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Bacillus subtilis: A Boom for Plant Health

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Agriculture today stands at a pivotal crossroads with global food demand rising due to population growth and shifting diets (Mahapatra *et al*., 2022; Kumar *et al*. 2024). On one hand, the longstanding reliance on chemical pesticides and synthetic inputs has intensified crop yields but raised serious sustainability concerns. Extensive use of chemical pesticides has been linked to soil degradation, biodiversity loss, contamination of water and food chains and adverse effects on human health (Kumar *et al*. 2024; Bhanushankar *et al*. 2025). These impacts underscore the urgent need for eco-friendly and sustainable alternatives in crop protection and productivity enhancement (Mahapatra *et al*., 2022).

In this context, the soil-inhabiting bacterium *B. subtilis* emerges as a powerful ally for sustainable agriculture (Hashem *et al*., 2019). A Gram-positive, endospore forming rhizobacterium, *B. subtilis* is well adapted to survive under variable soil conditions, making it an ideal candidate for field application (Hashem *et al*., 2019; Mahapatra *et al*., 2022). Recent advances highlights its multifaceted role in plant health, disease suppression, plant growth promotion and induction of systemic resistance (ISR) in plants (Kloepper *et al*., 2004; Hashem *et al*., 2019). Its eco-friendly and non toxic nature, compatibility with beneficial soil microorganisms and ability to reduce dependency on chemical inputs position *B. subtilis* as a cornerstone for sustainable crop protection and productivity enhancement (Mahapatra *et al*., 2022; Hashem *et al*., 2019).

Taxonomy and Characteristics of *B. subtilis*

Domain: Bacteria

Phylum: Firmicutes

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *B. subtilis*

B. subtilis is a Gram-positive bacterium first described by Ehrenberg in 1835 and later renamed by Cohn in 1872. This bacterium is rod shaped, measuring approximately 0.7–0.8 µm in diameter and 2–3 µm in length. Cells are motile due to peritrichous flagella and typically occur singly or in pairs. *B. subtilis* is capable of forming ellipsoidal to cylindrical endospores, which are centrally or subcentrally located within the cell (Blanco Crivelli *et al*., 2024). *B. subtilis* is ubiquitously found in soil, the rhizosphere and decomposing organic matter. It also inhabits the gastrointestinal tracts of humans and animals, contributing to its widespread distribution (Akinsemolu *et al*., 2024). *B. subtilis* forms highly resistant endospores, enabling survival under extreme conditions such as desiccation, UV radiation and high temperatures. It shows remarkable resilience to stresses like nutrient deprivation and disinfectants, allowing persistence in diverse environments. Additionally, it produces various secondary metabolites, including lipopeptides such as surfactin, iturin, and fengycin, which exhibit strong antimicrobial activity and enhance its biocontrol potential (Zhang *et al*., 2023).

Mechanisms of Action

B. subtilis is a versatile plant growth promoting rhizobacterium (PGPR) that enhances plant health through multifaceted mechanisms, categorized into direct and indirect modes of action.

- **Antagonism against plant pathogens**

  B. subtilis combats plant pathogens by producing antimicrobial compounds such as lipopeptides (surfactin, iturin, fengycin), which disrupt pathogen cell membranes and inhibit spore germination. These compounds exhibit broad-spectrum activity against fungi like *Fusarium*, *Rhizoctonia*, *Alternaria* and *Sclerotium* species (Zhang *et al*., 2023).

- **Competition for nutrients and space**

  By effectively colonizing plant roots, *B. subtilis* outcompetes pathogens for space and resources. It produces siderophores that sequester iron, depriving pathogens of this essential nutrient and thereby inhibiting their growth (Blake *et al*., 2021).

- **Induced systemic resistance (ISR)**

  B. subtilis triggers systemic plant defenses by inducing the expression of defense related enzymes such as peroxidase, chitinase and β-1,3-glucanase. This priming effect enhances the plant's resistance to a wide range of pathogens, both fungal and bacterial (Hashem *et al*., 2019).

- **Plant growth promotion**

  B. subtilis promotes plant growth through various mechanisms, including the production of phytohormones like indole-3-acetic acid (IAA) and gibberellins, which stimulate root development and overall plant vigor. Additionally, it solubilizes phosphates and enhances nutrient uptake, further supporting plant growth (Tsotetsi *et al*., 2022).

Methods of application of ***B. subtilis in agriculture***

B. subtilis is utilized in agriculture through various application methods, each tailored to specific crop needs and environmental conditions:

- **Seed treatment:** Coating seeds with *B. subtilis* before sowing enhances early plant growth and provides protection against seedborne pathogens. This method ensures direct contact between the bacterium and emerging seedlings, facilitating effective colonization and disease suppression (Ocwa *et al*., 2024).
- **Soil application:** Soil drenching or incorporation of *B. subtilis* into compost or carrier based inoculants introduces the bacterium to the rhizosphere, promoting root colonization and competition against soil borne pathogens. Regular applications can maintain beneficial microbial populations in the soil (Mahapatra *et al*., 2022).
- **Foliar spray:** Applying *B. subtilis* as a foliar spray involves suspending the bacterium in water and spraying onto plant leaves. This method is effective against foliar pathogens and can be used preventively or curatively. Reapplication every 7–10 days ensures sustained protection (Santos *et al*., 2022).

Compatibility of ***B. subtilis*** **with other biocontrol agents**

B. subtilis demonstrates excellent compatibility with various biocontrol agents, enhancing its efficacy in integrated disease management strategies.

- **With** ***Trichoderma*** **spp.**: Studies have shown that combining *B. subtilis* with *Trichoderma* species, such as *T. harzianum*, results in synergistic effects, enhancing plant growth and disease suppression. This combination leverages the complementary mechanisms of action of both organisms, leading to more effective biocontrol (Silva *et al*., 2023).
- **With** ***Pseudomonas*** **spp.**: Co-inoculation of *B. subtilis* with *Pseudomonas fluorescens* has been reported to improve disease resistance and promote plant growth. This synergistic interaction is attributed to the combined production of antimicrobial compounds and the enhancement of plant defense mechanisms (Shukla *et al*., 2022).

Compatibility of ***B. subtilis*** **with fungicides**

B. subtilis exhibits broad compatibility with several commonly used fungicides, allowing it to function effectively within integrated disease management programs without compromising its biological activity.

- **With contact fungicides**

  Studies show that *B. subtilis* is tolerant to a range of contact fungicides like carbendazim and mancozeb when tested under laboratory conditions, indicating compatibility at recommended field concentrations. This tolerance allows the bacterium to survive alongside these chemicals and maintain its biocontrol activity when integrated into disease management approaches. For example, *B. subtilis* strains displayed growth in media amended with carbendazim, hexaconazole, and other contact fungicides, suggesting their use together can be feasible in integrated disease management systems (Basamma and Kulkarni, 2017).

❖ **With systemic fungicides**

Studies on the interaction between *B. subtilis* and systemic fungicides such as tebuconazole show that compatibility is dependent on application rates and timing. Research found that low rates of tebuconazole can actually promote *B. subtilis* colonization and biofilm formation, leading to enhanced disease suppression, while higher rates may reduce bacterial performance (Lui *et al*., 2023).

Role of *B. subtilis* in disease management

B. subtilis serves as an effective biocontrol agent against various plant pathogens, enhancing crop health and yield.

❖ **Fusarium wilt**

- Tomato: *B. subtilis* has demonstrated significant efficacy in controlling Fusarium wilt in tomatoes. *B. subtilis* treatment improved plant growth and reduced disease severity in tomatoes infected with *Fusarium oxysporum* (Abd-Allah *et al*., 2007).
- Banana: In banana cultivation, *B. subtilis* application has been reported to suppress Fusarium wilt, enhancing plant health and fruit yield (Zhang *et al*., 2014).
- Pigeonpea: *B. subtilis* effectively managed Fusarium wilt in pigeonpea, promoting plant growth and reducing disease incidence (Reddy *et al*., 2024).

❖ **Alternaria Blight**

- Potato and Tomato: *B. subtilis* has shown potential in controlling Alternaria blight in both potato and tomato plants. *B. subtilis* effectively suppressed *Alternaria solani*, the causative agent of early blight in these crops (Irmawatie *et al*., 2025).

❖ **Sheath blight**

- Rice: *B. subtilis* strain RH5 exhibited significant antagonistic activity against *Rhizoctonia solani*, a pathogen causing sheath blight in rice. The application of this strain improved plant growth and triggered resistance in rice plants (Jamali *et al*., 2020).

❖ **Stem rot**

- Sunflower and Mustard: *B. subtilis* strain RSS-1 has been identified as a potential biological agent for controlling Sclerotinia stem rot caused by *Sclerotinia sclerotiorum* in oilseed crops like sunflower and mustard (Cao *et al*., 2023).

Advantages of *B. subtilis* in agriculture

❖ **Environmentally safe:** *B. subtilis* is non-toxic to humans, animals, and beneficial insects, making it a safe alternative to chemical pesticides (Miljaković *et al*., 2020).

- **Multiple modes of action:** It employs various mechanisms, including antibiotic production, competition for nutrients and induction of plant systemic resistance, to suppress a wide range of pathogens (Etesami *et al*., 2023).
- **Compatibility with other biocontrol agents:** *B. subtilis* can be effectively combined with other beneficial microbes, such as *Trichoderma* spp. and *Pseudomonas* spp. enhancing integrated disease management and promoting sustainable agriculture (Silva *et al*., 2023).

Limitations of *B. subtilis* in agriculture

- **Shelf life and storage issues**: While endospores are durable, the viability of *B. subtilis* can decline over time, necessitating proper storage conditions (Bonaterra *et al*., 2012).
- **Variability under field conditions:** Environmental factors such as soil pH, temperature and moisture can affect the efficacy of bacteria, leading to inconsistent performance (Bonaterra *et al*., 2012).
- **Sensitivity to high temperature and ultraviolet light:** Despite endospore formation, *B. subtilis* can be sensitive to extreme temperatures and ultraviolet light, which may reduce its effectiveness (Bonaterra *et al*., 2012).

Future prospects

B. subtilis holds great promise for sustainable agriculture, yet further research and innovation are essential to fully harness its potential. Genetic improvement of strains to enhance production of antimicrobial and plant growth-promoting metabolites can boost biocontrol efficacy. Developing multi-strain consortia with beneficial microbes like *Trichoderma* and *Pseudomonas* offers synergistic effects for disease suppression and crop growth. Nano formulations can improve shelf life, stability and field performance. Integration into climate smart and precision agriculture can help crops tolerate abiotic stresses while reducing chemical inputs. Additionally, policy support, awareness programs and farmer training are crucial for proper application and maximizing benefits.

Conclusion

B. subtilis is a versatile and promising biological agent with significant potential in sustainable agriculture. Its multifaceted role in suppressing a wide range of plant pathogens, enhancing nutrient uptake, and promoting overall plant growth makes it an indispensable tool for eco-friendly crop management. By reducing reliance on chemical pesticides and supporting soil and plant health, *B. subtilis* contributes directly to environmental protection and long-term agricultural sustainability. The continued development and application of such biological solutions are vital for achieving resilient, productive and climate-smart farming systems. Moreover, the integration of *B. subtilis* into modern agricultural practices can complement other sustainable approaches, including organic farming, precision agriculture and integrated pest management. With ongoing research focusing on strain improvement, formulation stability and synergistic combinations with other beneficial microbes, the efficacy of *B. subtilis* is expected to increase further. Adoption of this bioagent not only enhances crop yield and quality but also fosters ecosystem health, supporting the goal of sustainable food security. Ultimately, embracing *B. subtilis* and similar biological tools represents a forward looking strategy for agriculture, balancing productivity with environmental stewardship and resilience to future challenges.

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