



AGRI MAGAZINE

(International E-Magazine for Agricultural Articles)

Volume: 03, Issue: 06 (June, 2026)

Available online at <http://www.agrimagazine.in>

© Agri Magazine, ISSN: 3048-8656

Role of *Bacillus* spp. in Sustainable Agriculture and Disease Management

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Plant diseases impact agricultural output and cause significant yield losses. They are caused by a variety of microbes, such as bacteria, viruses, nematodes, fungus, and protozoa. Pathogenic infections account for between 20 and 40 percent of crop output losses. Pesticides, less sensitive cultivars, crop rotation, and other control methods have all been used to lessen the incidence of plant diseases, but their effectiveness is typically insufficient because of the persistence and resistance of soil-borne infections. Furthermore, overuse of synthetic pesticides disrupts ecosystem functioning, reduces agricultural sustainability, and has negative consequences on the environment and living things. These days, research focuses on eco-friendly ways to reduce plant diseases and boost crop yields.

The most significant alternative that helps decrease plant diseases through competition or antagonism may be *Bacillus* species. *Bacillus* species inhibit the growth of pathogens by a variety of processes, including competition for nutrients and space, the synthesis of antibiotics, hydrolytic enzymes, siderophores, or the induction of systemic resistance. Additionally, *Bacillus* species can function as biofertilizers or biostimulators by either supplying the plant with a chemical (biosynthesis of plant hormones) or enabling the uptake of specific nutrients from the environment (nitrogen fixation, phosphate solubilization). Therefore, *Bacillus* species are a substitute for agrochemicals that promote plant growth, such as artificial fertilizers and pesticides. The beneficial effects of *Bacillus* spp. on plant growth and yield have been reported in several agricultural crops. This article summarizes the different mechanisms utilized by *Bacillus* spp. in plant disease control and plant growth promotion.

Genus *Bacillus*

More than 200 species and subspecies from the phylum Firmicutes are included in the genus *Bacillus*, which was created by Cohn in 1872. Bacteria of this genus are classified as rod-shaped, Gram-positive, aerobic or facultatively anaerobic, and catalase-positive based on their morphological traits. *Bacillus* species are ubiquitous in a variety of habitats, including soil, and are resistant to harsh environmental circumstances because of their extensive physiological ability and capacity to generate endospores. Up to 95% of the Gram-positive bacterial communities in soil and the rhizosphere are *Bacillus* species. They are also among of the most common endophytic bacteria. Commercial *Bacillus*-based preparations are developed and distributed worldwide and contain beneficial strains of *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus pumilus*, *Bacillus licheniformis*, *Bacillus megaterium*, *Bacillus velezensis*, *Bacillus cereus* and *Bacillus thuringiensis*, etc.

Mechanisms of Biological Control

Antibiotics: The generation of secondary metabolites with antibiotic qualities is often associated with the antagonistic activities of *Bacillus* species. These substances mostly consist of low molecular weight peptides that are produced either non-ribosomally (lipopeptides, peptides, polyketides) or ribosomally (bacteriocins). Many bacteria create ribosomally manufactured peptides called bacteriocins, which may be effective against pathogenic and antibiotic-resistant bacteria. Bacteriocins work against target cells by either creating holes in the cell membrane or interfering with the formation of the cell wall. The most researched antibiotic compounds in *Bacillus* species are cyclic lipopeptides (LPs), which are well-known for their antagonistic effect against a variety of plant diseases. These peptides are synthesized by large non-ribosomal peptide synthetases (NRPSs). The primary mechanisms of LPs' actions usually involve an interaction with the cell membrane of the target pathogens, causing changes in its structure and permeability through disruption, solubilization or formation of ion-conducting pores.

Lytic Enzymes: The production of hydrolytic enzymes such chitinases, chitosanases, glucanases, cellulases, lipases, and proteases, which effectively hydrolyze the main constituents of the bacterial and fungal cell walls, may also contribute to the antimicrobial activity of *Bacillus* species. Chitinases are glycoside hydrolases (GHs) that break down the β -1,4-glycosidic linkages in chitin, which is the primary component of fungal cell walls and the second most abundant naturally occurring polysaccharide after cellulose. While some bacterial chitinases are potential biological control agents against a number of plant diseases caused by phytopathogenic fungus, bacteria mainly manufacture chitinases to break down chitin for use as an energy source. The synthesis of lytic enzymes from *Bacillus* spp. biocontrol agents has been reported in a number of recent studies.

Rhizoctonia solani was successfully combated by *B. subtilis*, which produces chitinase. *Fusarium oxysporum* was effectively biocontrolled by both crude and purified *B. amyloliquefaciens* protease. *B. amyloliquefaciens*'s capacity to biocontrol *Clavibacter michiganensis*. The synthesis of lytic enzymes (cellulase, lipase, protease, and chitinase) was linked to michiganensis. *Bacillus* sp. generated hydrolytic enzymes (protease, glucanase, and chitinase) that had a potent inhibitory effect on *Fusarium verticillioides*, which causes maize stalk and ear rot.

Siderophores: Certain microbes and plants, particularly those that are iron-starved, create siderophores, which are low molecular weight, non-ribosomal peptides that chelate metals. Many biological functions, including oxygen metabolism, DNA and RNA synthesis, electron transfer, and enzymatic reactions, depend on iron (Fe). Depending on the functional group, siderophores are divided into three major families, hydroxamates, catecholates, and carboxylates. The majority of bacterial siderophores are catecholates, such as bacillibactin, which is produced by a number of *Bacillus* species, including *B. subtilis*, *B. amyloliquefaciens*, *B. cereus*, *B. thuringiensis*, and others. Numerous siderophores, including pyoverdine, pyochelin, schizokinen, petrobactin, and others, are produced by *Bacillus* species in addition to bacillibactin. Compared to other bacterial isolates from the rhizosphere of maize, *Bacillus* species produced more siderophores. Numerous plant diseases have been suppressed by siderophores produced by *Bacillus* species. For example, siderophore-producing *B. subtilis* increased pepper growth and yield while decreasing the occurrence of Fusarium wilt.

Systemically Induced Disease Resistance: Plant defense mechanisms, including induced systemic resistance (ISR), can be triggered by a localized infection, leading to systemic acquired resistance (SAR), or they can be started by external agents prior to infection. To induce ISR in plants against several plant diseases, both biotic and abiotic stimuli have been employed. While SAR is mediated by a salicylic acid (SA)-dependent mechanism, ISR is facilitated by non-pathogenic rhizobacteria and primarily depends on the jasmonate (JA) and/or ethylene (ET) signaling pathways. By producing a variety of metabolites, including antibiotics, siderophores, volatile organic compounds (VOCs), and others, *rhizobacteria*

encourage ISR in plants. Among the most researched rhizobacteria that cause ISR in plants are *Bacillus* species, which can also induce resistance against many diseases in a single plant. *B. amyloliquefaciens* delayed the systemic accumulation of *Potato virus Y*, decreased the incidence of *Tomato spotted wilt virus*, and produced salicylic acid-dependent resistance in tomato plants. By activating ISR, the application of *B. cereus* dramatically decreased the incidence of disease caused by *Botrytis cinerea*. *B. subtilis* used ethylene (ET), jasmonic acid (JA), abscisic acid (ABA), and auxin signaling to induce ISR in rice against *Rhizoctonia solani*.

Mechanisms of Plant Growth Promotion

Nutrient Availability: Numerous metabolites produced by *Bacillus* species can enhance the availability of nutrients to plants, hence directly promoting plant growth and yield. The majority of the necessary nutrients for plants are provided via mineral fertilizer, a method that has serious negative effects on the environment and results in large financial losses. Using biofertilizers with N₂-fixing and P-solubilizing *Bacillus* species is a reasonable way to lessen the harmful effects of synthetic fertilizers without sacrificing food safety. *Bacillus* species that fix N₂ and solubilize P are directly linked to the intake of nutrients and the ensuing stimulation of plant growth. Nitrogen (N) is essential for plant growth, albeit largely unavailable in its atmospheric form (more than 80%). Biological nitrogen fixation (BNF) is carried out by several groups of microorganisms that are able to absorb elemental nitrogen from the atmosphere and form compounds, which serve as plant nutrients. The bacteria that fix nitrogen are either symbiotic or free-living. Through asymbiotic nitrogen fixation, a number of PGPR, such as *Bacillus* species, can boost plant growth. Up to 12–70% of the total N₂ uptake in agricultural crops has been found to be attributed to BNF by *rhizobacteria*. *B. pumilus* may fix atmospheric N₂ and greatly raise the total N₂ content and dry biomass of maize. Multiple *Bacillus* species key species including *B. megaterium*, *B. cereus*, *B. pumilus*, *B. circulans*, *B. licheniformis*, *B. subtilis*, *B. brevis*, and *B. firmus* exhibit significant nitrogenase activity, enabling them to function as free-living or associative nitrogen-fixing *rhizobacteria*.

Phytohormone Production: Through processes that promote the synthesis of phytohormones or plant growth regulators (PGRs), such as auxins, cytokinins, gibberellins, ethylene, and abscisic acid, *Bacillus* species may directly boost plant yield. Plant hormones are chemical compounds that, at extremely low concentrations, affect the physiology and growth of plants. The production of plant hormones by *Bacillus* species has been directly linked to the subsequent enhancement of growth in many plants. Auxins are a class of plant hormones that promote plant development primarily by controlling tissue differentiation, cell division, and cell elongation. Indole-3-acetic acid (IAA) is the primary auxin found in nature. A class of plant hormones known as gibberellins (GAs) influences a number of higher plant developmental processes, such as fruiting, flowering, stem elongation, and seed germination. Various studies documented the production of gibberellins by *B. pumilus* and *B. licheniformis*. By raising the percentage of lettuce, muskmelon, soybean, and vegetable mustard seeds that germinate, *Bacillus methylotrophicus* was shown to have a positive effect on plants through the release of a variety of gibberellins. A class of plant hormones known as cytokinins (CKs) is essential for encouraging cytokinesis, or cell division, in plant roots and shoots. Other physiological and developmental plant processes, including seed germination, apical dominance, nutrient mobilization, and leaf senescence, are significantly regulated by them. The gaseous plant hormone ethylene primarily controls the processes of maturity and senescence as well as the plant's reaction to biotic and abiotic stressors. Several PGPR, including *Bacillus* spp., synthesize the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase that modulates ethylene levels in plants which might otherwise become growth inhibitory. Abscisic acid (ABA) is a plant hormone with an important role in many plant physiological processes, including seed germination and stress tolerance. The bacterial endophyte *B. amyloliquefaciens* has been found to produce ABA and increase plant growth and resistance to salinity stress.

Conclusion

Beneficial *Bacillus* species stand out as exceptional, eco-friendly alternatives to harmful chemical fertilizers and synthetic pesticides by driving both plant growth promotion and biological disease control. Due to their high environmental resilience and unique ability to form durable endospores, excel at suppressing diverse plant pathogens. They successfully achieve this protection through active nutrient competition, antibiotic peptide production, cell-wall-degrading lytic enzymes, and iron-chelating siderophores, while simultaneously triggering induced systemic resistance within the host. Furthermore, they function as robust biofertilizers that optimize nutrient availability via biological nitrogen fixation and phosphate solubilization while synthesizing vital growth-promoting phytohormones. Ultimately, integrating these commercial bacterial formulations effectively maximizes sustainable crop yields while safely protecting biodiversity and preserving vital global ecosystem functions.