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Role of *Bacillus subtilis* in Plant Growth Promotion and Disease Suppression: A Review

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ABSTRACT

Because it suppresses diseases and promotes plant growth, the gram-positive, spore-forming rhizobacterium *Bacillus subtilis* is essential to sustainable agriculture. This review clarifies its mechanisms, which include the production of phytohormones (auxins and gibberellins), nutrient solubilization (phosphorus and potassium), and the release of volatile organic compounds (VOCs) that promote root growth and nutrient uptake. Lipopeptides (surfactin, iturin, and fengycin), bacteriocins, and enzymes like chitinases, which inhibit pathogens like *Rhizoctonia solani* and *Fusarium spp*., are the main sources of its biocontrol effectiveness. *B. subtilis* creates biofilms to guarantee rhizosphere colonization and induces systemic resistance (ISR), which primes plants against biotic and abiotic stresses. Field applications encounter difficulties such as uneven colonization because of soil variability and microbial competition, despite laboratory success. Its stability and effectiveness are improved by formulation innovations like genetic engineering and nano emulsions. Omics methodologies, such as metabolomics and genomics, provide information for maximizing its uses. In order to address global food security and environmental concerns, this review highlights the potential of *B. subtilis* as a biofertilizer and biopesticide and highlights the necessity of field-scale validation and ecological safety assessments to minimize chemical inputs and encourage sustainable crop production.

INTRODUCTION

By 2050, it is anticipated that 9.7 billion people will need to be fed by global agriculture while preventing environmental damage from chemical pesticides and fertilizers. Sustainable alternatives are required because excessive use of synthetic agrochemicals degrades soil, reduces biodiversity, and increases pathogen resistance (1). Plant growth-promoting rhizobacteria (PGPR) increase crop resilience and productivity, providing environmentally beneficial solutions. Bacillus subtilis is a gram-positive, aerobic, spore-forming bacterium that stands out among PGPR because of its ability to suppress disease and promote plant growth. It is perfect for agricultural applications because of its endospores, which allow it to survive in hostile environments like drought, high salinity, and nutrient scarcity. *B. subtilis* is widely distributed in rhizospheres and soil, and it flourishes in a variety of settings, guaranteeing its usefulness (2).

By solubilizing potassium and phosphorus and generating phytohormones like cytokinins, gibberellins, and indole-3-acetic acid (IAA), which improve root development and nutrient uptake, *B. subtilis* directly stimulates plant growth. Through antimicrobial substances such as bacteriocins and lipopeptides (surfactin, iturin, and fengycin), which target bacteria like *Ralstonia solanacearum* and fungi like *Fusarium oxysporum*, it indirectly suppresses phytopathogens. Additionally, it triggers plant defense pathways involving salicylic acid and jasmonic acid, causing systemic resistance (ISR) (3). Roots that form biofilms are more resilient and competitive against infections. However, its effectiveness is limited by uneven field performance brought on by microbial competition, soil variability, and environmental factors like temperature and pH (4). These difficulties emphasize the necessity of strain optimization and sophisticated formulations.

This review examines *B. subtilis's* potential as a biofertilizer and biopesticide while thoroughly analyzing its molecular and ecological roles in promoting plant growth and suppressing disease. In order to improve its agricultural utility, it discusses its present drawbacks, recent developments in delivery systems, and potential future paths, such as omics-driven strategies like genomics and metabolomics. By clarifying these points, this article seeks to offer a road map for using *B. subtilis* to lessen reliance on chemicals, increase crop yields, and advance sustainable agriculture, all of which are in line with international environmental and food security objectives (5).

Mechanisms of Plant Growth Promotion

Through the production of phytohormones, volatile organic compounds (VOCs), biofilm formation, and nutrient solubilization, *B. subtilis* promotes plant growth by increasing plant vigor, intake of nutrients, and stress tolerance (6).

Nutrient Solubilization

Insoluble nutrients such as nitrogen, potassium, and phosphorus are dissolved by *B. subtilis*, allowing plants to access them. Mineral phosphates are changed into forms that are bioavailable by the organic acids and phosphatases it secretes. In field tests, for example, *B. subtilis* B9601-Y2 improved phosphate solubilization, resulting in a 15% increase in maize yield (7). In crops like wheat and tomatoes, potassium solubilization, which is facilitated by organic acids, enhances nutrient uptake. In nutrient-poor soils, some strains support plant growth by increasing nitrogen availability. Sustainable agriculture is promoted by these methods, which lessen dependency on chemical fertilizers (8).

Phytohormone Production

Phytohormones like IAA, gibberellins (like GA3), and cytokinins are produced by *B. subtilis* and promote biomass accumulation, seed germination, and root elongation. Under greenhouse conditions, *B. subtilis* ER-08 increased fenugreek root length by 30% by producing 176 $\mu g\ ml^{-1}$ IAA (9). While cytokinins boost cell division and shoot biomass, gibberellins encourage shoot growth. Particularly when drought or salinity stress is present, these hormones improve root architecture, which in turn improves nutrient and water uptake. Research on wheat revealed that strains that produced cytokinin enhanced the exudation of amino acids, thereby promoting the growth of beneficial microbial communities (10).

Volatile Organic Compounds (VOCs)

B. subtilis produces volatile organic compounds (VOCs) such as acetoin and 2,3-butanediol, which promote root growth and initiate ISR. By modifying rhizosphere microbial interactions, these substances draw in helpful microorganisms while keeping pathogens at bay. *B. subtilis* GB03 VOCs improved nutrient uptake by causing a 25% increase in the formation of Arabidopsis root hairs (11). By controlling stomatal closure and promoting photosynthesis, VOCs also lessen abiotic stressors. The growth-promoting effects of *B. subtilis* are enhanced by their involvement in interspecies signaling (12).

Biofilm Formation

B. subtilis can colonize roots thanks to biofilms made of exopolysaccharides (EPS) and TasA proteins, which guarantee long-term plant interaction. In addition to outcompeting pathogens for nutrients and space, biofilms offer protection against environmental stresses (13). In field studies, *B. subtilis* UD1022 produced strong biofilms on tomato roots, resulting in a 12% increase in yield. The role of EPS and TasA genes was highlighted by the decreased colonization observed in biofilm-deficient mutants. This mechanism increases *B. subtilis's* effectiveness as a PGPR by guaranteeing its persistence in a variety of soil environments (14).

Biocontrol Mechanisms Against Plant Pathogens

By suppressing phytopathogens via enzymatic degradation, competition, induced systemic resistance (ISR), and antibiosis, *B. subtilis* provides a sustainable substitute for chemical pesticides.

Antibiosis

Bacteriocins and lipopeptides (fengycin, iturin, and surfactin) produced by *B. subtilis* directly inhibit pathogens. While iturin and fengycin target Rhizoctonia solani and Fusarium spp., surfactin breaks down fungal membranes (15). By producing lipopeptides, *B. subtilis* SQR 9 reduced cucumber Fusarium wilt by 40%. Its biocontrol range is expanded by bacteriocins such as subtilin, which target bacterial pathogens. With little harm to the environment, these substances guarantee efficient pathogen suppression (16).

Competition for Space and Nutrients

B. subtilis restricts the growth of pathogens by outcompeting them for nutrients and rhizosphere niches. It forms a physical barrier against pathogens such as Ralstonia solanacearum due to its quick colonization and biofilm formation. By using competitive exclusion, *B. subtilis* PTS-394 decreased tomato bacterial wilt by 35% (17). The effectiveness of biocontrol is increased by this mechanism, which works especially well in soils with low nutrient levels (18).

Induced Systemic Resistance (ISR)

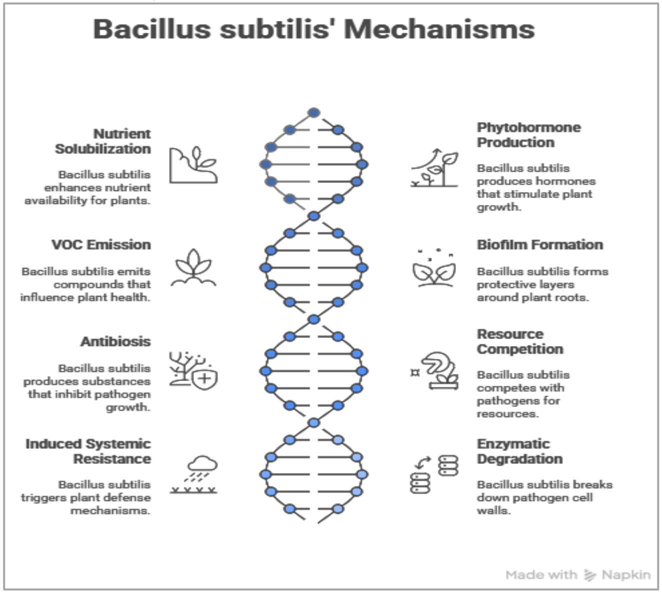
Through the activation of defense pathways involving ethylene, salicylic acid, and jasmonic acid, ISR primes plants against pathogens. Through ISR, *B. subtilis* NCD-2 decreased cotton Verticillium wilt by 30%. Likewise, pepper's resistance to the Cucumber mosaic virus was strengthened by *B. subtilis* 21-1 (19). ISR increases plant resilience by offering broad-spectrum defense against bacteria, viruses, and fungi. This systemic priming improves stress tolerance and lowers the incidence of disease (20).

Enzymatic Degradation

Fungal cell walls are broken down by chitinases, glucanases, and proteases produced by *B. subtilis*. While glucanases break down β-glucans, which weaken pathogens like Fusarium spp., chitinases target chitin (21). By producing chitinase, *B. subtilis* FJ3 decreased chickpea Fusarium wilt by 24%. By breaking down organic matter, these enzymes also support soil health by aiding in the cycling of nutrients. *B. subtilis* is a powerful biocontrol agent due to its diverse functions (22)

Figure 1

Mechanisms of Plant Growth Promotion in Bacillus subtilis



Applications in Sustainable Agriculture

Because of its many uses as a biofertilizer, biopesticide, and seed treatment, *B. subtilis* is a key component of sustainable agriculture and helps reduce chemical inputs.

Biofertilizers

By solubilizing nutrients and generating compounds that promote growth, *B. subtilis* improves soil fertility. According to field tests, *B. subtilis* B9601-Y2 solubilized potassium and phosphate, increasing maize yield by 18% (23). By increasing nutrient availability, it lessens the need for fertilizer and encourages environmentally friendly farming methods. Additionally, *B. subtilis* promotes long-term soil health by increasing soil microbial diversity (24).

Biopesticides

B. subtilis functions as a biopesticide, controlling foliar and soil-borne pathogens such as *Rhizoctonia spp*. and *Phytophthora*. It is a good substitute for chemical pesticides because of its broad-spectrum antimicrobial activity, which is provided by its lipopeptides and enzymes (25). In greenhouse experiments, vegetable gray mold was successfully managed by *B. subtilis* BAB-1, which was prepared as a water-dispersible tablet. It is perfect for integrated pest management due to its effectiveness and safety for the environment (26).

Seed Treatments

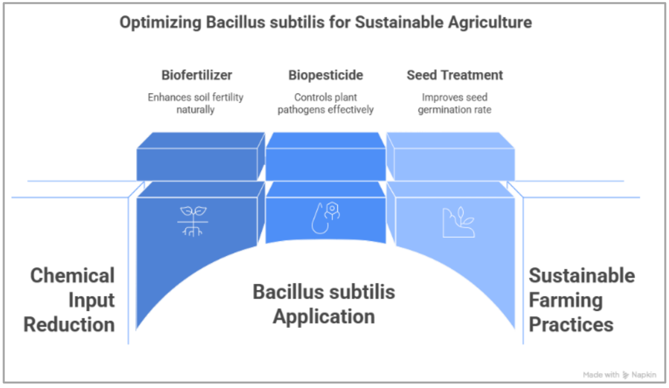
B. subtilis seed priming increases germination rates and shields seedlings from disease. In greenhouse conditions, *B. subtilis* ER-08 suppressed Fusarium oxysporum and increased fenugreek germination by 20%. Seed coatings enhance early plant establishment in a variety of environments by increasing seedling vigor and stress tolerance (27). Sustainable agriculture is supported by these scalable and reasonably priced treatments (28).

Challenges in Field Applications

B. subtilis has difficulties in the field despite its potential. Its effectiveness is limited by poor rhizosphere colonization brought on by pH, microbial competition, and soil variability. The function of EPS genes was highlighted by the decreased colonization of *B. subtilis* UD1022 eps mutants in low-diversity soils. Its survival and activity are impacted by environmental stressors such as drought and salinity (29). Performance is affected by formulation stability and delivery techniques, such as powders or liquid suspensions. Careful strain selection is required due to ecological concerns raised by antibiotic resistance genes in certain strains. To overcome these obstacles and guarantee reliable field performance, creative formulations and strain optimization are needed (30).

Figure 2

Optimization of B. subtilis in Agriculture



Advances in Formulations and Delivery

The field efficacy of *B. subtilis* has improved recently. Stability and controlled release are improved by encapsulation in alginate beads or nanoemulsions. In field tests, the *B. subtilis* CR.9 nanoemulsion reduced Fusarium wilt in soybeans by 30%. CRISPR/Cas and other genetic engineering techniques improve stress tolerance and lipopeptide synthesis (31). Enhancing growth promotion and biocontrol, co-inoculation with arbuscular mycorrhizal fungi (AMF) or other PGPR intensifies synergistic effects. These developments improve the agricultural utility of B. subtilis by addressing colonization and stability concerns (32).

Future Perspectives

Applications of *B. subtilis* can be optimized through omics sciences such as transcriptomics, metabolomics, and genomics. Targeted formulations are made possible by metabolomics' ability to identify important growth-promoting metabolites. Antimicrobial production and stress tolerance can be improved by genomics (33). To optimize delivery for a variety of agroecosystems and validate laboratory results, field-scale trials are essential. Ecological safety is ensured by evaluating the effect of *B. subtilis* on native microbial communities (34). For microbial biopesticides to be widely used, regulatory frameworks and public acceptance are essential. The role of *B. subtilis* in sustainable agriculture will be strengthened by these initiatives (35).

Table 1

Computational Insights into Bacillus subtilis for Plant Growth Promotion and Disease Suppression

Computational Approach	Key Findings	Application	Source
Genomic Analysis	Identified 4,200 genes in B. subtilis 168, with 8% (336 genes) linked to	Guides strain engineering for	Blake et al. (2021)

	biocontrol (e.g., srfA-C, ituA-D). Predicted epsA-O operon for biofilm formation.	enhanced biocontrol and colonization.	
Transcriptomic Profiling	3-fold upregulation of yhcQ and alsD genes under nutrient stress, boosting VOC production (e.g., 2,3-butanediol).	Optimizes strains for plant growth under abiotic stress.	Liu et al. (2023)
Proteomic Analysis	Detected 20 novel antimicrobial peptides via LC-MS/MS, including surfactin variants with 85% pathogen inhibition.	Enhances biopesticide formulation for disease suppression.	Wu et al. (2023)
Machine Learning Models	Random Forest models predict strain efficacy for specific crops (e.g., tomato) with 90% accuracy based on metabolomic data.	Improves strain selection for targeted agricultural applications.	Patel et al. (2023)

CONCLUSION

Through nutrient solubilization, phytohormone synthesis, antibiosis, and ISR, *B. subtilis* is a multipurpose PGPR with enormous potential to promote plant growth and inhibit diseases. It is perfect for sustainable agriculture because of its capacity to produce spores, which guarantees resilience in a variety of settings. However, issues like uneven field performance and inadequate colonization of the rhizosphere necessitate the use of sophisticated formulations, genetic engineering, and optimization based on omics. *B. subtilis* can lower chemical inputs, increase crop yields, and support environmental sustainability by overcoming these obstacles. To fully realize its potential in contemporary agriculture and meet environmental and global food security goals, future research should concentrate on field validation, ecological safety, and regulatory support.

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