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Bacillus spp. as Bioagents-Applications and Effective Strategies in Plant Bacterial Disease Management: A Review

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ABSTRACT

Phytopathogenic bacteria (PPB) cause plant diseases, resulting in significant global economic losses. Over 200 bacterial species across 25 genera damage various plant species, predominantly from the Pseudomonadaceae, Xanthomonadaceae and Enterobacteriaceae families. These bacteria invade plant tissues and surfaces to live and obtain nourishment, often in collaboration with fungi and viruses, along with the impact of abiotic stress factors like chemical pollution, climate change, biodiversity loss, post-harvest loss, food waste and environmental degradation. These challenges collectively pose a substantial threat to global agricultural food production. Achieving global food security, sustainability in agriculture and enhancing the yield of high-quality healthy crops require effective control of plant bacterial diseases. Traditional chemical control methods have led to bacterial resistance, environmental pollution, high costs and negative impacts on human and ecological health. To address these issues, attention has shifted towards the alternatives of synthetic agrochemicals, with a focus on biopesticides. This paper comprehensively analyzes using *Bacillus* species as bioagents and investigating their mechanisms of action, including competition, antibiosis and induced plant resistance and evaluating their effectiveness in managing bacterial plant diseases. The findings suggest that *Bacillus* spp. offer a promising solution to sustainable agricultural practices, providing a safer and more eco-friendly approach to plant disease management.

Key words: *Bacillus* spp., Biocontrol agent, Biopesticides, Mechanisms, Phytopathogenic bacteria.

Plant pathogenic bacteria (PPB) cause diseases that result in significant economic losses, with crop damage estimated at 30-40%, amounting to between one billion dollars and five billion euros annually, particularly affecting pears, vineyards and apple orchards (Kannan *et al.*, 2015; Khan *et al.*, 2023; Mansfýeld *et al.*, 2012; Verhaegen *et al.*, 2023). More than 200 bacterial species from 25 genera cause significant damage to diverse plant species (Buttimer *et al.*, 2017). Most of these bacteria belong to the families Pseudomonadaceae, Xanthomonadaceae and Enterobacteriaceae, targeting both plant surface structures and internal tissues where they can obtain nutrients and establish habitats. These families include *Acidovorax, Agrobacterium* (some strains)*, Pectobacterium, Xanthomonas, Clavibacter, Burkholderia, Pseudomonas* (some strains)*, Streptomyces, Spiroplasma, Erwinia, Pantoea, Ralstonia* and *Xylella,* which are a significant number of highly destructive phytopathogenic bacteria (Kannan *et al.*, 2015; Sharma *et al.*, 2023). The interaction of these bacteria with other pathogens such as fungi and viruses, alongside abiotic stressors like climate change, pollution and biodiversity loss, presents a substantial challenge to global agricultural food production (Martins *et al.*, 2018). Therefore, maintaining global food security requires the application of management strategies to eradicate plant pathogenic bacteria by reducing their survival chances (Rizzo *et al.*, 2021; Strange *et al.*, 2005). Farmers often depend extensively on chemical fertilizers and pesticides (Satyadev Prajapati and Maurya, 2020). While chemical pesticides have proven effective in eradicating plant diseases in agriculture, the unfortunate consequence is that the misuse of certain chemicals, coupled with prolonged and excessive use, causes numerous environmental problems, the rapid emergence of resistance in phytopathogenic bacteria and pests and can be costly. Furthermore, when these chemicals accumulate in soil or plants, they can be harmful to humans and affect non-target animals, microbial communities and non-target plants (Said, 2023; Tudi *et al.*, 2021). Consequently, scientists turned their attention to natural alternatives to artificial agrochemicals, leading to the improvement of biopesticides for controlling diseases and pests.

Biopesticides derive from various sources, including microorganisms, natural compounds and pesticidal substances with additional genetic material (Kumar *et al.*, 2021). They offer safe, environmentally acceptable solutions for hazardous pesticides when used in agricultural and horticultural applications. This paper comprehensively analyzes the potential of *Bacillus* species as biocontrol agents, exploring their mechanisms of action and the advantages they provide in managing plant bacterial diseases.

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Characteristics of the bacillus genus

Bacillus subtilis, the first identified Bacillus species, was discovered by Christian Gottfried Ehrenberg in 1835. He named the bacterium *Vibrio subtilis* because of its rod-shaped appearance (Jörg Stülke *et al.*, 2023; Sella *et al.*, 2014). In 1872, Cohn renamed the bacterium to *Bacillus subtilis* (Harirchi *et al.*, 2022). Since then, *Bacillus* has been discovered in a variety of environments, including ponds, air, soil, fresh and saline water and food as contaminants. It can also be present in the digestive tracts of animals like pigs (Haque *et al.*, 2022; Wei *et al.*, 2015). *Bacillus* species are rod-shaped, facultatively anaerobic, endospore-forming and catalase-positive bacteria with flagellar motility and variable sizes (0.5 to 10 µm*)* bacteria that grow best in a neutral pH (Márquez *et al.*, 2011; Radhakrishnan *et al.*, 2017; Zhou *et al.*, 2022). These species are frequently employed as bioagents for plant diseases because of their capability to form spores, which enable them to live in harsh environments. They release extracellular proteins, exhibit rapid growth and possess efficient biosynthetic pathways (Liu *et al.*, 2020). Additionally, numerous organic and inorganic substances can be used by *Bacillus* species for growth and energy. Moreover, there are significant differences in nutritional needs among species. Certain strains, classified as prototrophs rely solely on an organic carbon source, while others, categorized as auxotrophs depend on the substrate for essential organic compounds (Logan NA and P, 2009). Certain *Bacillus* species, such as *B. licheniformis, B. anthracis and B. cereus*, can infect humans and animals, whereas *B. thuringiensis* is harmful to invertebrates (Pinos *et al.*, 2021; Ramirez-Olea *et al.*, 2022).

Use of the *Bacillus* genus as a bioagent

Using *Bacillus* species for biological control is a practical, eco-friendly approach to managing plant diseases. Studies on employing *Bacillus* species as biological agents to manage plant diseases have been ongoing for a long time. *Bacillus* spp., particularly *B. subtilis*, are widely recognized as plant growth-promoting rhizobacteria that live in soil. They are crucial in giving plants resistance against abiotic and biotic stresses, as shown in Fig 1, through the formation of biofilms, induced systemic resistance and lipopeptide production. These species, at controlled concentrations, boost carbon sequestration, denitrify soils and aid in metal-contaminated soil bioremediation (Mahapatra *et al.*, 2022). They release antimicrobial metabolites that can supplement or replace synthetic chemicals in biofertilizers and biopesticides to prevent plant diseases. They also produce endospores to survive adverse conditions, along with phytohormones, siderophores and the ability to solubilize potassium and phosphorus, enhancing plant growth and nutrient uptake (Collins and Jacobsen, 2003; Fan *et al.*, 2019; Ongena *et al.*, 2005).

Many *Bacillus* species have antagonistic activity against a variety of phytopathogenic bacteria found in field crops including fruit trees, rice, corn and others (Li *et al.*, 2015).

The mode of action of *Bacillus* biological control for phytopathogenic bacteria is as follows.

Direct mode of action

Antibiosis

Antibiotics are small, low molecular-weight molecules produced mainly by soil-dwelling microbes as secondary metabolites. It is known that some *Bacillus* species, like *B. amyloliquefaciens, B. mycoides, B. megaterium, B. subtilis, B. cereus* and *B. licheniformis*, can generate strong antibiotic substances that prevent phytopathogenic growth. These include both non-ribosomal and ribosomal cyclic peptides, which researchers have extensively studied (Cawoy *et al.*, 2011; Li *et al.*, 2015). A study by Bottone *et al.* (2003) stated that the Bacilli class produces about 167 different antibiotics. Of these, 23 are obtained from *Bacillus subtilis* and 66 from *Bacillus brevis*, with other *Bacillus* species contributing the remaining antibiotic peptides (Bottone and Peluso, 2003). Different *Bacillus* strains produce antimicrobial peptides that vary significantly and this variation impacts their effectiveness in inhibiting plant pathogenic bacteria (Basi-Chipalu *et al.*, 2022; Cladera-Olivera *et al.*, 2004).

Bacillus species produce various bacteriocins with antimicrobial properties, including subtilin, thuricin, amylolysin, amylocyclicin, subtilosin A, subtilosin B and amysin (Abriouel *et al.*, 2011). Some of these are trained in the biological management of phytopathogens. As an example, *B. clausii* GM17 produces Bac GM17, which is active in combating *Agrobacterium tumefaciens*, or *B. thuringiensis* subsp. *kurstaki* Bn1's thuricin Bn1 inhibits *Pseudomonas syringae* and *Pseudomonas savastanoi* (Mouloud *et al.*, 2013; Ugras *et al.*, 2013). Furthermore, several antimicrobial substances, like bacillomycin D, zwittermicin A, fengycins, iturins and surfactins, are formed by *Bacillus* strains. These substances, which are referred to as cyclic lipopeptides (CLPs), have potent pathogen-inhibiting properties (Farace *et al.*, 2014; Li *et al.*, 2019). Several *Bacillus* variants, including *Bacillus amyloliquefaciens*

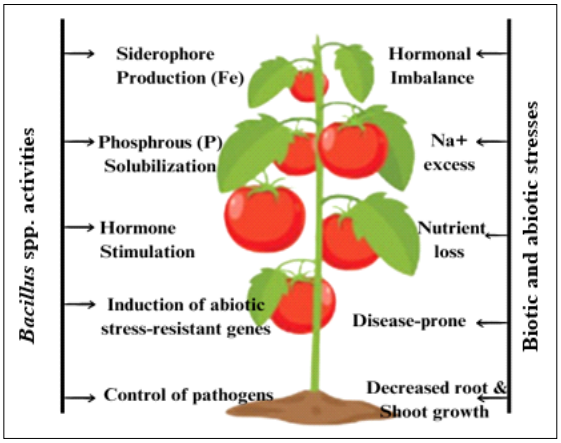


Fig 1: Roles of *Bacillus* spp. in managing abiotic and biotic stresses in crops.

A17 (currently *B. velezensis*) and *B. amyloliquefaciens* KPS46, have been shown to produce CLPs, with antibacterial activity (Chaisit Preecha *et al.*, 2010; Mora *et al.*, 2011, 2015; Saha *et al.*, 2016).

Siderophore production

Soil organisms frequently face competition for vital resources including nutrients, oxygen and space. Competition for space and nutrients around host plants between pathogenic and non-pathogenic microorganisms can result in biological control (Pal and McSpadden Gardener, 2006). The most common nutrient element over which beneficial microbes, such as *Bacillus* spp. and pathogenic microorganisms compete is Iron (Fe). There is intense competition because there is a shortage of bioavailable iron in the soil environment. The process responsible for this competition is known as Siderophore. Its primary function is to chelate iron, allowing it to be soluble and extracted from organic materials and minerals (Miljakoviæ *et al.*, 2020). It is essential to biological control because it combats infectious agents for iron, limiting their accessibility (Beneduzi *et al.*, 2012). A variety of bacteria, including *Azospirillum*, *Azotobacter*, *Bacillus*, *Dickeya*, *Enterobacter*, *Kosakonia*, *Klebsiella*, *Methylobacterium*, *Nocardia*, *Pantoea*, *Paenibacillus*, *Pseudomonas*, *Serratia*, *Streptomyces* and others, can produce siderophore.

Most studies documented the significance of siderophores in inhibiting plant bacterial diseases. In 2004, Kloepper *et al.* (1989) investigated the importance of siderophores in suppressing pathogens like *Pectobacterium carotovorum*, showcasing the potential of PGPR in managing plant diseases biologically (Kloepper *et al.*, 2004). The effectiveness of *Bacillus amyloliquefaciens* strain S1 against *C. michiganensis* spp. *Michiganensis*, which causes canker disease in tomatoes, was reported. The effectiveness of strain S1 was linked to the synthesis of siderophores, antibacterial metabolites and lytic enzymes *in vitro* conditions (Gautam *et al.*, 2019).

Production of hydrolytic and lytic enzymes

Bacillus species are known as valuable reservoirs for a broad range of enzymes. *B. licheniformis*, *B. subtilis and* other microorganisms produce Keratinases which are widely used in animal feed, leather industries, detergent and feed, as well as in biomedical and healthcare applications (Gupta and Ramnani, 2006; Silva *et al.*, 2014). The hydrolytic enzymes found in *Bacillus* species, such as glucanases, cellulases, lipases, proteases, chitinases and chitosanases, contribute to the effective degradation of essential elements of bacterial and fungal cell walls (Miljaković *et al.*, 2020). Bacteria predominantly produce chitinases to break down chitin for energy consumption. Moreover, particular bacterial chitinases are utilized as potent bioagents for combating a range of plant diseases induced by fungal pathogens (Kumar *et al.*, 2018; Saber *et al.*, 2015). The breakdown of cell walls that results from interactions between *Bacillus* species and pathogens may be facilitated by the action of bacterial cellulases, lipases and proteases (Guleria *et al.*, 2016). Previous research has been published on isolating these enzymes from *Bacillus brevis, Bacillus subtilis, Bacillus halodurans, Bacillus circulans* and *Bacillus licheniformis* (Planas, 2000). Recent studies have extensively examined the production of lytic and hydrolytic enzymes by *Bacillus* species, emphasizing their promising role as biocontrol agents in managing plant diseases. The ability of *B. amyloliquefaciens* to form lytic enzymes like cellulase, protease, lipase and chitinase is associated with its potential to function as a bioagent against *Clavibacter michiganensis* ssp. *Michiganensis* (Gautam *et al.*, 2019).

Indirect mode of action

Plant growth-promoting rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria (PGPR) are beneficial living soil bacteria that colonize plant roots and promote plant growth (Kloepper *et al.*, 1989). PGPRs improve plant growth directly by supplying compounds like phytohormones or aiding nutrient absorption and indirectly by limiting phytopathogens or inducing plant resistance (Glick, 1995). Some PGPRs form biofilms, which are structures made of bacteria encased in organic and inorganic compounds. Biofilms help PGPRs colonize plant roots, promoting a stable and sustained interaction with the host plant. Consequently, this may improve PGPR's capacity to encourage plant development and offer pathogen protection (Haque *et al.*, 2020; Karimi *et al.*, 2022). Toxins such as bacillomycin, fengycin, iturin, surfactin and macrolactin, are released by *Bacillus* species when they form a biofilm on the root surface. By doing this activity, harmful bacterial populations are eliminated and the frequency of plant diseases is reduced (Elshakh *et al.*, 2016; Huang *et al.*, 2014).

The *Bacillus* genus, broadly studied and utilized in agriculture for its practical potential as PGPB, includes species like *Priestia megaterium* (formerly *Bacillus megaterium*), *B. circulans*, *B. coagulans*, *B. subtilis*, *B. azotofixans*, *B. macerans* and *B. velezensis* (Blake *et al.*, 2021; Etesami *et al.*, 2023; Fan *et al.*, 2018).

Biocontrol agents derived from the *Bacillus* genus are frequently more potent compared to other PGPB species such as *Pseudomonas* spp., because These species have the superior capability to produce metabolites and form spores, thereby enhancing cell viability in commercially viable products (Haas and Défago, 2005). Three *Bacillus* strains isolated from the pepper rhizosphere in Turkey significantly reduced bacterial spot disease severity, achieving reductions ranging from 11% to 62% in field conditions and 38% to 67% in greenhouse experiments. Additionally, these strains enhanced plant growth and increased yield (Mirik *et al.*, 2008).

Induction of systemic resistance (ISR) and SAR

Plants have evolved defenses against abiotic and biotic stresses, including threats from herbivores, pests and

phytopathogens. Their defense mechanisms, known as systemic acquired resistance (SAR), remain dormant until activated by pathogens, triggering a widespread response throughout the plant (Pandey *et al.*, 2016; Pieterse *et al.*, 2014). Two types of plant systemic resistance are: induced systemic resistance (ISR) and systemic acquired resistance (SAR). ISR refers to resistance activated by beneficial microbes and is typically independent of salicylic acid (SA), while, SAR is termed when induced resistance is initiated by pathogens and is closely associated with the salicylic acid signaling pathway (Pieterse *et al.*, 2014; Yu *et al.*, 2022). Beneficial microorganisms can activate defense mechanisms in the host through various pathways, providing plants resistance against several pathogens. *B. cereus, B. atrophaeus, Bacillus amyloliquefaciens, Bacillus megaterium, Bacillus subtilis* and similar microbes have been indicated to be effective against bacterial, viral and fungal invasions through ISR (Yu *et al.*, 2022). Various studies investigated the impact of ISR-producing *Bacillus* spp. and SAR on phytopathogenic bacteria including *Erwinia carotovora* subsp. *Carotovora*, *Pseudomonas syringae* pv. *tomato*, *Pectobacterium carotovorum*, *Xanthomonas citri* subsp. *Citri* and *Clavibacter michiganensis* subsp. *Michiganensis* (Dadaşoğlu *et al.*, 2020; Jang *et al.*, 2022).

CONCLUSION

This review discusses the challenges posed by agrochemicals and explores viable alternatives, focusing on employing *Bacillus* species to biologically control plant-pathogenic bacteria (PPB). It also delves deeply into its mechanisms including antibiosis, the production of siderophores, lytic and hydrolytic, as well as ISR and SAR. Members of multiple *Bacillus* species, such as *Bacillus subtilis, Bacillus licheniformis, Bacillus megaterium, Bacillus cereus, Bacillus mycoides, Bacillus amyloliquefaciens* and *Bacillus pumilus*, are recognized as prolific producers of highly effective antibiotic molecules. These antibiotics, encompassing ribosomal (bacteriocins) and non-ribosomal cyclic peptides, inhibit the growth of phytopathogenic agents. Siderophore production is one of the main properties of *Bacillus* spp. enabling them to chelate iron and reduce its availability, thereby succeeding in competition with pathogens. *Bacillus* Species are recognized as valuable reservoirs for a wide range of enzymes. The hydrolytic enzymes found in *Bacillus* species, such as glucanases, cellulases, lipases, proteases, chitinases and chitosanases, may facilitate the effective degradation of key elements of bacterial and fungal cell walls. *Bacillus* spp. also create biofilm surrounding the root surface and releases toxic substances, including surfactin, macrolactin, bacillomycin, iturin and fengycin. This action results in the elimination of harmful bacterial populations and a decrease in disease incidence in plants. *Bacillus amyloliquefaciens, B. atrophaeus, B. cereus, Bacillus megaterium, Bacillus subtilis* and similar microbes have demonstrated efficacy against fungal, bacteria and viral invasions through induced systemic resistance. Finally, we recommend further in-depth research on beneficial bacteria such as *Bacillus* species and their genetic interactions with pathogens and plants to maintain biodiversity balance and mitigate the environmental challenges posed by pesticides.

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Conflict of interest

The author confirms the absence of any conflicts of interest related to the publication of this paper.

REFERENCES

Abriouel, H., Franz, C.M.A.P., Omar, N.B. and Gálvez, A. (2011). Diversity and applications of *Bacillus* bacteriocins. *FEMS Microbiology Reviews*. **35(1):** 201-232. https://doi.org/10.1111/j.1574-6976.2010.00244.x.

Basi-Chipalu, S., Sthapit, P. and Dhital, S. (2022). A review on characterization, applications and structure-activity relationships of *Bacillus* species-produced bacteriocins. *Drug Discoveries and Therapeutics*. **16(2):** 55-62. https://doi.org/10.5582/ddt.2021.01087.

Beneduzi, A., Ambrosini, A. and Passaglia, L.M.P. (2012). Plant growth-promoting rhizobacteria (PGPR): Their potential as antagonists and biocontrol agents. *Genetics and Molecular Biology*. **35(4 suppl 1):** 1044-1051. https://doi.org/10.1590/s1415-47572012000600020.

Blake, C., Christensen, M.N. and and Kovács, Á.T. (2021). Molecular aspects of plant growth promotion and protection by *Bacillus subtilis*. *Molecular Plant-Microbe Interactions®*. **34(1):** 15-25. https://doi.org/10.1094/mpmi-08-20-0225-cr.

Bottone, E.J. and Peluso, R.W. (2003). Production by *Bacillus pumilus* (MSH) of an antifun gal compound that is active against Mucoraceae and Aspergillus species preliminary report. *J. Med Microbiol.* **52(1):** 69-74. https://doi.org/10.1099/jmm.0.04935-0.

Buttimer, C., McAuliffe, O. and Ross, R.P., H.C., O'Mahony J. and Coffey, A. (2017). Bacteriophages and bacterial plant diseases. *Front. Microbiol.* **8:** 34.

Cawoy, H., Bettiol, W., Fickers, P. and Onge, M. (2011). Pesticides in the Modern World - Pesticides Use and Management. https://doi.org/10.5772/17184.

Chaisit Preecha, Sadowsky, M.J. and Prathuangwong, S. (2010). Lipopeptide surfactin produced by *Bacillus amyloliquefaciens* KPS46 is required for biocontrol efficacy against *Xanthomonas axonopodis* pv. *glycines*. *Kasetsart Journal Natural Sciences*. **44(1):** 84-99.

Cladera-Olivera, F., Caron, G.R. and Brandelli, A. (2004). Bacteriocin-like substance production by *Bacillus licheniformis* strain P40. *Letters in Applied Microbiology*. **38(4):** 251-256. https://doi.org/10.1111/j.1472-765x.2004.01478.x.

Collins, D.P. and Jacobsen, B.J. (2003). Optimizing a *Bacillus subtilis* isolate for biological control of sugar beet cercospora leaf spot. *Biological Control.* **26(2):** 153-161. https://doi.org/10.1016/s1049-9644(02)00132-9.

Dadaşoğlu, F., Maldonado Coy, J.F., Özyurt, G. and Kotan, R. (2020). *In vitro* effect of bacterial biocontrol organisms against *Pectobacterium carotovorum* on potato. *Journal of Agricultural Production.* **1(1):** 8-11. https://doi.org/10.29329/agripro.2020.341.3.

Elshakh, A.S.A., Anjum, S.I., Qiu, W., Almoneafy, A.A., Li, W., Yang, Z., Cui, Z.Q., Li, B., Sun, G.C. and Xie, G.L. (2016). Controlling and defence-related mechanisms of *Bacillus* strains against bacterial leaf blight of rice. *Journal of Phytopathology.* **164(7-8):** 534-546. https://doi.org/10.1111/jph.12479.

Etesami, H., Jeong, B.R. and Glick, B.R. (2023). Potential use of *Bacillus* spp. as an effective biostimulant against abiotic stresses in crops-A review. *Current Research in Biotechnology.* **5:** 100128. https://doi.org/10.1016/j.crbiot.2023.100128.

Fan, B., Wang, C., Song, X., Ding, X., Wu, L., Wu, H., Gao, X. and Borriss, R. (2018). Bacillus velezensis FZB42 in 2018: The gram-positive model strain for plant growth promotion and biocontrol. *Front. Microbiol.* **9:** 2491. doi: 10.3389/fmicb.2018.02491.

Fan, B., Wang, C., Song, X., Ding, X., Wu, L., Wu, H., Gao, X. and Borriss, R. (2019) Corrigendum: Bacillus velezensis FZB42 in 2018: The gram-positive model strain for plant growth promotion and biocontrol. *Front. Microbiol.* **10:** 1279. doi: 10.3389/fmicb.2019.01279.

Farace, G., Fernandez, O., Jacquens, L., Coutte, F., Krier, F., Jacques, P., Clément, C., Barka, E.A., Jacquard, C. and Dorey, S. (2014). Cyclic lipopeptides from *Bacillus subtilis* activate distinct patterns of defence responses in grapevine. *Molecular Plant Pathology.* **16(2):** 177-187. https://doi.org/10.1111/mpp.12170.

Gautam, S., Chauhan, A., Sharma, R., Sehgal, R. and Shirkot, C.K. (2019). Potential of *Bacillus amyloliquefaciens* for biocontrol of bacterial canker of tomato incited by *Clavibacter michiganensis* ssp. *michiganensis*. *Microbial Pathogenesis*. **130:** 196-203. https://doi.org/10.1016/j.micpath.2019.03.006.

Glick, B.R. (1995). The enhancement of plant growth by free-living bacteria. *Canadian Journal of Microbiology.* **41(2):** 109-117. https://doi.org/10.1139/m95-015.

Guleria, S., Walia, A., Chauhan, A. and Shirkot, C.K. (2016). Molecular characterization of alkaline protease of *Bacillus amyloliquefaciens* SP1 involved in biocontrol of *Fusarium oxysporum. International Journal of Food Microbiology.* **232:** 134-143. https://doi.org/10.1016/j.ijfoodmicro.2016.05.030.

Gupta, R. and Ramnani, P. (2006). Microbial keratinases and their prospective applications: An overview. *Applied Microbiology and Biotechnology.* **70(1):** 21-33. https://doi.org/10.1007/s00253-005-0239-8.

Haas, D. and Défago, G. (2005). Biological control of soil-borne pathogens by fluorescent pseudomonads. *Nature Reviews Microbiology.* **3(4):** 307-319. https://doi.org/10.1038/nrmicro1129.

Haque, M.A., Wang, F., Chen, Y., Hossen, F., Islam, M.A., Hossain, M.A., Siddique, N., He, C. and Ahmed, F. (2022). *Bacillus* spp. Contamination: A novel risk originated from animal feed to human food chains in South-Eastern Bangladesh. *Frontiers in Microbiology*. **12.** https://doi.org/10.3389/fmicb.2021.783103.

Haque, M.M., Mosharaf, M.K., Khatun, M., Haque, M.A., Biswas, M.S., Islam, M.S., Islam, M.M., Shozib, H.B., Miah, M.M.U., Molla, A.H. and Siddiquee, M.A. (2020). Biofilm producing rhizobacteria with multiple plant growth-promoting traits promote growth of tomato under water-deficit stress. *Frontiers in Microbiology.* **11.** https://doi.org/10.3389/fmicb.2020.542053.

Harirchi, S., Sar, T., Ramezani, M., Aliyu, H., Etemadifar, Z., Nojoumi, S.A., Yazdian, F., Awasthi, M.K. and Taherzadeh, M.J. (2022). Bacillales: From Taxonomy to Biotechnological and Industrial Perspectives. *Microorganisms.* **10(12):** 2355. https://doi.org/10.3390/microorganisms10122355.

Huang, J., Wei, Z., Tan, S., Mei, X., Shen, Q. and Xu, Y. (2014). Suppression of bacterial wilt of tomato by bioorganic fertilizer made from the antibacterial compound producing strain *Bacillus amyloliquefaciens* HR62. *Journal of Agricultural and Food Chemistry*. **62(44):** 10708-10716. https://doi.org/10.1021/jf503136a.

Islam Shafiqul, M.D., Hasanuzzaman, M. and M.D, A. (2025). Heat stress tolerance indices and their contribution in identifying heat tolerant bottle gourd [*Lagenaria siceraria* (Molina) Standl.] genotypes . *Indian Journal of Agricultural Research*. **59(6):** 859-867. https://doi.org/10.18805/IJARe.AF-926.

Jang, H., Kim, S.T. and Sang, M.K. (2022). Suppressive effect of bioactive extracts of *Bacillus* sp. H8-1 and *Bacillus* sp. K203 on tomato wilt caused by *Clavibacter michiganensis* subsp. *Michiganensis Microorganisms.* **10(2):** 403. https://doi.org/10.3390/microorganisms10020403.

Jörg Stülke, Grüppen, A., Bramkamp, M. and Pelzer, S. (2023). *Bacillus subtilis*, a Swiss Army knife in science and biotechnology. *American Society for Microbiology.* **205(5).** https://doi.org/10.1128/jb.00102-23.

Kannan, R., Dhivya, V. and V., S. (2023). Promoting rhizosphere microorganisms and biopesticides: A review. *Agricultural Reviews*. **44(4):** 485-492. https://doi.org/10.18805/ag.R-2262.

Kannan, V.R. and Bastas and (Eds.), K.K. (2015). Sustainable Approaches to Controlling Plant Pathogenic Bacteria. CRC Press. https://doi.org/10.1201/b18892 .

Karimi, E., Aliasgharzad, N., Esfandiari, E., Hassanpouraghdam, M.B., Neu, T.R., Buscot, F., Reitz, T., Breitkreuz, C. and Tarkka, M.T. (2022). Biofilm forming rhizobacteria affect the physiological and biochemical responses of wheat to drought. *AMB Express.* **12(1).** https://doi.org/10.1186/s13568-022-01432-8.

Khan, S., Srivastava, S., Karnwal, A. and Malik, T. (2023). Streptomyces as a promising biological control agents for plant pathogens [Review]. *Frontiers in Microbiology.* **14.** https://doi.org/10.3389/fmicb.2023.1285543.

Kloepper, J.W., Lifshitz, R. and Zablotowicz, R.M. (1989). Free-living bacterial inocula for enhancing crop productivity. *Trends in Biotechnology.* **7(2):** 39-44. https://doi.org/10.1016/0167-7799(89)90057-7.

Kloepper, J.W., Ryu, C.M. and Zhang, S. (2004). Induced systemic resistance and promotion of plant growth by *Bacillus* spp. Phytopathology®. **94(11):** 1259-1266. https://doi.org/10.1094/phyto.2004.94.11.1259.

Kumar, J., Ramlal, A., Mallick, D. and Mishra, V. (2021). An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants*. **10(6):** 1185. https://doi.org/10.3390/plants10061185.

Kumar, M., Brar, A., Yadav, M., Chawade, A., Vivekanand, V. and Pareek, N. (2018). Chitinases-potential candidates for enhanced plant resistance towards fungal pathogens. *Agriculture*. **8(7):** 88. https://doi.org/10.3390/agriculture8070088.

Kumar, S., J.K., Monica, S.S., Vinothkumar, B., Suganthi, A. and M., P. (2024). Impact of pesticide exposure on environment and Biodiversity: A review. *Agricultural Reviews*. **45(1):** 01-12. https://doi.org/10.18805/ag.R-2325.

Li, Y., Gu, Y., Li, J., Xu, M. and, W.Q. and Y., W. (2015). Biocontrol agent *Bacillus amyloliquefaciens* LJ02 induces systemic resistance against cucurbits powdery mildew. *Frontiers in Microbiology*. **6.** https://doi.org/10.3389/fmicb.2015.00883.

Li, Z., Cui, S., Anne de Jong and Kuipers, O.P. (2019). Draft genome sequences of six *Bacillus* Strains and one brevibacillus strain isolated from the rhizosphere of perennial ryegrass (*Lolium perenne*). *Microbiology Resource Announcements*. **8(4).** https://doi.org/10.1128/mra.01586-18.

Liu, Y., Su, A., Tian, R., Li, J., Liu, L. and Du, G. (2020). Developing rapid growing *Bacillus subtilis* for improved biochemical and recombinant protein production. *Metabolic Engineering Communications*. **11:** e00141. https://doi.org/10.1016/j.mec.2020.e00141.

Logan, N.A. and P.D.V. (2009). *Bacillus*. In: Bergey's Manual of Systematics of Archaea and Bacteria. George M. Garrity (red.) *et al.* John Wiley and Sons, Inc. **41.**

Mahapatra, S., Yadav, R. and Ramakrishna, W. (2022). *Bacillus subtilis* impact on plant growth, soil health and environment: Dr. Jekyll and Mr. Hyde. *Journal of Applied Microbiology*. **132(5):** 3543-3562. https://doi.org/10.1111/jam.15480.

Mansfıeld, Genin, S., Toth, I., Magori, S., Salmond, G., Citovsky, V., Sriariyanum, M., Ronald, P., Dow, M., Verdier, V., Machado8, M.A., Foster, G.D. and Beer7, S.V. (2012). Top 10 plant pathogenic bacteria in molecular plant pathology. *Molecular Plant Pathology*. **13(6):** 614-629. https://doi.org/10.1111/J.1364-3703.2012.00804.X.

Márquez, M.C., Sánchez-Porro, C. and Ventosa, A. (2011). Halophilic and Haloalkaliphilic, Aerobic Endospore-forming Bacteria in Soil. pp.309-339. doi:10.1007/978-3-642-19577-8_16.

Martins, P.M.M., Merfa and M.V., T., M.A. and De Souza, A.A. (2018). Persistence in Phytopathogenic Bacteria: Do We Know Enough? https://doi.org/10.3389/fmicb.2018.01099.

Miljaković, D., Marinković, J. and Balešević-Tubić, S. (2020). The significance of *Bacillus* spp. in disease suppression and growth promotion of field and vegetable crops. *Microorganisms*. **8(7): 1037** doi:10.3390/microorganisms8071037.

Miljaković D., Marinković J., Tamindžić G., Đorđević V., Ignjatov M., Milošević D. and Z., N. (2022). Effect of plant growth promoting *Bacillus* spp. on germination and seedling growth of soybean. *Legume Research*. **45(4):** 487-491. https://doi.org/10.18805/LRF-665.

Mirik, M., Aysan, Y. and Özden, Ç. (2008). Biological control of bacterial spot disease of pepper with *Bacillus* strains. *Turkish Journal of Agriculture and Forestry*. **32(5).**

Mora, I., Jordi Cabrefiga and Seguí, E.M. (2011). Antimicrobial peptide genes in *Bacillus* strains from plant environments. *PubMed*. **14(4):** 213-223. https://doi.org/10.2436/20.1501.01.151.

Mora, I., Jordi Cabrefiga and Seguí, E.M. (2015). Cyclic lipopeptide biosynthetic genes and products and inhibitory activity of plant-associated *Bacillus* against phytopathogenic bacteria. *PLOS ONE*. **10(5):** e0127738-e0127738. https://doi.org/10.1371/journal.pone.0127738.

Mouloud, G., Daoud, H., Bassem, J., Laribi Atef, I. and Hani, B. (2013). New bacteriocin from *Bacillus clausii* strainGM17: purification, characterization and biological activity. *Applied Biochemistry and Biotechnology*. **171(8):** 2186-2200. https://doi.org/10.1007/s12010-013-0489-3.

Ongena, M., Jacques, P., Touré, Y., Destain, J., Jabrane, A. and Thonart, P. (2005). Involvement of fengycin-type lipopeptides in the multifaceted biocontrol potential of *Bacillus subtilis*. *Applied Microbiology and Biotechnology*. **69(1):** 29-38. https://doi.org/10.1007/s00253-005-1940-3.

Pal, K.K. and McSpadden Gardener, B. (2006). Biological control of plant pathogens. *The Plant Health Instructor*. **2:** 1117-1142. https://doi.org/10.1094/phi-a-2006-1117-02.

Pandey, D., Rajendran, S.R.C.K., Gaur, M., Sajeesh, P.K. and Kumar, A. (2016). Plant defense signaling and responses against necrotrophic fungal pathogens. *Journal of Plant Growth Regulation*. **35(4):** 1159-1174. https://doi.org/10.1007/s00344-016-9600-7.

Pieterse, C.M.J., Zamioudis, C., Berendsen, R.L., Weller, D.M., Van Wees, S.C.M. and Bakker, P.A.H. M. (2014). Induced systemic resistance by beneficial microbes. *Annual Review of Phytopathology*. **52(1):** 347-375. https://doi.org/10.1146/annurev-phyto-082712-102340.

Pinos, D. andrés-Garrido, A., Ferré, J. and Hernández-Martínez, P. (2021). Response mechanisms of invertebrates to *Bacillus thuringiensis* and its pesticidal proteins. *Microbiology and Molecular Biology Reviews*. **85(1).** https://doi.org/10.1128/mmbr.00007-20.

Planas, A. (2000). Bacterial 1,3-1,4-β-glucanases: Structure, function and protein engineering. *Biochimica et Biophysica Acta*. **1543:** 361-382. https://doi.org/10.1016/S0167-4838(00)00231-4.

Radhakrishnan, R., Hashem, A. and Abd_Allah, E.F. (2017). *Bacillus*: A Biological tool for crop improvement through bio-molecular changes in adverse environments. *Frontiers in Physiology*. **8:** 667. https://doi.org/10.3389/fphys.2017.00667.

Ramirez-Olea, H., Reyes-Ballesteros, B. and Chavez-Santoscoy, R.A. (2022). Potential application of the probiotic *Bacillus licheniformis* as an adjuvant in the treatment of diseases in humans and animals: A systematic review. *Frontiers in Microbiology*. **13.** https://doi.org/10.3389/fmicb.2022.993451.

Rizzo, D.M., Lichtveld, M. and Mazet, J.A.K., Togami, E. and Miller, S.A. (2021). Plant health and its effects on food safety and security in a one health framework: Four case studies. *One Health Outlook*. **3(1).** https://doi.org/10.1186/s42522-021-00038-7.

Saber, W.I.A., Ghoneem, K.M., Al-Askar, A.A., Rashad, Y.M., Ali, A.A. and Rashad, E.M. (2015). Chitinase production by *Bacillus subtilis* ATCC 11774 and its effect on biocontrol of Rhizoctonia diseases of potato. *Acta Biologica Hungarica.* **66(4):** 436-448. https://doi.org/10.1556/018.66.2015.4.8.

Saha, M., Sarkar, S., Sarkar, B., Sharma, B.K., Bhattacharjee, S. and Tribedi, P. (2016). Microbial siderophores and their potential applications: A review. *Environmental Science and Pollution Research.* **23(5):** 3984-3999. https://doi.org/10.1007/s11356-015-4294-0.

Said, M. (2023). An overview of impact of agrochemicals on human health and natural environment. *Scientific Research Communications*. **3(2):** 2023. https://doi.org/10.52460/src.2023.009.

Satyadev Prajapati, N.K., Kumar, S., Lakharan, L. and Maurya, S. (2020). Biological control a sustainable approach for plant diseases management: A review. *Journal of Pharmacognosy and Phytochemistry.* **9(2):** 1514-1523.

Sella, S.R.B.R., Vandenberghe, L. and P.S., S., C.R. (2014). *Bacillus atrophaeus*: Main characteristics and biotechnological applications- A review. *Critical Reviews in Biotechnology.* **35(4):** 533-545 https://doi.org/10.3109/07388551.2014.922915.

Sharma, A., Gupta, A.K. and Devi, B. (2023). Current trends in management of bacterial pathogens infecting plants. *Antonie van Leeuwenhoek*. **116:** 303-326. https://doi.org/10.1007/s10482-023-01809-0.

Silva, L.A.D., Macedo, A.J. and Termignoni, C. (2014). Production of keratinase by *Bacillus subtilis* S14. *Annals of Microbiology*. **64(4):** 1725-1733. https://doi.org/10.1007/s13213-014-0816-0.

Strange, R.N.A. and Scott, P.R. (2005). Plant disease: A threat to global food security. *Annu. Rev. Phytopathol.* **43:** 83-116. https://doi.org/10.1146/annurev.phyto.43.113004.133839.

Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C. and Phung, D.T. (2021). Agriculture development, pesticide application and its impact on the environment. *International Journal of Environmental Research and Public Health.* **18(3).** https://doi.org/10.3390/ijerph18031112.

Ugras, Serpil, Kazim Sezen , Hatice Kati , A. and Demirbag, Z. (2013). Purification and characterization of the bacteriocin thuricin bn1 produced by *Bacillus thuringiensis* subsp. *kurstaki* Bn1 isolated from a hazelnut pest. *Journal of Microbiology and Biotechnology.* **23(2):** 167-176. https://doi.org/10.4014/jmb.1209.09056.

Verhaegen, M., Stancanelli, G., Bergot, T., Liebana, E., Streissl, F., Mingeot-Leclercq, M.P., Mahillon, J. and Bragard., C. (2023). On the use of antibiotics to control plant pathogenic bacteria: A genetic and genomic perspective.fmicb. *Frontiers in Microbiology.* **122:** 1478. https://doi.org/10.3389.

Wei, X., Di, X., Xin, Y., Zhang, H., Wang, T. and Zhang, J. (2015). *Bacillus* depressus sp. nov., isolated from soil of a sunflower field. *Antonie van Leeuwenhoek.* **109(1):** 13-20. https://doi.org/10.1007/s10482-015-0605-1.

Yu, Y., Gui, Y., Li, Z., Jiang, C., Guo, J. and Niu, D. (2022). Induced systemic resistance for improving plant immunity by beneficial microbes. *Plants.* **11(3):** 386. https://doi.org/10.3390/plants11030386.

Zhou, J., Xie, Y., Liao, Y., Li, X., Li, Y., Li, S., Ma, X., Lei, S., Lin, F., Jiang, W. and He, Y. (2022). Characterization of a *Bacillus velezensis* strain isolated from *Bolbostemmatis rhizoma* displaying strong antagonistic activities against a variety of rice pathogens. *Frontiers in Microbiology.* **13.** https://doi.org/10.3389/fmicb.2022.983781.