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Bacillus subtilis and its role in biological control of plant pathogens

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Abstract

Objective

The increasing request for sustainable agriculture and reduced chemical pesticide apply has driven interest in eco-friendly alternatives to control plant pathogens. Among biological agents, *Bacillus subtilis* has emerged as a hopeful biocontrol agent due to its diverse mechanisms of action, containing antibiotic production, induction of systemic resistance in plants, and plant growth promotion. This review aims to examine the biological and ecological characteristics of *B. subtilis*, its mechanisms in suppressing plant pathogens, and summarize recent research on its effectiveness as a biocontrol agent.

Materials and methods

This review synthesized results from a broad range of peer-reviewed investigations, field experiments, and laboratory trials centralized on the applying of *B. subtilis* against fungal, bacterial, and viral plant pathogens. Key mechanisms of action were analyzed, containing rhizosphere colonization, antibiotic production, induction of systemic resistance (ISR), and growth-promoting traits. Specific case investigations and commercial applications were reviewed to prepare a comprehensive perspective on the organism's potential and limitations in integrated pest management programs.

Results

Bacillus subtilis demonstrated high effectiveness in suppressing major plant pathogens like *Fusarium spp.*, *Rhizoctonia solani*, *Phytophthora infestans*, and *Ralstonia solanacearum* through multiple synergistic mechanisms. The bacterium generates over 66 known antibiotics (e.g., surfactin, fengycin, subtilin), hydrolytic enzymes like chitinase and β-1,3-glucanase, and forms robust biofilms in the rhizosphere, enhancing its colonization capability. ISR triggered by *B. subtilis* involves improved expression of defense-related enzymes and hormone pathways, notably jasmonic acid and ethylene. Furthermore, *B. subtilis* enhances nutrient uptake, nitrogen fixation, and stress resilience in plants. Field investigations and commercial formulations (e.g., Kodiak, Serenade, Subtilex) affirm its effectiveness under varied environmental conditions. The reviewed evidence supports its broad-spectrum antifungal and plant growth-promoting effects.

Conclusions

Bacillus subtilis shows a powerful, environmentally safe tool for the biological control of plant pathogens and the enhancement of crop productivity. Its multifaceted role in disease suppression, plant defense activation, and soil health improvement positions it as a key component of sustainable agriculture. Adoption of *B. subtilis*-based biocontrol products aligns with global goals for reducing chemical pesticide reliance, promoting organic farming, and achieving long-term agricultural sustainability without adverse ecological or health effects.

Key words: antibiotics, *Bacillus subtilis*, biological control, pathogens, plant diseases

Paper Type: Review Paper.

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Introduction

Soil microorganisms play a fundamental role in the decomposition of organic matter, nutrient cycling, and the improvement of soil fertility. They facilitate the breakdown of dead plant and animal tissues, releasing essential nutrients and minerals back into the soil, thereby enhancing its productivity and supporting sustainable plant growth. In addition to natural organic matter, certain microbial communities are capable of degrading industrial waste and pollutants, making these nutrients available to plants and reducing the harmful effects of environmental contamination. Furthermore, these microorganisms contribute to soil structure by decomposing complex soil particles, increasing aeration, enhancing water retention, and promoting root development (Alabouvette et al., 2006; Hashem et al., 2019). Understanding the ecological and functional roles of soil microorganisms, exclusively bacteria has opened new avenues for sustainable pest and disease management in agriculture. Among the most meaningful breakthroughs in this area is the utilization of beneficial microorganisms for the biological control of plant pathogens. Numerous investigations have highlighted the effectiveness of bacteria exist in the rhizosphere, the soil region directly influenced by root secretions and related microbial communities, in suppressing soilborne plant diseases (Johansson et al., 2003). Crawford et al. (1993) were among the early researchers to demonstrate the superior capability of rhizosphere bacteria to biologically control root pathogens in numerous crop species. Bacteria represent the most abundant and diverse group of microorganisms in the soil ecosystem. They surpass fungi, protozoa, and algae in both abundance and metabolic versatility (Matloob, 2019; Matloob and Al-Baldawi, 2020). It is estimated that a single gram of soil may contain up to 6×10^8 bacterial cells, representing almost half the total microbial biomass in the soil. The population density and diversity of soil bacteria are influenced by different factors, containing soil type, organic matter content, moisture, temperature, aeration, root density, and agricultural practices like tillage and fertilization (Brill, 1981; Mahaffee and Kloeber, 1997). One of the most hopeful bacterial species in biological control is *Bacillus subtilis*, a Gram-positive, spore-forming bacterium broadly distributed in numerous environments, containing soil, water, and decaying organic matter. *B. subtilis* has demonstrated remarkable effectiveness in controlling a broad spectrum of fungal and bacterial pathogens, owing to its capability to generate an array of antimicrobial compounds, containing lipopeptides, antibiotics, and enzymes. It also enhances plant defenses by inducing systemic resistance (ISR) and acts as a plant growth-promoting rhizobacterium (PGPR), contributing to improved nutrient uptake and plant vigor (Yao et al., 2006; Alshawi et al., 2024). The historical significance of *Bacillus subtilis* dates back to 1835 when Ehrenberg first named it *Vibrio subtilis* (Snaith, 1986). Later, in 1872, Ferdinand Cohn reclassified and renamed it *Bacillus subtilis*. This bacterium is relatively easy to isolate and cultivate under laboratory conditions, and its cells typically appear as single rods or chains with endospores visible under microscopic examination. The presence of a robust peptidoglycan-based cell wall gives *B. subtilis* structural integrity and resilience, while its spore-forming capability enables survival under harsh environmental conditions (Schleifer and Kandler, 1972; Navarre and Schneewind, 1999). The utility of *B. subtilis* in biocontrol strategies stems from its capability to adapt to diverse and often unfavorable soil conditions. Its spores can withstand desiccation, high salinity, and temperature extremes, making it a suitable candidate for commercial formulation and long-term storage (Zhang et al., 2023). Furthermore, *B. subtilis* rapidly colonizes the rhizosphere, forming biofilms on root surfaces, which play a crucial role in excluding pathogenic microorganisms and enhancing nutrient availability (Akinsemolu et al., 2023). Given the increasing challenges posed by pesticide-resistant pathogens and the global push towards sustainable and eco-friendly agricultural practices, biological control agents like *Bacillus subtilis* are gaining meaningful attention. However, in spite of its proven effectiveness and commercial success in some products, comprehensive understanding and documentation of *B. subtilis*'s mechanisms of action, strain-specific effects, and application methods stay areas of active research (Khan et al., 2022). This review aims to prepare an in-depth analysis of *Bacillus subtilis* as a biological control agent. It will investigate its taxonomy, physiological characteristics, ecological roles, mechanisms of pathogen suppression, and plant growth promotion. Furthermore, the review highlights the latest research results and applications of *B. subtilis* in modern agriculture, with a centralizing on its effectiveness in reducing plant disease incidence and enhancing crop productivity (Etesami et al., 2023). By consolidating current knowledge, this review seeks to promote the wider adoption of *B. subtilis* in integrated pest management systems and contribute to the development of sustainable agriculture.

Characteristics and environment of *Bacillus subtilis*

Bacillus subtilis is a well-described, Gram-positive bacterium belonging to the phylum Bacillota, class Bacilli, order Bacillales, and family Bacillaceae. It is ubiquitously distributed in natural environments, containing soil, water, air, and decomposing plant material. As a free-living saprophyte, *B. subtilis* thrives in a broad range of ecological niches, exclusively in the rhizosphere, where it plays a pivotal role in nutrient cycling and soil health. This bacterium exhibits optimal growth at mesophilic temperatures, with a preferred range of 25–35°C, although it can survive and grow in conditions spanning 15 to 50°C. Although *B. subtilis* is primarily aerobic, it is facultatively anaerobic under certain conditions, allowing it to persist in varying oxygen concentrations. One of its distinguishing features is its remarkable adaptability to extreme environmental stressors, containing drought, salinity, and temperature fluctuations, which contributes to its ecological success and utility in agricultural applications. Morphologically, *B. subtilis* is a rod-shaped bacterium, typically calculating 2-6 µm in length and less than 1 µm in diameter (Gao et al., 2011). Under favorable conditions, its doubling time is notably short, often less than 20 minutes, making it one of the fastest-growing soil bacteria. Through nutrient-rich growth phases, cells may appear singly or in chains due to incomplete separation after cell division. The bacterium is motile, propelled by peritrichous (peripheral) flagella that facilitate its movement through soil and rhizosphere environments (Morikawa, 2006; van Dijl & Hecker, 2013; Errington & Art, 2020; Cui et al., 2025). A defining characteristic of *B. subtilis* is its capability to form endospores, highly resistant, dormant structures that enable survival under

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adverse environmental conditions like desiccation, high temperatures, UV radiation, and nutrient scarcity. This endospore-forming capacity not only ensures long-term persistence in the environment but also enhances its commercial applicability. Spores maintain viability through storage and formulation processes, making *B. subtilis* an ideal candidate for apply in seed treatments, foliar sprays, and soil amendments in sustainable agriculture (Khan et al., 2022). In culture, *B. subtilis* colonies display distinct morphological features. When grown on solid media, the colonies are typically large, round, opaque, and irregularly wrinkled. The pigmentation may vary from cream to gray, yellow, brown, or orange, often forming a granular or mucoid texture depending on the medium and environmental conditions. These physical traits are not only species-specific but also influenced by sporulation and biofilm formation stages (Akinsemolu et al., 2023). Biochemically, *B. subtilis* exhibits different enzymatic capabilities that enhance its ecological function and biocontrol potential (Zhang et al., 2023). It can hydrolyze complex macromolecules like starch, gelatin, and casein, thereby contributing to the degradation of organic matter in soil ecosystems. Jones (1983) highlighted the organism's high capacity for sporulation and its capability to grow in environments containing up to 7% sodium chloride, reflecting its halotolerant nature. The structural features of *B. subtilis* also include a robust cell wall composed of thick peptidoglycan layers, which confer mechanical strength and resistance to osmotic stress. This cell wall also plays a crucial role in determining Gram staining characteristics and in species identification through microbiological assays. Additionally, cell surface properties, containing exopolysaccharide production and biofilm-forming capability, are essential for root colonization and interactions with both host plants and microbial competitors (Akinsemolu et al., 2023). Overall, *Bacillus subtilis* is a highly adaptable, metabolically versatile, and environmentally resilient bacterium. Its physiological traits, like rapid growth, spore formation, enzymatic activity, and stress tolerance, make it exclusively well-suited for application in biological control and plant growth promotion strategies. These properties underscore its growing importance as a model organism in microbial ecology, industrial biotechnology, and sustainable agriculture.

Biological control applying *Bacillus subtilis*

Bacillus subtilis is a dynamic organism that both influences and is influenced by its surrounding environment. In the context of plant diseases, three core components are generally distinguished: the plant host, the pathogen, and environmental conditions. The introduction of biological control agents, like *B. subtilis*, can effectively modulate this disease triangle by directly or indirectly interacting with each of these components (Etesami et al., 2023). Biological agents impact the host plant by promoting growth, enhancing nutrient availability, and triggering defense mechanisms like induced systemic resistance (ISR). They affect pathogens by competing for space and resources, secreting antibiotics and lytic enzymes, and disrupting pathogen growth and metabolism. Furthermore, they contribute to the broader ecosystem by decomposing organic residues, mineralizing nutrients, forming humus, and recycling essential elements, thereby improving overall soil health (Hemalath and Shanthi, 2010). These multifaceted roles make *B. subtilis* an ideal candidate for incorporation into integrated and ecologically sound biological control strategies. When properly implemented, *B. subtilis*-based programs can meaningfully reduce the incidence and severity of plant diseases while simultaneously enhancing crop growth, resilience, and yield (Wang et al., 2018). Species within the *Bacillus* genus are among the most effective rhizosphere-associated biocontrol agents against a broad spectrum of plant pathogens, especially soilborne fungi (Zhang et al., 2023). When a plant is attacked by pathogens, it tries to absorb the biocontrol agents of Bacillus. In such cases, the plant roots can do this in two ways. In the first method, which is the active method, they start secreting special signals, like malic acid and citric acid, to attract the biocontrol Bacillus species. In the second method, which is the passive method, they start secreting polysaccharides, like pectin and xylan, to attract the biocontrol Bacillus species. In these two ways, the plant induces chemotaxis and biofilm formation and attracts the biocontrol Bacillus species. This reaction is known as the "cry for help" mechanism and is carried out to improve the plant's resistance to pathogens and also to form a soil that suppresses the disease created by the pathogen (Figure 1). Many strains generate a diverse array of antimicrobial compounds, which prevent pathogen growth and suppress disease development. Additionally, their presence in the rhizosphere stimulates plant growth, improves nutrient uptake, and contributes to both qualitative and quantitative yield improves (Kinsella et al., 2009). Investigations by Rooney et al. (2009) and Alina et al. (2015) demonstrated that specific strains of *Bacillus*, containing *B. subtilis*, *B. cereus*, *B. megaterium*, *B. circulans*, and *B. brevis*, are capable of inducing resistance responses in numerous plant species. These bacteria exhibit different desirable traits for biocontrol applications, like adaptability to diverse environmental conditions, rhizosphere colonization capacity, and competition with phytopathogens for ecological niches and nutrients (Zhang et al., 2023). Resistance induced by *B. subtilis* arises from its secretion of numerous bioactive substances, containing antibiotics, volatile organic compounds, and extracellular hydrolytic enzymes. These compounds interfere with pathogen development by degrading cell walls, disrupting metabolic pathways, and preventing spore germination. Notably, *B. subtilis* generates over 66 different antibiotics, many of peptide origin, like bacillicin, subtilin, mycosubtilin, eomycin, sapsporin, nucidin, toximycin, and bacitracin (Akhtar, 2010; Sorokulova, 2013). In addition, it secretes chitinases and β-1,3-glucanases, enzymes that degrade fungal cell walls and prevent fungal colonization.

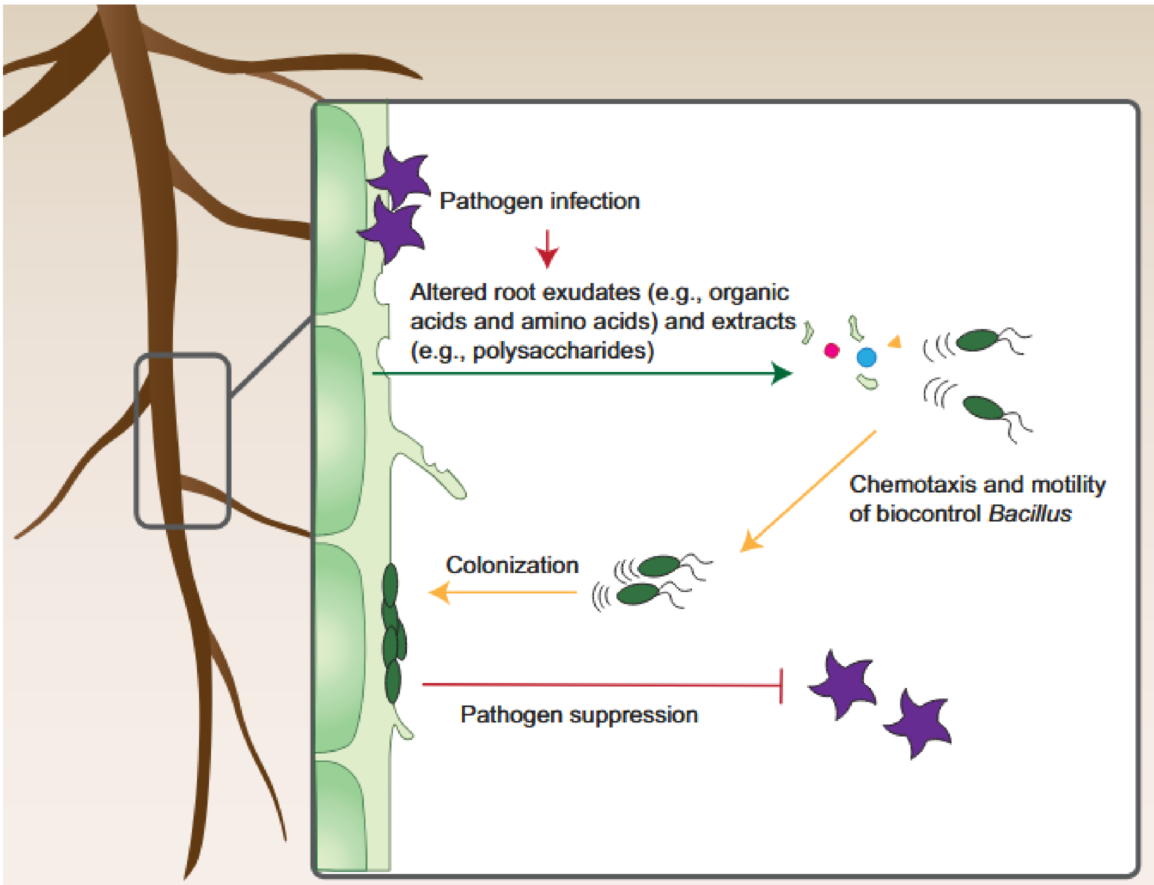

Figure 1. Two active and passive ways of plants in the face of pathogens to attract biocontrol Bacillus species (Zhang et al., 2023)

The effectiveness of *B. subtilis* in managing plant diseases has been well-documented, exclusively against soilborne pathogens like *Rhizoctonia solani* and *Fusarium solani*. Numerous investigations have highlighted the effectiveness of numerous *Bacillus* strains; containing *B. subtilis*, *B. pasteurii*, *B. cereus*, *B. pumilus*, *B. amyloliquefaciens*, *B. globisporus*, and *B. anilovibrioquefaciens* in reducing disease incidence and severity in greenhouse and field conditions. These outcomes are often linked to their capability to induce systemic resistance (ISR) in plants (Etesami et al., 2023).

Resistance-inducing compounds like lipopeptides (e.g., surfactin, fengycin, iturin) are exclusively effective in triggering defense responses. For instance, the S499 strain of *B. subtilis* is capable of producing these metabolites, which have been shown to meaningfully improve lipoxygenase activity in treated tomato plants. This enzyme is a known marker of plant defense responses, suggesting a clear role for these bacterial metabolites in disease suppression (Alina et al., 2015). It is important to note that the success of *B. subtilis* as a biocontrol agent depends on multiple factors, containing strain specificity, pathogen type, host plant species, environmental conditions, and the method and timing of application. Understanding these variables is essential for optimizing its effectiveness in real-world agricultural settings. The main mechanisms of action employed by *B. subtilis* in biological control will be discussed in detail in the following subsections.

Competition through colonization of the rhizosphere by *Bacillus subtilis:* The rhizosphere, the narrow zone of soil influenced by root exudates, is a dynamic environment inhabited by a complex community of microorganisms. These include bacteria that colonize the root surface, dead epidermal cells, root hairs, and surrounding soil particles. Among these, *Bacillus subtilis* stands out due to its exceptional adaptability and colonization efficiency. It utilizes root exudates like sugars, organic acids, and amino acids secreted by plants as nutrient sources for growth and establishment (Zhang et al., 2002). Successful colonization of the rhizosphere by *B. subtilis* needs a thin moisture film on the root surface, which facilitates bacterial motility and biofilm formation (Compant et al., 2005). Once established, *B. subtilis* can form robust biofilms, complex communities of cells encased in an extracellular matrix, on root surfaces. These biofilms prepare a protective barrier that supports long-term colonization and enhances resistance to environmental fluctuations and microbial competition (Akinsemolu et al., 2023). Bacillus shows strong biofilm formation capabilities (Figure 2) as well as the production of numerous enzymes for production purposes. The biological control potential of *B. subtilis* is often mediated indirectly through its presence and activity within the rhizosphere ecosystem. These indirect mechanisms include competition with phytopathogens for space and nutrients, the establishment of protective biofilms, and the stimulation of plant growth and immunity. The bacterium can also enhance plant resilience by triggering induced systemic resistance (ISR) and facilitating nutrient acquisition, exclusively nitrogen and phosphorus (Hashem et al., 2019).

Abdelaziz et al. (2023) emphasized that microbial competition in the rhizosphere primarily revolves around the availability of root exudates and essential nutrients. Since both pathogens and beneficial microbes rely on these restricted resources, early and effective colonization by *B. subtilis* can exclude pathogens from the root zone by occupying ecological niches and depleting shared nutrient pools. Furthermore, inoculating plant roots with *B. subtilis* or other plant growth-promoting rhizobacteria (PGPR) acts as a prophylactic plan. This practice prevents pathogen establishment by preemptively saturating the root environment with beneficial microbes. The

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displacement of pathogens from the rhizoplane (root surface) reduces their access to host tissues and lowers the probability of infection. Therefore, *B. subtilis* not only protects plants through the production of antimicrobial compounds but also plays a vital role in rhizosphere colonization and resource-based competition, which forms the first line of defense against many soilborne pathogens (Risanti et al., 2025).

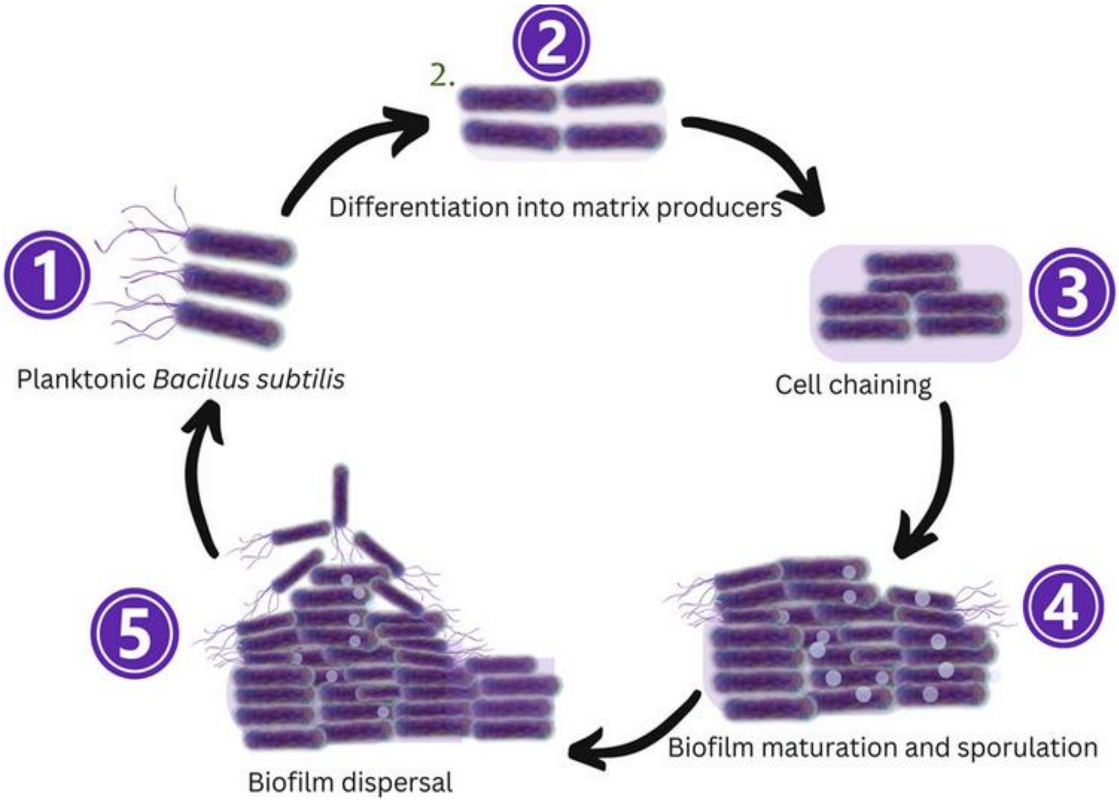

Figure 2. How Bacillus subtilis forms biofilms (Akinsemolu et al., 2023)

Formation of antibiotic metabolites: The capability of *Bacillus subtilis* to generate a diverse array of antibiotic metabolites has been a major factor in its success as a biocontrol agent in agriculture. This property was first documented in 1974, when researchers observed that certain *B. subtilis* strains secreted antimicrobial compounds capable of preventing soilborne plant pathogens. These antibiotics are now distinguished as key components of the bacterium's antagonistic activity, exclusively in the suppression of fungal and bacterial pathogens in the rhizosphere (Kai, 2020). In a seminal investigation examining the behavior of *B. subtilis* in the rhizosphere, Bochow and Gantcheva (1995) demonstrated that seed and soil treatments with *B. subtilis* enhanced root colonization and protected developing roots for up to two months. This protection was attributed to both the production of antibiotic compounds and the induction of systemic resistance (ISR) within the host plant. Treated plants exhibited enhanced growth and greater resistance to soilborne pathogens compared to untreated controls. Among the broad variety of antibiotics synthesized by *B. subtilis*, different have been shown to possess strong antifungal properties. These include subtilin, subtinolene, bacillomycin, bacillin, and bacitracin, which are especially effective against *Rhizoctonia solani*, the causal agent of tomato seedling damping-off disease. Experimental investigations have revealed that these antibiotics can create severe damage to fungal hyphae, containing cytoplasmic leakage and tip distortion when grown on PDA media (Asaka and Shoda, 1996; Montealegre et al., 2003). Additionally, the antifungal metabolites generated by *B. subtilis* have demonstrated meaningful inhibitory effects against *R. solani* in maize, helping to control seedling blight and improving overall plant survival rates (Muhammad and Amusa, 2003). The bacterium's metabolic arsenal includes a broad range of antimicrobial peptides and polyketides, many of which are non-ribosomally synthesized. Notable examples include plantazolicin, subtilosin, subtilin, irisin, mercacidin, amylysin, and amycyclin—each of which targets different microbial structures and functions (Arguelles Arias et al., 2013). The complexity and potency of these secondary metabolites not only prevent pathogen growth but also contribute to the suppression of pathogen populations in the soil, reducing the incidence and severity of disease outbreaks. These results emphasize the importance of *B. subtilis* in biological control strategies, exclusively in sustainable and organic agricultural systems where chemical fungicides are restricted or avoided (Etesami et al., 2023).

Plant resistance induced by *Bacillus subtilis*: All plants possess intrinsic defense mechanisms to protect themselves against a broad range of pathogens. These defenses can be innate or activated in response to environmental stimuli, containing microbial interactions. One of the most meaningful adaptive strategies plants employ is induced resistance, which enhances their defensive capacity following exposure to specific non-pathogenic microorganisms or stimuli. This phenomenon results in reduced susceptibility to subsequent pathogen attacks, without necessitating any genetic alters in the pathogen itself (Garcia et al., 2001). Induced resistance can be triggered by biotic factors like beneficial microbes, or by abiotic inducers like salicylic acid (SA) and other signaling molecules. Among biocontrol agents, *Bacillus subtilis* has been broadly studied for its capacity to induce systemic resistance (ISR) in plants. This form of resistance is exclusively effective against biotrophic fungal pathogens, containing those responsible for powdery mildew, downy mildew, and late blight created by *Phytophthora infestans*. Unlike direct antagonism, ISR functions by priming the plant's immune system, leading to a faster and stronger defense response upon pathogen attack. One of the hallmarks of ISR is the accumulation of pathogenesis-related (PR) proteins, which are synthesized by the plant in response to microbial interaction or environmental stress. These include enzymes like β-1,3-

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glucanases and chitinases, which play crucial roles in degrading fungal cell walls, thereby preventing pathogen development. Other PR proteins modulate signaling pathways or reinforce plant structural barriers. Research has shown that soil inoculation or foliar application of *B. subtilis* leads to improved expression of genes related to defense, containing those involved in signal transduction and transcriptional regulation (Zhou et al., 2000). ISR activation is often mediated by the jasmonic acid (JA) and ethylene signaling pathways, in contrast to salicylic acid-dependent systemic acquired resistance (SAR). Notably, *B. subtilis* has been shown to upregulate the expression of the NPR1 (Nonexpressor of Pathogenesis-Related Genes 1) gene, a central regulator of plant immune responses (García-Gutiérrez et al., 2013). In addition to JA and ethylene, *B. subtilis* can stimulate the biosynthesis of other defense-related compounds, like phenylalanine ammonia-lyase (PAL), peroxidases (POD), and phytoalexins, all of which contribute to fortifying the plant against diverse pathogens. The improve in these enzymatic activities is often accompanied by structural alters like lignification, cell wall thickening, and enhanced synthesis of secondary metabolites. García-Gutiérrez et al. (2013) further announced that certain strains of *B. subtilis* induced secretion of citric acid and activated jasmonic acid-associated responses in watermelon, meaningfully enhancing resistance to powdery mildew. Such results underscore the multifaceted nature of *B. subtilis*-induced resistance, which involves hormonal signaling, transcriptional reprogramming, and metabolic alters that collectively enhance the plant's capability to fend off viral, fungal, and bacterial pathogens.

Stimulating plant growth: Plant pathogens impose biotic stress on their hosts, often preventing development and, in severe cases, leading to plant death. Among the numerous biological agents that mitigate such stress and enhance plant vitality, *Bacillus subtilis* has emerged as a highly effective plant growth–promoting rhizobacterium (PGPR). This bacterium facilitates plant growth through a combination of direct and indirect mechanisms, making it a valuable tool in sustainable agriculture. Indirectly, *B. subtilis* promotes plant health by inducing systemic resistance and suppressing pathogen activity. Directly, it contributes to nutrient acquisition and hormonal modulation, thus improving the plant's physiological performance. The bacterium is capable of solubilizing insoluble forms of soil phosphorus, enhancing nitrogen fixation in leguminous crops, and producing siderophores, which sequester iron and limit its availability to competing pathogenic microorganisms. These combined actions not only restrict pathogen proliferation but also stimulate root and shoot development (Hashem et al., 2019). In addition to these traits, *B. subtilis* has been shown to modulate plant stress response pathways. It can enhance the expression of stress-related genes, improve the synthesis of phytohormones like auxins, cytokinins, and gibberellins, and promote the production of antioxidants and osmoprotectants, substances that play vital roles in plant survival under abiotic stress conditions like drought, salinity, or temperature extremes. A recent investigation by Chagas Junior et al. (2022) demonstrated that treating soybean soils with *B. subtilis* preparations meaningfully improved plant performance. Treated plants exhibited improved plant height, shoot and root biomass, nodule number, pod count, grain yield, phosphorus uptake, and nitrogen accumulation. The positive effects were dose-dependent, with bacterial inoculants ranging from 200 to 350 mL per treatment proving exclusively effective. Numerous investigations support the beneficial role of *B. subtilis* in controlling phytopathogens while simultaneously enhancing plant growth. For example, Mohammed and Amusa (2003) announced that *B. subtilis* suppressed different soilborne pathogens in vitro, reducing their growth by 44.4% to 75.6%. Similarly, Alippi and Monaco (1994) found that the bacterium generates a range of antifungal compounds; containing subtilin, bacteriocin, and basilomycin as well as lytic enzymes like chitinase and β-1,3-glucanase, which degrade fungal cell walls and prevent infection. Kloepper et al. (2004) highlighted that specific *Bacillus* strains, containing *B. subtilis*, meaningfully reduced the severity of fungal, bacterial, and viral diseases in multiple crops by activating induced systemic resistance (ISR). The bacterium has been employed successfully to manage Fusarium wilt in tomato (*Fusarium oxysporum*) and head blight in wheat created by *Gibberella zeae*, among other pathogens. The commercial relevance of *B. subtilis* is underscored by its incorporation into biofungicide products like *Kodiak*, *Serenade*, and *Subtilex*, which have shown effectiveness against a broad spectrum of plant pathogens (Kumar et al., 2013; Wang et al., 2018). More recent developments include the isolation of *B. subtilis* strain FJ3, which demonstrated strong biocontrol and plant growth-promoting activity (Jan et al., 2023). Molecular analysis revealed that this strain generates multiple lipopeptides, containing fengycin, surfactin, mycosubtilin, and bilbastatin, which exhibited antagonism against *Fusarium oxysporum* (52% inhibition), *Aspergillus flavus*, *A. niger*, and *Rhizopus oryzae*. These results affirm the strain's broad-spectrum antifungal potential and its suitability for development as a biostimulant or biopesticide in eco-friendly agriculture. Similarly, a investigation by Sun et al. (2023) announced that treatment with *B. subtilis* R31 meaningfully reduced the incidence of bacterial wilt in tomato created by *Ralstonia solanacearum*. The strain effectively colonized the rhizosphere and internal root tissues, reducing the pathogen population and reshaping the microbial community structure. Lipopeptides were identified as key factors in this protective effect, and the capability of R31 to persist in the rhizosphere underscores its potential for long-term plant protection and growth promotion. In greenhouse and field experiments, Hansel et al. (2024) evaluated *B. subtilis* strain AFS032321 for its effectiveness against late blight in sweet peppers (*Phytophthora capsici*). The results demonstrated a 52% reduction in disease severity compared to untreated controls, reinforcing the practical application of *B. subtilis* in commercial horticulture. Beyond its biocontrol capabilities, *B. subtilis* is also valued for its industrial and technological advantages. It is an aerobic bacterium with a high growth rate, low nutrient requirements, and the capability to metabolize a broad variety of substrates, containing lignocellulose, starch, proteins, and hydrocarbons (Schallmey et al., 2004; Elisashvili et al., 2019). These characteristics make it suitable for low-cost fermentation processes and large-scale production. Furthermore, its capability to form robust endospores ensures long-term product stability and shelf-life, making it ideal for commercial formulations in agriculture and biotechnology.

Conclusions: This review underscores the meaningful and multifaceted role of *Bacillus subtilis* in suppressing plant pathogens and enhancing plant growth and productivity. Drawing upon both foundational and recent research, it is evident that *B. subtilis* represents a powerful biological agent capable of contributing to more sustainable and environmentally conscious agricultural practices. Plant pathogens stay a persistent threat to global food security, responsible for considerable reductions in crop yields and economic losses. In response, many agricultural systems have historically relied on chemical pesticides as a primary line of defense. While effective in the short term, the excessive and continuous apply of such chemicals has led to numerous negative consequences, containing the development of resistant pathogen strains, contamination of soil and water, disruption of beneficial microbiota, and serious health hazards to humans and animals. This growing awareness of the limitations and risks related to synthetic agrochemicals has catalyzed a global movement toward sustainable alternatives. Biological control, exclusively through the apply of plant growth–promoting rhizobacteria (PGPR) like *B. subtilis*, is now distinguished as a hopeful, eco-friendly plan that aligns with modern agricultural goals, containing the United Nations Sustainable Development Goals (SDGs). Throughout this review, the multiple mechanisms by which *B. subtilis* benefits plant health have been investigated. These include its capability to generate a broad array of antimicrobial compounds (like lipopeptides and bacteriocins), its role in inducing systemic resistance in plants against a broad spectrum of pathogens; containing fungi, bacteria, and viruses, and its contribution to soil fertility through organic matter decomposition and nutrient solubilization. Additionally, *B. subtilis* generates phytohormones like auxins, gibberellins, and cytokinins, which contribute directly to enhanced root development, nutrient uptake, and stress resilience. Importantly, the application of *B. subtilis* has not been related to adverse side effects, either on the environment or on non-target organisms, making it a safe and natural component of integrated pest and crop management systems. Its adaptability, resilience, and ease of formulation have led to the development of commercial products already in use in different parts of the world. In summary, this review emphasizes the critical importance of embracing biological control agents like *B. subtilis* as part of a larger transition to sustainable agricultural practices. Future research should centralize on field-level optimization, strain specificity, and synergistic formulations with other beneficial microbes to maximize the benefits of *B. subtilis* for global agriculture.

Author contributions

Iqbal Harbi Kadhim: Conceptualization, result suitable papers, manuscript drafting. Ahed. A. H. Matloob: Supervision, manuscript review and editing.

Data availability statement

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Ethical approval

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Conflict of interest

The authors declare no conflicts of interest related to this research.

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باسیلوس سابتیلیس و نقش آن در کنترل بیولوژیکی پاتوژن‌های گیاهی

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چکیده

هدف: افزایش تقاضا برای کشاورزی پایدار و کاهش استفاده از سموم شیمیایی، علاقه به جایگزین‌های سازگار با محیط‌زیست برای کنترل پاتوژن‌های گیاهی را افزایش داده است. در میان عوامل بیولوژیکی، *باسیلوس سابتیلیس* به دلیل مکانیسم‌های متنوع عمل، از جمله تولید آنتی‌بیوتیک، تحریک مقاومت سیستمیک در گیاهان و تقویت رشد گیاه، به‌عنوان یک عامل کنترل بیولوژیکی نویدبخش ظاهر شده است. این مقاله مروری با هدف بررسی ویژگی‌های بیولوژیکی و اکولوژیکی *باسیلوس سابتیلیس*، مکانیسم‌های آن در سرکوب پاتوژن‌های گیاهی و خلاصه‌سازی تحقیقات اخیر در مورد اثربخشی آن به‌عنوان یک عامل کنترل بیولوژیکی انجام شد.

مواد و روش‌ها: این مطالعه یافته‌های حاصل از طیف گسترده‌ای از مطالعات داوری و چاپ شده، آزمایش‌های میدانی و آزمایش‌های آزمایشگاهی متمرکز بر استفاده از *باسیلوس سابتیلیس* علیه پاتوژن‌های قارچی، باکتریایی و ویروسی گیاهان را ترکیب کرده است. مکانیسم‌های کلیدی عمل، از جمله کلونیزاسیون ریزوسفر، تولید آنتی‌بیوتیک، تحریک مقاومت سیستمیک القایی (ISR) و ویژگی‌های تقویت‌کننده رشد، تحلیل شدند. مطالعات موردی خاص و کاربردهای تجاری بررسی شدند تا دیدگاهی جامع درباره پتانسیل و محدودیت‌های این موجود زنده در برنامه‌های مدیریت یکپارچه آفات ارائه شود.

نتایج: *باسیلوس سابتیلیس* کارایی بالایی در سرکوب پاتوژن‌های مهم گیاهی مانند *فوزاریوم* .spp، *ریزوکتونیا سولانی*، *فیتوفتورا اینفستانس* و *رالستونیا سولاناسئاروم* از طریق مکانیسم‌های هم‌افزای متعدد نشان داد. این باکتری بیش از ۶۶ آنتی‌بیوتیک شناخته‌شده (مانند سورفاکتین، فنگیسین، سابتیلین)، آنزیم‌های هیدرولیتیک مانند کیتیناز و-β-1,3 گلوکاناز تولید می‌کند و بیوفیلم‌های مقاومی در ریزوسفر تشکیل می‌دهد که توانایی کلونیزاسیون آن را افزایش می‌دهد. مقاومت سیستمیک القایی ناشی از *ب. سابتیلیس* شامل

افزایش بیان آنزیم‌های مرتبط با دفاع و مسیرهای هورمونی، به‌ویژه اسید جاسمونیک و اتیلن است. علاوه بر این، *باسیلوس سابتیلیس* جذب مواد مغذی، تثبیت نیتروژن و مقاومت در برابر استرس را در گیاهان تقویت می‌کند. مطالعات میدانی و فرمولاسیون‌های تجاری (مانندKodiak ، Serenade، و Subtilex) اثربخشی آن را در شرایط محیطی متنوع تأیید می‌کنند. شواهد بررسی‌شده از اثرات ضدقارچی گسترده و تقویت‌کننده رشد گیاه پشتیبانی می‌کند.

نتیجه‌گیری: *باسیلوس سابتیلیس* ابزاری قدرتمند و ایمن برای محیطزیست، برای کنترل بیولوژیکی پاتوژن‌های گیاهی و افزایش بهره‌وری محصولات کشاورزی ارائه می‌دهد. نقش چندوجهی آن در سرکوب بیماری‌ها، فعال‌سازی دفاع گیاهی و بهبود سلامت خاک، آن را به‌عنوان یک جزء کلیدی در کشاورزی پایدار قرار می‌دهد. پذیرش محصولات کنترل بیولوژیکی مبتنی بر *باسیلوس سابتیلیس* با اهداف جهانی برای کاهش وابستگی به سموم شیمیایی، ترویج کشاورزی ارگانیک و دستیابی به پایداری بلندمدت کشاورزی بدون اثرات منفی اکولوژیکی یا بهداشتی هم‌راستا است.

کلمات کلیدی: آنتی‌بیوتیک‌ها، *باسیلوس سابتیلیس*، بیماری‌های گیاهی، پاتوژن‌ها، کنترل بیولوژیکی

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