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Performance and Yield Increase in the Application of *Bacillus subtilis*: A Comprehensive Study

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The increasing demand for sustainable agricultural practices has led to the exploration of biological alternatives that not only enhance productivity but also restore soil health and ecological balance. *Bacillus subtilis*, a gram-positive rhizobacterium, is one such bio-inoculant that has gained prominence for its plant growth-promoting and biocontrol capabilities. Its ability to form endospores enables it to survive in harsh conditions, making it highly suitable for commercial bioformulations. This study explores in depth the impact of *B. subtilis* on crop performance and yield enhancement across different agro-climatic zones. Emphasis is placed on its biochemical and physiological modes of action—such as nutrient solubilization, phytohormone production, and induced systemic resistance (ISR). Field trial data from cereal, horticultural, and cash crops are critically analyzed, showing yield increments ranging from 15% to 40% depending on the crop, soil condition, and mode of application. This article presents not only the science behind the efficacy of *B. subtilis* but also its practical implications for organic and integrated farming systems worldwide.

Key words: Agriculture, Mode of Action, Yield , Crop performance ,*Bacillus subtilis*

Introduction

Modern agriculture is currently at a crossroads where the overuse of synthetic inputs has degraded soil health, polluted ecosystems, and led to pest resistance and yield stagnation. There is an urgent need to transition toward more sustainable and biologically-driven systems. Among the various microbial inputs available, Bacillus subtilis stands out as one of the most robust and versatile plant growth-promoting rhizobacteria (PGPR). *Bacillus subtilis* is widely distributed in soil, plant rhizospheres, and decaying organic matter. It is known for high tolerance to heat and desiccation due to spore formation, competitive colonization of the root surface, and multifaceted plant growth promotion, including nutrient uptake, disease suppression, and hormone modulation. Recent studies have documented that *B. subtilis* not only promotes early seed germination and vegetative growth but also contributes to flowering, fruit setting, and yield stability under biotic and abiotic stress. Unlike many other microbial agents, *B.subtilis* is compatible with a wide range of carriers and other biocontrol organisms, making it ideal for integrated nutrient and pest management strategies. The broad-spectrum antifungal and antibacterial activity, especially through lipopeptide production, also makes it a cornerstone of bio-based plant protection systems.

Biological Properties and Mechanisms of *Bacillus subtilis*

Bacillus subtilis demonstrates multiple plant-beneficial properties:

Spore Formation: Ensures long-term viability in formulations.

Rhizosphere Colonization: Promotes strong plant-microbe interaction.

Mechanisms of Action:
Antibiosis: Produces lipopeptides (surfactin, iturin, fengycin).
Enzyme Production: Chitinase, cellulase, protease attack pathogens.
Induced Systemic Resistance (ISR): Triggers plant defense.
Nutrient Solubilization: Improves phosphorus and potassium availability.

Application Methods
Seed Treatment: Enhances early root colonization.
Soil Drenching: Boosts microbial activity in rhizosphere.
Foliar Spray: Used for disease protection.
Compost Enrichment: Enhances compost quality and soil fertility.

Performance of *Bacillus subtilis* in Different Cropping Systems
The application of *Bacillus subtilis* has shown consistent performance in improving crop productivity through various mechanisms. The performance varies with crop species, mode of application, and local agroecological conditions.
1. Vegetable Crops: Tomato trials reported 20–35% yield increase with reduced Fusarium wilt. Brinjal and chili saw 22–33% improvements in yield and disease suppression.
2. Cereal Crops: Rice trials showed 15–25% improvement in panicle development and nitrogen-use efficiency. Wheat saw up to 20% improvement in shoot biomass and disease resistance.
3. Horticultural Crops: Banana and grapes benefited from better nutrient uptake and disease resistance with yield increases of 25–40%.
4. Pulses and Oilseeds: Groundnut and soybean showed 15–20% increase due to better nodulation and root health.
5. Soil Health: Long-term application increased microbial biomass, enzyme activity, and soil organic carbon.
6. Abiotic Stress Management: In drought areas, ***B. subtilis*** helped plants maintain water content and stomatal function.

Yield Improvement Mechanisms
Enhanced Root Development: Improves nutrient and water uptake.
Disease Suppression: Reduces pathogen attack, improves plant health.
Improved Soil Health: Boosts microbial biomass and enzymatic activity.
Hormonal Stimulation: Increases auxin and cytokinin levels.

Compatibility with Other Inputs
Bacillus subtilis is compatible with:
Organic manures (FYM, vermicompost)
Other biocontrol agents (e.g., Trichoderma spp., Pseudomonas fluorescens)
Low-dose fertilizers and biopesticides for integrated pest/nutrient management.

Challenges and Limitations
Shelf Life: Liquid formulations need stabilizers.
Environmental Sensitivity: Soil pH and temperature can affect efficiency.
Awareness Gaps: Farmer education and field trials are crucial for widespread adoption.

Future Prospects and Innovations
Nano-Formulations: Better delivery and longevity.
Genetic Engineering: Custom strains for specific crops.
AI and Precision Agriculture: Targeted use based on crop-soil profiles.
Policy Support: Government subsidies and training for bio-inoculants.

Conclusion
The use of *Bacillus subtilis* as a bio-inoculants represents a pivotal advancement in the realm of eco-friendly and sustainable crop production. Its proven role in enhancing plant health,

yield, and resistance to both biotic and a-biotic stresses underlines its significance in future farming systems. Notably, the yield improvements seen across diverse crop groups and geographies are not isolated instances but outcomes of well-documented biological mechanisms. Moreover, the commercial formulations of *B.subtilis* are increasingly available and easy to apply, making them accessible to both smallholders and large-scale farmers. As we transition into climate-resilient agriculture, *B. subtilis* holds promise not only as a yield booster but also as a vital component of soil and plant health restoration programs. Greater efforts must be directed toward awareness, training, and integration into national bio-fertilizer programs. The incorporation of *Bacillus subtilis* into mainstream agriculture is not just a choice—it is a necessity for achieving productivity and environmental balance.

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