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Bacillus spp.: Structural Biology, Mechanistic Insights and Applications in Sustainable Agriculture

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The genus *Bacillus* represents a diverse group of rod-shaped, Gram-positive bacteria widely distributed in nature. Members of this genus are commonly found in soil, water, air and even extreme environments such as hot springs and deserts. Their remarkable adaptability is largely due to their ability to form endospores—highly resistant, dormant structures that allow survival under harsh environmental conditions including heat, desiccation, radiation and chemical exposure. The genus was first described in the 19th century and has since become one of the most extensively studied bacterial groups. Among the many species classified under this genus, *Bacillus subtilis* has emerged as a model organism for studying bacterial physiology, genetics, and molecular biology. It has also gained significant recognition in agriculture, biotechnology, medicine and industry due to its ability to produce enzymes, antibiotics and growth-promoting compounds. Species within this genus exhibit a broad spectrum of characteristics. Some, such as *Bacillus anthracis*, are pathogenic, while others like *Bacillus thuringiensis* are beneficial and widely used in pest management. However, the focus of this article is on the beneficial aspects of *Bacillus subtilis*, especially its mechanisms of action and applications in agriculture.

Overview of *Bacillus subtilis*

Bacillus subtilis is one of the best-characterized species within the genus. Commonly referred to as the "hay bacillus," it is naturally found in soil and vegetation. It is non-pathogenic and generally regarded as safe (GRAS), which makes it suitable for agricultural and industrial applications. *Bacillus subtilis* has been used as a model organism to understand bacterial chromosome replication, sporulation and gene regulation. Its genome has been fully sequenced, revealing genes responsible for antibiotic production, stress resistance and plant-growth-promoting properties. The ecological role of *B. subtilis* in soil systems is highly significant. It interacts with plant roots, other microorganisms and soil particles, forming part of the rhizosphere microbiome. Through these interactions, it can enhance plant health and soil fertility.

Cell Structure and Physiology of *Bacillus subtilis*

The cellular architecture of *Bacillus subtilis* reflects typical Gram-positive characteristics:

1. Cell Wall Structure: The thick peptidoglycan layer provides structural integrity and protection. Teichoic and lipoteichoic acids embedded in the cell wall contribute to cell shape maintenance and ion transport.

2. Endospore Formation: Under unfavorable conditions such as nutrient limitation, *B. subtilis* initiates sporulation. This complex developmental process involves asymmetric cell division and the formation of a highly resistant endospore. The spore can survive extreme temperatures, radiation and chemical exposure.

3. Motility Many strains are motile due to the presence of peritrichous flagella. Motility enables colonization of plant roots and movement toward nutrient sources.

4. Biofilm Formation: *B. subtilis* can form biofilms—structured communities of cells embedded in extracellular polymeric substances. Biofilm formation enhances survival, root colonization, and resistance to environmental stress.

Mechanism of Action of *Bacillus subtilis*

The beneficial effects of *Bacillus subtilis* in agriculture are largely attributed to its multifaceted mechanisms of action. These mechanisms include antibiosis, competition, induced systemic resistance, nutrient solubilization, and biofilm formation.

1. Antibiosis

One of the most important mechanisms is the production of antimicrobial compounds. *B. subtilis* synthesizes a wide range of antibiotics and lipopeptides, including:

- Surfactin
- Iturin
- Fengycin
- Bacilysin

These compounds inhibit plant pathogens such as fungi and bacteria. Lipopeptides disrupt pathogen cell membranes, leading to leakage of cellular contents and eventual cell death. This direct antagonistic activity makes *B. subtilis* a powerful biocontrol agent.

2. Competitive Exclusion

In the rhizosphere, nutrients and space are limited. *B. subtilis* competes effectively with pathogenic microorganisms by rapidly colonizing root surfaces. Through biofilm formation and efficient nutrient uptake, it prevents pathogens from establishing themselves.

3. Induced Systemic Resistance (ISR)

B. subtilis can stimulate plant defense mechanisms through induced systemic resistance. When plant roots are colonized by the bacterium, signaling pathways involving jasmonic acid and ethylene are activated. This primes the plant to respond more quickly and effectively to pathogen attacks. Unlike direct chemical pesticides, ISR does not kill pathogens directly but enhances the plant's innate immune response. This leads to broad-spectrum and long-lasting protection.

4. Production of Plant Growth-Promoting Substances

B. subtilis produces phytohormones such as:

- Indole-3-acetic acid (IAA)
- Gibberellins
- Cytokinins

These hormones stimulate root elongation, cell division, and overall plant growth. Enhanced root systems improve nutrient and water uptake.

5. Nutrient Solubilization

Certain strains can solubilize phosphate and other minerals, converting them into forms accessible to plants. They also produce siderophores—iron-chelating compounds that facilitate iron uptake while limiting availability to pathogens.

6. Enzyme Production

The bacterium secretes enzymes such as chitinases, proteases and glucanases that degrade fungal cell walls. This enzymatic action further enhances its antifungal capabilities.

Role of *Bacillus subtilis* in Agriculture

The application of *Bacillus subtilis* in agriculture has gained momentum due to increasing concerns about chemical pesticide overuse and environmental sustainability.

1. Biological Control Agent

B. subtilis is widely used to manage plant diseases such as:

- Fusarium wilt

- Powdery mildew
- Root rot
- Leaf spot

Commercial formulations containing *B. subtilis* are applied as seed treatments, soil drenches, or foliar sprays. These biological products reduce reliance on synthetic fungicides.

2. Plant Growth Promotion

In addition to disease suppression, *B. subtilis* enhances crop productivity. Improved root development leads to better nutrient uptake and drought tolerance. Studies have shown increased yields in crops such as wheat, rice, maize, and vegetables when treated with *B. subtilis* formulations.

3. Soil Health Improvement

By participating in organic matter decomposition and nutrient cycling, *B. subtilis* contributes to soil fertility. Its enzymatic activities accelerate the breakdown of organic residues, releasing nutrients back into the soil.

4. Seed Treatment Applications

Coating seeds with *B. subtilis* spores protects seedlings from soil-borne pathogens during early growth stages. The endospore-forming ability ensures long shelf life and stability in commercial products.

5. Stress Tolerance Enhancement

Plants treated with *B. subtilis* often exhibit improved tolerance to abiotic stresses such as salinity, drought, and heavy metal contamination. This is attributed to improved antioxidant activity and hormonal balance in treated plants.

Formulation and Application Methods

The success of *Bacillus subtilis* in agriculture depends on effective formulation and delivery methods.

1. Powder Formulations

Spores are mixed with carriers such as talc or peat for easy application.

2. Liquid Formulations

Suspensions containing spores or vegetative cells are used for foliar sprays or soil application.

3. Granular Formulations

Granules are applied directly to soil, ensuring gradual release. The resilience of endospores makes *B. subtilis* suitable for storage and transportation without significant loss of viability.

Advantages over chemical pesticides

The shift toward microbial biocontrol agents such as *Bacillus subtilis* offers several advantages:

- Environmentally friendly
- Biodegradable
- Reduced chemical residues
- Minimal risk to non-target organisms
- Lower risk of pathogen resistance development

Unlike synthetic chemicals, biological agents integrate naturally into ecosystems and support sustainable agriculture.

Limitations and Challenges

Despite its advantages, certain challenges remain:

- Variable field performance due to environmental factors
- Sensitivity to ultraviolet radiation when applied as foliar sprays
- Requirement for proper storage and handling
- Regulatory approval processes

Research is ongoing to develop more stable and efficient strains through genetic improvement and advanced formulation techniques.

Future Prospects

The future of *Bacillus subtilis* in agriculture is promising. Advances in molecular biology and genomics are enabling scientists to identify genes responsible for beneficial traits. Genetic engineering and strain selection can enhance antibiotic production, stress tolerance, and colonization efficiency. Integration with sustainable farming practices such as organic agriculture, precision farming, and integrated pest management (IPM) will further expand its applications. Additionally, combining *B. subtilis* with other beneficial microbes may create synergistic effects.

Conclusion

The genus *Bacillus* comprises versatile and ecologically significant bacteria, among which *Bacillus subtilis* stands out as a model organism and valuable agricultural tool. Its ability to form endospores, produce antimicrobial compounds, promote plant growth and enhance soil health makes it an essential component of sustainable agriculture. Through mechanisms such as antibiosis, induced systemic resistance, nutrient solubilization and biofilm formation, *B. subtilis* offers environmentally friendly solutions to plant disease management and crop productivity enhancement. Although challenges exist in formulation and field performance, ongoing research and technological advancements continue to strengthen its role in modern agriculture. As global agriculture shifts toward eco-friendly and sustainable practices, *Bacillus subtilis* will undoubtedly remain at the forefront of biological innovation, contributing to food security and environmental conservation.

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