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Using Bacterial Bioagents as an Effective Alternative to Pesticides in Managing Plant Diseases

Enas A. Almanzalawi* **and Tahani M. Alqahtani**

Department of Biological Sciences, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia
*Corresponding author. E-mail: ealmanazalawy@kau.edu.sa

ABSTRACT

This review uses a critical lens on the possibilities of bacterial bioagents as sustainable and ecologically friendly substitutes for chemical pesticides in plant disease management. Using peer-reviewed studies released between 2000 and 2025, it compiles the present understanding of the genera Bacillus, Pseudomonas, and Streptomyces - the most researched groups for their antagonistic action against phytopathogens. To assess experimental techniques, modes of action, and performance results under laboratory, greenhouse, and field settings, a structured literature review was carried out. Special consideration was paid to the biochemical and molecular routes underlying bacterial antagonism, including antibiotic synthesis, hydrolytic enzyme secretion, nutrient rivalry, niche exclusion, and the induction of systemic resistance in plants. Evidence points toward these genera's broad-spectrum activity against fungal, bacterial, viral, and nematode pathogens; their lipopeptide synthesis and sturdy spores characterize *Bacillus* species; *Pseudomonas* and *Streptomyces* by their strong antifungal chemicals and strains by their metabolic variety and rhizosphere ability; and, despite significant advancement, environmental and formulation elements continue to affect variable field performance. Future studies should focus on formulation improvement, symbiotic microbial consortia, and long-term field validation. Progress in omics technologies are expected to accelerate the development of next-generation, stable biocontrol agents for food security and organic agriculture.

Keywords: bacterial bioagents, biological control, *Bacillus spp*., *Pseudomonas spp.*, *Streptomyces spp*., plant disease management.

INTRODUCTION

In agriculture, chemical control has been a commonly applied method for managing diseases in economically important crops. Farmers often prefer this approach due to its lower cost and faster results compared to natural control methods. However, prolonged use of these chemicals can lead to significant long-term adverse effects on the environment, impacting human health and other living organisms.

They can affect both beneficial and harmful organisms, causing ecological imbalances and contaminating the food chain through the accumulation of toxic residues. organisms, causing ecological imbalances and contaminating the food chain through the accumulation of toxic residues. (Hashimi et al., 2020; Ali and Agri, 2023). Biological control represents a highly advantageous approach to managing diseases, playing a crucial role in fostering an environmentally sustainable approach (Ahmed et al., 2019; Ali, 2021; Pandit et al., 2022; Jalal et al., 2024; Mohdly et al., 2025). Since the introduction of the first commercial biological agent, a variety of microorganisms, including bacteria, actinomycetes, and fungi, have been identified for their potential to control plant diseases. Several of these microorganisms are now employed to manage various plant diseases effectively. Currently, a combination of these microorganisms is utilized for successful plant disease management in commercial greenhouses and fields (Samavat et al., 2011; Ali and Ayoub, 2017; Nurcahyanti and Ayu, 2020; Mohdly et al., 2024; Farag et al., 2026). Gram-positive bacteria possess a distinctive advantage over Gram-negative bacteria: the ability to form spores. Despite being less represented in biocontrol research, the spore-forming capability of Gram-positive bacteria and their historical use in industry contribute significantly to their effectiveness in biocontrol (Emmert and Handelsman, 1999; Boulahouat et al., 2023).

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Gram-positive bacteria that produce spores provide effective biological solutions to formulation challenges in biocontrol. Bacteria like Bacillus and Streptomyces generate spores resistant to heat and dehydration, making it easy to create stable products from them. These spore-based products can be manufactured as dry powders, in contrast to Gram-negative bacteria such as Pseudomonas sp., which are typically prepared as frozen cell pellets (Kumar et al., 2012; Compant et al., 2005; Haas and Défago, 2005; O'Brien, 2020; Tariq et al., 2020). Recently, eco-smart biocontrol approaches have gained increasing attention as sustainable and environmentally safe alternatives to chemical pesticides, focusing on the use of potent microbial consortia for plant protection (Haq et al., 2024).

Biological control of plant diseases entails regulating plant pathogen populations by utilizing living organisms (Heimpel and Mills, 2017; Negm et al., 2025; Prabhu et al., 2025). While synthetic pesticides provide a straightforward method for disease management, they pose significant risks to human health and the environment. Consequently, there is a growing need to explore alternative solutions to chemical pesticides for managing plant diseases. This review will focus on the role of beneficial bacteria in biological control and evaluate their effectiveness as substitutes for synthetic chemical pesticides.

Bacterial bio-agents

For decades, bacteria have been applied to soil, seeds, roots, and other planting structures to promote plant growth. Their primary objectives include enhancing nitrogen fixation, breaking down toxic chemicals, supporting plant development, and providing biological control of pathogens. Research indicates that bacteria can effectively manage a range of plant diseases, such as nematode infestations and fungal or bacterial infections. However, biological control alone has often been insufficient for reducing nematode populations, as its success largely depends on interactions with other soil organisms and the host plant. Integrating biological control with nematicides, soil organic amendments, and crop rotation has proven to be a more effective approach for managing plant-parasitic nematodes (Prapagdee et al., 2008; Timper, 2011; Lee and Kim, 2016; Mohan et al., 2017; Mohdly et al., 2025) in Figure 1.

Biological control is an effective and environmentally friendly method for managing post-harvest fungal diseases. This approach offers protection to plants against fungal pathogens and serves as a viable alternative for safeguarding fruits during the postharvest stage (Ghazanfar et al., 2016). Various fungal species, such as Aspergillus sp., Alternaria sp., Fusarium sp., and Penicillium sp., produce mycotoxins that are detrimental to leafy vegetables and contribute to post-harvest diseases. Fruits and vegetables contaminated with these fungal species may release several mycotoxins, including aflatoxins, ochratoxins, alternaria toxins, and fumonisins (Ongena and Jacques, 2008; Raaijmakers et al., 2009; Sansinenea and Ortiz, 2011; Santoyo et al., 2012; Sanzani et al., 2016; Mahmoud et al., 2025). Recent insights have emphasized microbial metabolites as key determinants of effective biocontrol, providing sustainable and multi-target suppression of phytopathogens (Prabhu et al., 2025).

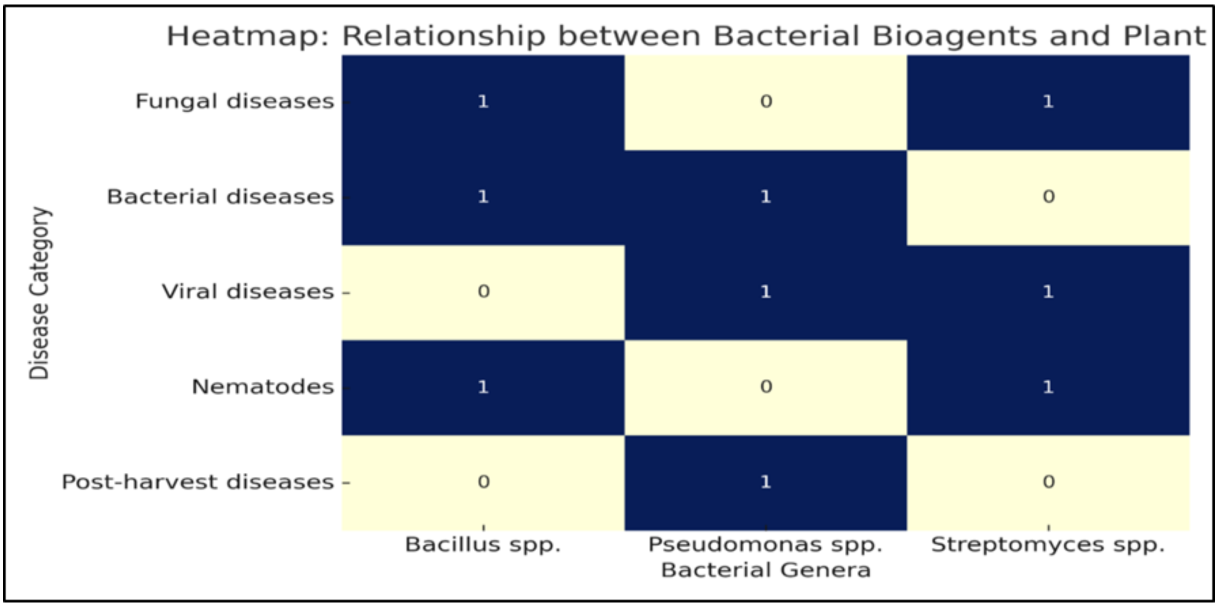

Figure 1. The overall interactions between bacterial genera and plant disease categories are summarized

Soil microorganisms play a crucial role in soil dynamics and are essential for the decomposition process. They are pivotal in soil formation and the breakdown of organic matter, as well as in material transformation, energy transfer, and bioremediation (Zhang et al., 2020).

Advantage of using bacterial biocontrol agents:

1. Biocontrol agents successfully eradicate pathogens from infection sites and can be combined with biofertilizers.
2. Biocontrol agents help prevent resistance and enhance systemic resistance in various crop species.
3. Biological control is the sole method for managing crown gall disease caused by Agrobacterium tumefaciens using bio-bacteria, Agrobacterium radiobacter strain K84.
4. Biocontrol agents play an important part in agriculture. It is cost-effective, environmentally friendly, and prevents the spread of pathogenic microorganisms over time.
5. Biocontrol agents can produce antibiotics, siderophores, enzymes, compete for nutrients, and promote the growth of plants via rhizosphere microorganisms.
6. Biological control is a highly effective strategy for controlling plant diseases, especially in organic farming.
7. Biological control manages plant diseases without disrupting the flora and fauna, while also enhancing soil fertility.

Bacillus spp.

Numerous studies have demonstrated the effectiveness of Bacillus spp. as biocontrol agents for protecting plants against various soil and airborne diseases. Some researchers attribute this protective effect to antibiosis, which occurs during the infection process (Attia et al., 2011). Others have observed changes in plant physiology and chemical composition in plants treated with these bacteria (Mazaro et al., 2008; Hafez et al., 2012). According to Stein (2005), Bacillus acts as an antagonistic agent in biocontrol by producing peptide antibiotics such as subtilisin, subtilosin, bacilysin, and surfactin. Additionally, Bacillus spp. has been effectively used to manage root-knot nematode infestations (Lee and Kim, 2016). Numerous bacteria produce lytic enzymes capable of breaking down a range of polymeric substances, such as hemicellulose, cellulose, chitin, and proteins. These extracellular enzymes are essential for effective plant disease control. Bacillus licheniformis acts as an antagonistic agent against Xanthomonas axonopodis pv. Glycines, which have a faster growth capability, play a role in the inhibitory mechanism through competition for growth space or nutrients. Bacillus with a high inhibitory effect can better suppress the metabolic process, inhibiting harmful bacteria more effectively Kumar et al. (2012) examined seven Bacillus spp. Isolates from the rhizosphere of common beans. Isolated bacteria demonstrated both plant growth-promoting (PGP) and negative properties. The isolate BPR7 was identified as Bacillus sp. BPR7. This strain was found to produce a range of bioactive compounds, including IAA, siderophores, phytase (an enzyme that breaks down phytic acid), organic acids, cyanogens, lytic enzymes, and oxalate oxidase. Additionally, it was capable of solubilizing various organic compounds. Strain BPR7 demonstrated significant suppression of the growth of several phytopathogens, such as Rhizoctonia solani, Fusarium solani, Macrophomina phaseolina, and Sclerotinia sclerotiorum in vitro. Yagmur and Gunes (2021), have shown that numerous plant growth-promoting rhizobacteria (PGPRs), including Bacillus spp., can act as effective biological control agents. These bacteria are instrumental in managing plant diseases, enhancing soil nutrient availability, and improving plant nutrition through several mechanisms. These include biological nitrogen fixation, phosphorus solubilization, and the production of plant hormones, amino acids, and organic acids. Additionally, they significantly promote plant growth, which makes them widely utilized as biofertilizers in agriculture (Chen et al., 2009; Borriss, 2011; Cawoy et al., 2015; Islam et al., 2022; Riseh, 2025)

Pseudomonas fluorescens

Pseudomonas fluorescens is a typical bioagent used to treat foliar and soil-borne diseases. P. fluorescens is one of the most promising rhizosphere bacteria since it not only suppresses illness but also promotes plant growth. Wei et al. (1991) report that HCN production plays an important role in disease control. Some P. fluorescens isolates have also been shown to create volatile chemicals as part of the antibiotic production procedure in order to inhibit pathogens. P. fluorescens produces several kinds of volatile chemicals, including hydrocyanic acid (HCN), acids, alcohols, ketones, aldehydes, and sulphides (Bouizgarne, 2013).

Table 1. Representative examples of bacterial biocontrol agents used to suppress major plant pathogens in economically important crops

Bacterial biocontrol agent	Major target pathogens/disease groups	Representative host crops	Key references
Bacillus subtilis, *B. amyloliquefaciens*, *B. pumilus*	Soil-borne fungi (*Fusarium*, *Rhizoctonia*, *Pythium*, *Sclerotinia*); bacterial wilt (*Ralstonia*); aflatoxin-producing *Aspergillus* spp.	Tomato, maize, cotton, banana, pepper	Müller et al. (2014); Hanif et al. (2019); Moyne et al. (2004); Hasinu et al. (2021)
Pseudomonas fluorescens, *P. chlororaphis*, *P. putida*, *P. aeruginosa*	Fungal and bacterial pathogens (*Phytophthora*, *Xanthomonas*, *Ralstonia*, *Rhizoctonia*); viral infections (TMV, CMV, BBTV)	Tomato, rice, potato, wheat, banana	Thomashow and Weller (1988); Hunziker et al. (2015); Abdelbaset et al. (2024)
Paenibacillus polymyxa, *P. alvei*	Root and crown rot fungi (*Phialophora*, *Fusarium*, *Sclerotinia*); nematode-related diseases	Soybean, cotton, sorghum	Schoina et al. (2011); Zhou et al. (2008); Budi et al. (2000)
Streptomyces spp. (*S. griseoviridis*, *S. setonii*, *S. cacaoi*)	Wilt and rot fungi (*Fusarium*, *Sclerotinia*, *Rhizoctonia*, *Botrytis*); *Erwinia* soft rot	Tomato, potato, rice, sweet potato	Lahdenperä et al. (1991); Wu et al. (2012); Gong et al. (2022)
Serratia plymuthica, *Rhizobium japonicum*	*Botrytis cinerea*, *Fusarium* spp., *Macrophomina phaseolina*	Strawberry, soybean, tomato	Frankowski et al. (2001); Al-Ani et al. (2012)
Burkholderia cepacia, *B. vietnamiensis*	*Colletotrichum* spp., *Phytophthora capsici*	Chili pepper, bell pepper	Burkhead et al. (1994)

Saravanakumar et al. (2007) explored the potential of a fluorescent-pseudomonad-based bioformulation for managing Macrophomina root rot disease, caused by M. phaseolina, in mung beans. In vitro tests revealed that the isolate Pf1 effectively inhibited the mycelial growth of M. phaseolina. Plants treated with Pf1 showed elevated levels of defense-related enzymes, including phenylalanine ammonia-lyase, peroxidase, polyphenol oxidase (catechol oxidase), chitinase, and β-1,3-glucanase (endo-1,3(4)-β-glucanase), as well as increased phenolic compounds. Attia et al. (2011) evaluated the effects of various plant growth-promoting rhizobacteria (PGPR), both individually and in combination (including Pseudomonas fluorescens, Azotobacter chroococcum, and Bacillus cereus), on treated plants. Their results demonstrated that these PGPRs were effective in reducing diseases caused by M. phaseolina. Soil application of these PGPRs significantly enhanced peroxidase, chitinase, and β-1,3-glucanase activities, as well as phenolic compound accumulation in soybean plants compared to the control. These findings suggest that increased activity of defense enzymes and higher phenolic content can help soybean plants better combat M. phaseolina. Chang et al. (2011) and Mohamed et al. (2026) investigated the inhibitory mechanism and ability of the Ps. fluorescens strain FD6 against B. cinerea, the causative agent of grey mould on tomatoes. (Raaijmakers et al., 2002; Haas and Keel, 2003; Mercado-Blanco and Bakker, 2007; Andreata et al., 2025)

The results demonstrate that strain FD6 produced a wide range of antifungal substances, including pyrrolnitrin, 2,4-diacetylphloroglucinol, pyoluterorin, siderphore, hydrogen cyanide, and extracellular proteinase. Pyrrolnitrin directly inhibited both spore germination and mycelial growth of B. cinerea. Samavat et al. (2011) conducted a greenhouse experiment to determine the effectiveness of two *Ps. fluorescens* isolates as biocontrol agents against Rhizoctonia solani damping off. All treatments were effective in reducing the severity of bean damping-off compared to the untreated control. In addition to controlling the disease, seed treatment with any of *Ps. fluorescens* isolates, whether applied individually or in combination, significantly enhanced bean growth parameters, including shoot and root fresh and dry weights. On the other hand, all tested rhizobia and *Ps. fluorescens* isolates produced siderophores, HCN, IAA, chitinase, and exopolysaccharides. It is well known that eradicating nematodes from the soil is quite challenging. Mohan et al. (2017) used two *Pseudomonas* sp. to control nematodes in the potato crop. P. fluorescens + P. lilacinus treatment resulted in a decreased nematode population in soil, as well as in the roots and tubers, compared to the untreated control. (Doumbou et al., 2001; Ji et al., 2012; Tyagi et al., 2024).

Table 2. Functional classification of antibiotics produced by bacterial biocontrol agents and their target plant pathogens

Antibiotic class	Representative compounds	Producing bacterial genera	Target plant pathogens	Key references
Lipopeptides	Surfactin, Iturin, Fengycin, Mycosubtilin, Bacillomycin D	*Bacillus subtilis, B. amyloliquefaciens, B. cereus*	*Rhizoctonia solani, Fusarium oxysporum, Aspergillus flavus, Phytophthora spp.*	Bais et al. (2004); Hanif et al. (2019); Moyne et al. (2004)
Phenazines	Phenazine-1-carboxamide, Phenazine-1-carboxylic acid	*Pseudomonas chlororaphis, P. aureofaciens, P. fluorescens*	*Fusarium oxysporum, Gaeumannomyces graminis, Sclerotinia homeocarpa*	Thomashow and Weller (1988); Jain and Pandey (2016)
Polyketides	Bacillaene, Macrolactin, Difficidin	*Bacillus subtilis, B. amyloliquefaciens*	*Rhizoctonia solani, Fusarium spp., Botrytis cinerea*	Müller et al. (2014); Fan et al. (2017)
Aminoglycosides	Kasugamycin	*Streptomyces kasugaensis*	*Pyricularia oryzae* (rice blast fungus)	Kasuga et al. (2017)
Quinones and Flavonoids	Geldanomycin, 5,7-Dimethoxyflavone, 2,6-Di-tert-butylquinone	*Streptomyces hygroscopicus, S. sampsonii*	*Rhizoctonia solani, Fusarium spp.*	Wu et al. (2012); Ren et al. (2023); Jannu et al. (2015)
Phenolic derivatives	2,4-Diacetylphloroglucinol (2,4-DAPG), Pyoluteorin, Pyrrolnitrin	*Pseudomonas fluorescens, P. cepacia*	*Pythium ultimum, Rhizoctonia solani, Ralstonia solanacearum*	Howell and Stipanovic (1980); Burkhead et al. (1994); Suresh et al. (2022)
Peptides/ Cyclic peptides	Mycobacillin, Cyclic dipeptides	*Bacillus subtilis, Pseudomonas sp.*	*Phytophthora infestans, Fusarium spp.*	Wang et al. (2020); Betancur et al. (2019)
Others (Amino-sugar and mixed types)	Zwittermicin A, Kanosamine	*Bacillus cereus, B. thuringiensis*	*Phytophthora medicaginis, Sclerotinia sclerotiorum*	Milner et al. (1996);

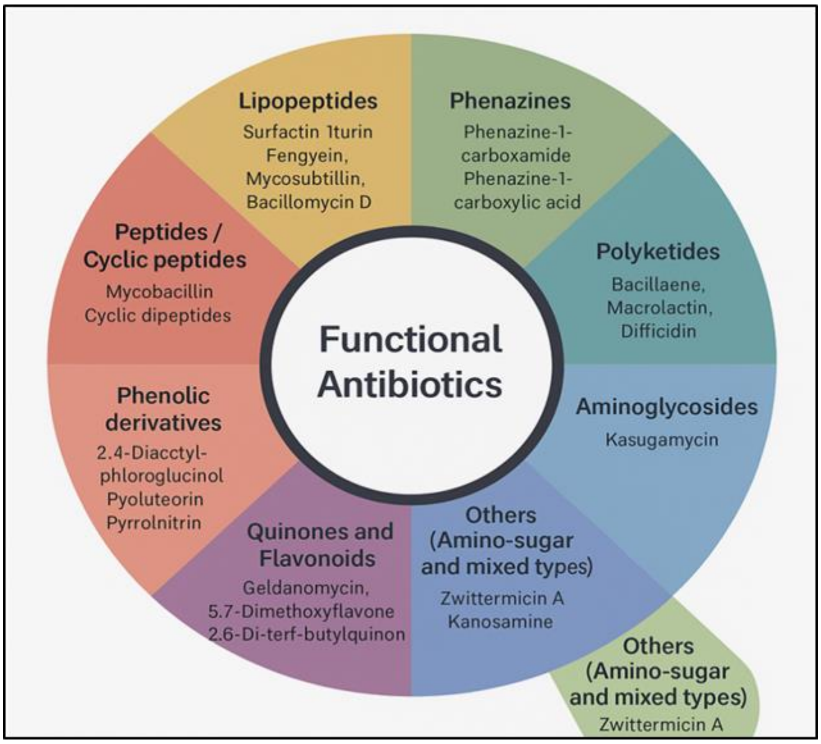

Figure 2. Functional classification of antibiotics produced by biocontrol bacteria

Streptomyces spp.

Streptomyces are Gram-positive bacteria and represent a distinctive group within the actinobacteria. These bacteria are renowned for their ability to produce a diverse array of bioactive secondary metabolites, including antibiotics, antifungals, antibacterial agents, antioxidants, and compounds that promote plant growth (Zhao et al. 2019). Actinobacteria's secondary metabolites include antibiotics, enzymes, organic volatiles, pigments, vitamins, and other substances. Actinomycetes, like other plant-growth-promoting microorganisms, produce phytohormones. Most examined actinomycetes plant growth-promoting species involve antibacterial or antifungal activity, which were expected during their screening as biocontrol agents (Chen et al., 2018; Oluwaseyi and Olubukola, 2019). Streptomyces interacts with pathogenic fungi by producing enzymes that degrade cell walls, such as glucanases, cellulases, chitinases, and amylases. Streptomyces may also parasitize the pathogen's mycelium and/or sclerotia (Kong et al., 2019). Additionally, Streptomyces spp. is well-known for producing a wide range of natural bioactive secondary metabolites and volatile organic compounds with applications in agrochemicals (Danaei et al., 2013; Sharma et al., 2020; Marks, 2025). Kurth et al. (2014), investigated how Streptomyces sp. strain AcH 505 inhibited the growth of oak powdery mildew. They found that this Streptomyces strain triggered a systemic defense response in oak plants, which was slightly enhanced by pathogen exposure. Additionally, the jasmonic acid/ethylene-dependent pathway was activated. There was an increase in transcripts related to tryptophan and phenylalanine biosynthesis, and phenylalanine ammonia-lyase activity was elevated, suggesting that Streptomyces spp. Play a role in this defense mechanism. This study offers new insights into the priming mechanisms of actinobacteria and highlights their ability to enhance plant defensive responses even in the absence of an actual pathogen threat. Odumosu et al. (2017) isolated and examined Streptomyces coelicolor culture filtrate with a gas chromatography-mass spectrometer (GC-MS). The GC-MS chromatogram of S. coelicolor crude extract revealed 16 secondary metabolites. Mutamicin, hybrimycin, daunorubicin, kanamycin, streptomycin, indolyl-3-carboxylic acid, mitomycin, pilacamycin, gentamycin, 2-phenylacetamide, etamycin, hydroxygentamycin, chloromycetin, tetracycline, and pimprinine were all found, a majority of which have already been identified for their antibacterial, antifungal, and antioxidant properties. Streptomyces sp. significantly reduced the incidence of Botrytis cinerea disease by 28-47% compared to the uninoculated control in chickpea plants. The study included genotypes ICC4954 (sensitive), ICCV05530 (moderately resistant), and JG11 (resistance unknown) in Figure 3.

Streptomyces sp. was found to improve host-plant resistance across all genotypes by inducing various antioxidant enzymes and phenolic compounds (Vijayabharathi et al., 2018). Shen et al. (2021), identified Streptomyces microflavus strain G33 as a potent inhibitor of the pathogen R. solanacearum, which causes tomato bacterial wilt. Strain G33 exhibited significant β-1,3-glucanase activity, demonstrating its ability to degrade pathogenic bacteria's cell walls. The G33 strain additionally showed high cellulase activity, indicating that it could enhance the decomposition of cellulose in compost.

This review highlights critical findings supported by comprehensive data summarized clearly in two structured tables. Table 1 systematically compiles several studies that confirm the efficiency of bacterial bioagents, such as Bacillus spp., Pseudomonas spp., and Streptomyces spp., in managing a variety of plant pathogens affecting economically important fruit and vegetable crops essential for food security. These bacterial genera have demonstrated significant disease suppression through multiple mechanisms, including antibiotic production, secretion of enzymes like chitinases and glucanases, and competition for nutrients (Saravanakumar et al., 2007;

Kumar et al., 2012; Shen et al., 2021). Such varied biological activities not only suppress pathogen populations effectively but also contribute positively to plant health, enhance resistance, and improve soil fertility - fundamental aspects for achieving sustainable agricultural systems (Attia et al., 2011; Nurcahyanti and Ayu, 2020). Additionally, Table 2 provides detailed insights into specific secondary metabolites and antibiotics produced by these bacterial agents, reinforcing their direct antagonistic actions against various plant pathogens. Metabolites such as subtilisin, pyrrolnitrin, and surfactin have been highlighted in previous studies for their significant roles in pathogen inhibition, supporting the notion that these compounds can effectively replace traditional chemical pesticides (Stein, 2005; Chang et al., 2011). The proven effectiveness of such bioactive compounds further emphasizes the potential of bacterial bioagents as reliable, eco-friendly alternatives in plant disease management. Integrating these bacteria into agricultural practices not only promises enhanced crop productivity but also aligns strongly with global objectives of reducing environmental contamination, promoting ecological balance, and ensuring food safety (Ghazanfar et al., 2016; Pandit et al., 2022).

In Figure 2, the principal functional categories of antibiotics made by bacterial biocontrol agents that significantly control many plant pathogens are shown on the graph, and known for their potent antifungal and surfactant characteristics, lipopeptides (surfactin, iturin, fengycin, bacillomycin D), phenazines, and phenolic derivatives act as polyketides with broad-spectrum antibacterial activity like bacillaene and difficidin, as well as redox-active molecules destroying pathogen metabolism. By disrupting cell integrity and enzyme activity, aminoglycosides, cyclic peptides, and quinones/flavonoids further help to inhibit pathogens. Moreover, mixed-type molecules such as zwittermicin A and kanosamine increase synergic interaction between microbial metabolites. Together, these classes of antibiotics comprise an integrated biochemical arsenal supporting bacterial antagonism and fostering eco-friendly and sustainable disease management inside contemporary agricultural systems.

Several studies on bacterial bioagents have shown that they may mitigate a variety of plant diseases, including nematode infestation, fungal, bacterial, and viral infections. These bioagents can act in different modes of action, including by producing antibiotics, siderophores, enzymes, and competing for nutrients, which makes them helpful in controlling various diseases. Table 1 provides an overview of various studies on bacterial bioagents applied for controlling several plant diseases (fungi, bacteria, and viruses) on several kinds of high-value vegetable and fruit crops that are also critical to food security. Table 2 shows specific examples of antibiotics (secondary metabolites) produced by a variety of bacterial bioagents (Carrión et al., 2019; Zhao et al., 2019; Sivasakthi et al., 2020).

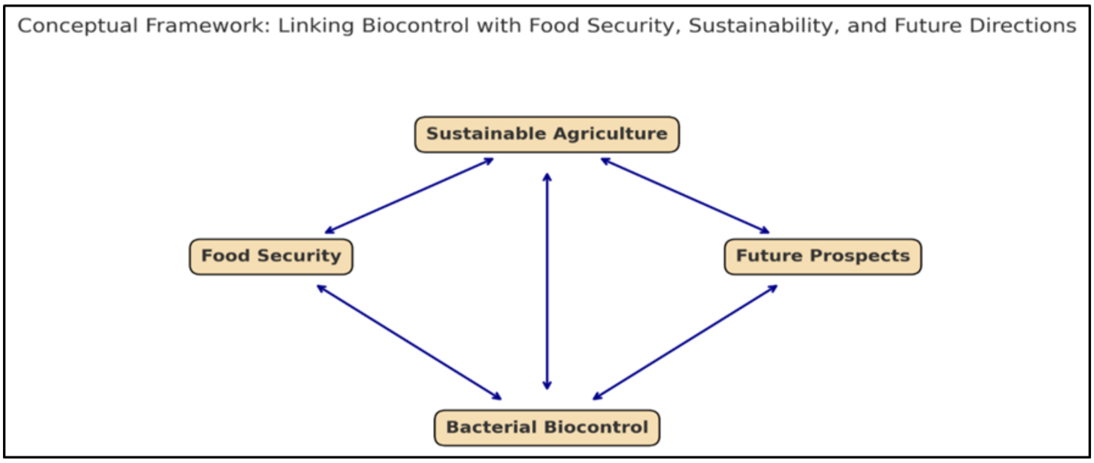

Figure 3. A conceptual framework linking bacterial biocontrol with food security, sustainable agriculture, and future research directions is depicted

CONCLUSIONS

This review underscores the pivotal role of bacterial bioagents as sustainable alternatives to chemical pesticides in the management of plant diseases. Genera such as *Bacillus*, *Pseudomonas*, and *Streptomyces* have demonstrated remarkable versatility, exhibiting a broad spectrum of antagonistic activities against fungal, bacterial, viral, and nematode pathogens. Their capacity to produce antibiotics and lytic enzymes, compete for nutrients and ecological niches, and trigger systemic resistance in plants highlights the multifaceted strategies by which these microorganisms safeguard crops. Collectively, these attributes make bacterial biocontrol agents indispensable components of environmentally responsible agriculture.

Beyond their scientific value, the practical significance of bacterial bioagents lies in their potential to reduce reliance on chemical pesticides, mitigate ecological damage, and enhance food security in the face of rising global demand. By integrating these biological tools into crop protection strategies, agriculture can advance toward greater resilience and sustainability. However, the translation of laboratory success to consistent field-level efficacy remains a challenge. Variability in environmental conditions, limited formulation stability, and inconsistent regulatory frameworks continue to hinder large-scale adoption.

Future research should prioritize the refinement of microbial formulations, long-term multi-site field evaluations, and the exploration of synergistic consortia that combine complementary mechanisms of action. Emerging technologies in genomics, metabolomics, and systems biology provide promising avenues to deepen our understanding of plant–microbe interactions and accelerate the development of next-generation biocontrol solutions. Ultimately, harnessing the full potential of bacterial bioagents requires not only scientific innovation but also strong integration into agricultural policies and practices, ensuring that these eco-friendly strategies contribute meaningfully to global food security and sustainable development.

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