee et al., 2023) and rot in peach fruits (Zeng et al., 2022). In addition, other *Bacillus* species have also been implicated in plant and animal diseases; for example, *B. pumilus* has been associated with fruit rot of muskmelon (*Cucumis melo*) in China (Song et al., 2018). Although *B. subtilis* is widely regarded as a safe and efficient microbial cell factory, certain strains have exhibited pathogenic potential in animals (Zhu et al., 2017), and *B. cereus* was historically considered harmless for decades before being recognized as a human pathogen (Tuipulotu et al., 2021).

Therefore emphasized that strains intended for biocontrol applications must be carefully evaluated at the strain level to avoid unintended phytopathogenic effects (Rabbee et al., 2023). The development, registration, and commercialization of *Bacillus*-based biocontrol products also require navigating complex regulatory procedures, including efficacy evaluation, safety assessments, and risk analysis, which can be both costly and time-consuming (Vedamurthy et al., 2020).

Recent Advances and Future Directions

Significant progress in DNA sequencing technologies and bioinformatics has enabled precise identification and characterization of gene clusters responsible for secondary metabolite production in Bacillus strains, playing a crucial role in the development of more effective biocontrol agents (Su et al., 2020, Toymentseva et al., 2019). Moreover, modern technologies such as genetic engineering and synthetic biology have been employed to optimize the performance of these bacteria in biocontrol and biofertilizer applications (Pal et al., 2024, Liu et al., 2013). Today, Bacillus-based products are increasingly integrated into sustainable agricultural strategies, contributing to reduced use of chemical fertilizers and pesticides (Pal et al., 2024, Liu et al., 2013). The growth of the global market for these products, along with numerous patents and extensive research activities, reflects the dynamic nature of this field and strong interest from the private sector (Piedra-Buena et al., 2015, Sales and Rigobelo, 2024).

Conclusion

Bacillus Spp. have gained a prominent position in sustainable agriculture and organic crop production due to their diverse and effective mechanisms in pest control and plant growth promotion. Their ability to form resistant spores, survive under harsh environmental conditions, produce antimicrobial compounds, induce systemic resistance in plants, and enhance nutrient availability makes them one of the most important biological control agents.

Nevertheless, challenges such as reduced efficacy under real field conditions, complexity in developing effective formulations, and the need for precise strain selection and continuous monitoring remain obstacles to their widespread development and commercialization.

Recent advances in areas such as genomic sequencing, synthetic biology, and genetic engineering have paved the way for optimizing the performance of Bacillus strains and developing innovative biological products. Ultimately, integrating these products into Integrated Pest Management (IPM) and Integrated Crop Management (ICM) programs not only enhances agricultural system productivity but also plays a vital role in environmental protection and the provision of safe and sustainable food.

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