



REVIEW ARTICLE

# Microbial biofertilizers: A sustainable agricultural approach to augment crop resilience against biotic and abiotic stresses

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## Abstract

Increasing plant growth and yield with the aid of plant growth-promoting bacteria is a widely accepted, eco-friendly and economic approach in modern agriculture. Their use as an alternative to widely used harmful chemical fertilizers and pesticides can improve overall soil health and fertility, thereby enhancing crop yield. The positive modulation of genes related to growth and development, fruit formation, stress tolerance and phytohormone production helps plants significantly during maturation. Furthermore, the enhanced production and expression of defence-related hormones aid in survival under various stress conditions, such as drought, pH fluctuations, salinity and water stress. In addition, the application of growth-promoting bacteria, mainly from species such as *Azospirillum*, *Bacillus*, *Klebsiella*, *Enterobacter*, *Pseudomonas*, *Azotobacter*, *Burkholderia*, *Rhizobium*, *Alcaligenes*, *Arthrobacter* and *Serratia* supports plant growth and development by improving soil porosity, pH and salinity conditions. This review briefly outlines the role of the plant growth-promoting bacteria as microbial biofertilizers that enhance crop resilience under both biotic and abiotic stress conditions. By highlighting recent advances in understanding the mechanisms of microbe-plant interactions under these stresses, it also provides unique insights into how microbial biofertilizers can be employed for sustainable agriculture. This has direct relevance for policymakers and farmers by reducing dependence on chemical fertilizers, which have various negative impacts, thereby promoting long-term environmental sustainability and improved agricultural practices.

**Keywords:** defence; gene expression; growth promotion; phytohormones; plant stress; rhizobacteria

## Introduction

Plant growth depends on various factors, namely light, water, soil type, temperature and multiple macro- and micro-nutrients. Among these, microbial association is one of the most important factors that positively affects plant growth (1). Some microbes play an important role in supporting plant growth by initiating mutualistic association in the root, solubilizing inorganic compounds in the soil, degrading and mineralizing organic compounds, fixing atmospheric nitrogen, solubilizing inorganic phosphate and mediating the secretion of biologically active substances such as chelators, phytohormones and antibiotics. Examples of plant growth-promoting bacteria are mainly from species such as *Azospirillum*, *Bacillus*, *Klebsiella*, *Enterobacter*, *Pseudomonas*, *Azotobacter*, *Burkholderia*, *Rhizobium*, *Alcaligenes*, *Arthrobacter* and *Serratia* (2). Plants are targeted by a plethora of pathogens, from small species such as viroids to larger species such as bacteria, oomycetes, viruses, fungi and nematodes, all of which contribute significantly to reduced crop productivity. Studies indicate that 20–40 % of loss in crop productivity is due to pathogen infection (3). These microbes primarily act through the synthesis of iron-chelating siderophores, chitinase-like lytic enzymes,  $\beta$ -1,3-glucanase and other biocontrol agents, which enable colonization around specific plant tissues such as stems, roots, fruits and leaves, thereby promoting protection against various pathogens (4).

According to FAOSTAT, the total use of chemical pesticides in 2021 reached an alarming 3.54 million tonnes (5). Chemical fertilizers alter the physico-chemical and biological properties of soil and degrade the quality of groundwater. They also reduce soil fertility, weaken microbial activity, alter soil pH, cause acidification, harden soil texture, decrease the availability of essential nutrients and minerals and may even contribute to the emission of greenhouse gases. For instance, organochlorine insecticides such as endrin, aldrin, dieldrin and endosulfan cause food poisoning, whereas C14-DDT, heptachlor and chlorpyrifos affect the metabolism of animals and interfere with the proper functioning of internal organs (6, 7). Due to excessive pesticide use, soil degradation and other anthropogenic actions, the concentrations of elements such as Ni, Cr, Zn, Cd, Pb, As, Cu and Co increase significantly (8). However, only H, C, O, N, K, P, Mg, Ca, Fe, S, B, Cl, Zn, Mo, Cu, Ni and Mn function as essential elements required for plant growth, development and optimal production (9).

Another important factor that plays a major role in plant growth is phytohormones such as IAA, ABA, cytokinin, jasmonic acid, gibberellins and salicylic acid (10). Numerous strains of *Azospirillum brasilense* promote plant growth by upregulating the production of plant phytohormones, mainly IAA, zeatin (Z), GA<sub>3</sub>, ABA and ethylene. They also produce growth regulators such as putrescine, spermidine, spermine and cadaverine (11). The genus

*Bacillus* has great importance in the biocontrol of plant pathogens through the production of antibiotics, siderophores and enzymes such as cell wall hydrolases. Several *Bacillus* species with antibacterial properties have been reported, including *B. subtilis*, *B. amyloliquefaciens*, *B. thuringiensis*, *B. coagulans* and *B. cereus* (12). *Bacillus subtilis* can solubilize soil phosphate, enhance nitrogen fixation and exhibit antioxidant properties (13). *Klebsiella* spp. influence plant growth and yield by producing various organic acids. These organic acids help produce indole compounds, solubilize phosphate in the soil ( $550.16 \pm 0.04 \mu\text{g/mL}$ ), enhance siderophore and ACC deaminase production and play a significant role in nitrogen fixation (14). *Azospirillum*, *Cyanobacteria* and *Azocarus* also exhibit a high capacity for nitrogen fixation (15). Nitrogen-fixing bacteria are classified into different genera: *Rhizobium* (fast-growing), *Mesorhizobium*, *Sinorhizobium* and *Bradyrhizobium* (slow-growing). These bacteria form symbiotic associations with plants and are present in root nodules (16). Omics techniques can be adopted to sense signals and observe plant characteristics related to soil metabolites, salinity, minerals and metals (17).

In the microbial root zone, plant growth-promoting rhizobacteria (PGPR), nodule-promoting rhizobacteria (NPR) and plant health-promoting rhizobacteria (PHPR) initiate interactions within the rhizosphere region (18). The rhizosphere effect determines the structure of the microbial flora present in different regions and it varies between cultivated and uncultivated soils (19). The bacteria present in the rhizosphere can recognise chemical signals from the roots and respond accordingly. PGPR can secrete compounds with antimicrobial and antibiotic properties and their volatile compounds can restrict the growth and colonization of potentially phytopathogenic microorganisms, thereby keeping the plant healthy (20, 21).

Hence, this review discusses the importance of microbial fertilizers as an environmentally sustainable strategy in agriculture, designed to improve crop resilience against both biotic and abiotic stress factors, along with their underlying mechanisms. It also evaluates future perspectives and identifies the existing research gaps.

### Microbes and plant interaction

The association of plant hosts with a group of microorganisms in the plant holobiont is influenced by several parameters that affect the interaction between the plant and the microbial consortium for enhanced plant growth (22). The selected microbes for inoculation must fulfil specific criteria for supporting plant growth and development by acting as plant strengtheners, biopesticides, biofertilizers or phytostimulators. These microbes are highly target-specific and effective in very small quantities, as they can multiply on their own but function under the regulation of both the plant and the local microbial communities (23). The various mechanisms

through which microbial biofertilizers function as plant growth regulators include the induction of signaling pathways, hormone and enzyme production, phosphorus and potassium solubilization, nitrogen fixation and enzymatic probiotics (AAC deamination) (18). The PGPR act on the plant through both direct and indirect mechanisms, as demonstrated in Table 1. The direct mechanisms include enhanced solubilization of potassium and phosphate, biological nitrogen fixation and increasing the production of various phytohormones. In contrast, the indirect mechanisms involve increased allelochemical biosynthesis, induced resistance against pathogens and antimicrobial production. These mechanisms vary according to plant species, climate, soil pH, salinity, water and nutrient availability and the different barriers present in the immediate environment (24).

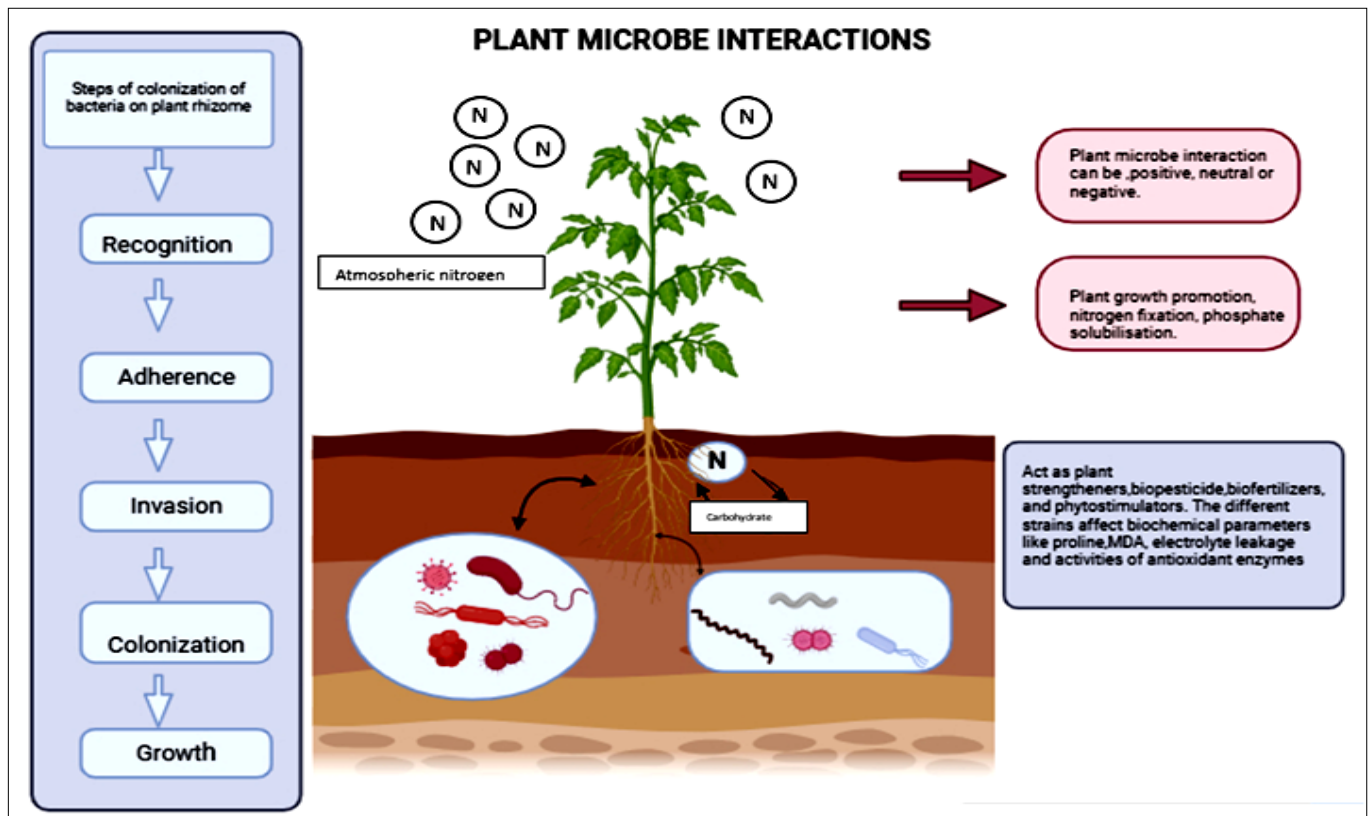
The application of chemical pesticides such as pyriproxyfen, fipronil, thiamethoxam and imidacloprid severely affects the phosphate-solubilizing activity of the strain, while thiamethoxam, pyriproxyfen, fipronil and imidacloprid also affect its salicylic acid production. Plant exudates contain a variety of organic and inorganic compounds, including carbohydrates, carboxylic acids, phenolics, amino acids, protons and other inorganic ions, which can alter the chemical and biological nature of the root microenvironment according to the specific requirements of the plant (25).

Some microbes are capable of colonizing both the aerial parts and the roots/soil of plants and can induce the production of antibiotics and organic volatile compounds that protect the plant from the attack of pathogenic bacteria, as shown in Fig. 1. For instance, *B. amyloliquefaciens* strain GB03 can enhance plant tolerance to drought conditions (26). *Pseudomonas fluorescens* can produce vitamins that support better plant growth and survival under adverse conditions. Co-inoculation of *P. fluorescens* and *Rhizobium* has been shown to improve symbiotic nitrogen fixation in different plant species, particularly in clover. Chitinase, cellulase and lyases are important enzymes that can lyse fungal cell walls and protect plants from severe fungal attacks. The volatile antibiotic compound hydrogen cyanide (HCN), produced by specific bacterial strains under stress conditions, plays a pivotal role in disease suppression (27). Multi-strain biological control agents (MSBCAs) can be used to increase stability and disease resistance. These MSBCAs stimulate the synthesis of antimicrobial substances, biofilm formation, syntrophic microbial growth, migration process, competition for resources and plant defence responses. Differentiating between plant growth-promoting bacteria and disease-suppressing bacteria is challenging, as they colonize the plant rhizosphere in a similar manner and often coexist (28).

The microbes present in the soil and plant roots cross-talk with each other through signals, which can be phytohormones, volatile compounds produced by plants, or other small molecules. Among plant-derived signals, phytohormones such as cytokinin

**Table 1.** Mechanism of action of plant growth-regulating rhizobacteria

Direct mechanism	Indirect mechanism
Uplift the nitrogen fixation	Increases the systematic acquired resistance against different pathogens
Enhances the potassium and phosphate solubilization	Protect the plant from fungi and nematode attack
Magnify the production of IAA, gibberellic acid, abscisic acid and cytokinin	Allelochemical biosynthesis is uplifted
Produces extracellular polysaccharides and exopolysaccharides	Enhances the production of antimicrobials in the plant
Enhances the production of ACC deaminase, volatile compounds and non-volatile compounds	Increases the production of PR proteins for the resistance mechanism



**Fig. 1.** The plant-microbe interactions and steps of colonization.

and auxin play a major role, whereas microbial signals include *N*-acyl-L-homoserine lactones (AHLs) and volatile compounds such as acetoin and 2,3-butanediol. AHLs are composed of a homoserine lactone residue linked to an acyl side chain and are involved in siderophore production, swarming, plasmid conjugal transfer and antibiotic biosynthesis (29).

The quorum-sensing mechanism is used within bacterial populations for efficient signal transduction. Bacteria employ Type III and Type IV secretion systems to deliver proteins or DNA-protein complexes into target plant cells (30). The Type III system transfers Yop proteins from *Yersinia*, Inv proteins from *Shigella* and *Salmonella*, Avr proteins from phytopathogenic *Pseudomonas* and *Xanthomonas* and other virulence factors from *Escherichia coli*. The induction of the hypersensitive response and the presence of pathogenicity-associated genes are observed in pathogenic variants of *Ralstonia*, *Xanthomonas*, *Pseudomonas* and *Erwinia*. Chaperone-like proteins and a specialized secretory apparatus are essential for *Yersinia enterocolitica* to secrete YopE and YopH proteins into the host plant (31). However, the *Streptomyces* species form filamentous outgrowths on the plant root, aerial parts and the associated soil. They produce active antibiotics and lytic enzymes that can solubilize insoluble organic polymers and volatile organic compounds for the survival of the host. *Rhizophagus irregularis* CD1 promotes plant growth and has been shown to make plants wilt-resistant after *Verticillium* infection. *Microbotryum lychnidis-dioicae* causes anther smut disease in the plants, while *Methylobacterium* sp. Cp3 is known to infect seeds and transmit to later generations (30, 32). The induced plant defense mechanism produces reactive oxygen species, pathogenesis-related (PR) proteins, phytoalexins and phenolic compounds. MSBCAs are capable of producing these and various other potential microbe-associated molecular patterns (MAMPs) such as EF-Tu, glucan, superoxide dismutase, a 23-amino-acid peptide, Pep13 trans-glutaminase, sterol-binding elicitors, cellulose-binding elicitors, chitin and xylan which can act as defense

elicitors. *Phytophthora megasperma* and *Trichoderma viride* are organisms known to produce specific MAMPs. Lipophilic MAMPs include ergosterol and arachidonic acid, while oligosaccharide MAMPs include several N-glycosylated yeast peptides (33).

#### Microbes and plant biotic stress

Biotic stress affects mitochondrial homeostasis and elevates the formation of mitochondrial reactive oxygen species. This causes dysfunction of mitochondrial genes and gradually leads to cell death. Biotic stress results in necrosis, morphological modifications, chlorosis and eventually death of the infected tissue (34, 35). Viruses, nematodes, herbivorous insects, fungi and bacteria destroy plants by causing irregularities in their metabolism. Pesticides and fungicides can restrict the action of some biotic stresses to a certain extent. Biotic stress also affects the phyllosphere microflora and is countered by numerous physical and chemical barriers. The chemical barriers consist of toxic secondary metabolites and proteins that inhibit the enzymatic activity. Rotting bacteria are necrotrophic; *Phytophthora* and many viruses are hemibiotrophic; while fungal mildews and nematodes are biotrophic. The plant defense mechanism leads to the thickening of the cell wall, defense gene modulation by transcription and translation and to apoplast acidification (36). However, the “zero-avoidance” phenomenon helps plants become resistant to different biotic stresses. Pathogen-induced genetic control functions as an additional defense mechanism in plants. This includes the epigenetic markers that can be transferred across several generations as transgenerational memory. In response to pathogen attack, plants undergo genetic and metabolic reprogramming. In jasmonic acid signaling, MYC2 and MYC3 act as key regulators. The cytosolic calcium concentration varies under abiotic stresses and during pathogen attacks on plants (37). In addition to experimental findings, several microbial inoculants are commercially formulated to support plants against various abiotic stresses. This has been highlighted

**Table 2.** Microbial inoculants for enhanced plant defence and development (23)

Microorganisms	Product name	Pathogens, plants or pathosystems	Producing company
<i>Trichoderma harzianum</i> T22	Planter box, PlantShield T22	<i>Pythium</i> spp., <i>Rhizoctonia solani</i>	Bioworks
<i>Ampelomyces quisqualis</i> M-10	AQ10 Biofungicide	Powdery mildew on cucurbits, ornamentals, apples	Ecogen
<i>Streptomyces griseoviridis</i> K61	Mycostop	<i>Botrytis</i> spp., <i>Phytophthora</i> spp.	Kemira Agro Oy
<i>Azospirillum</i> spp.	Biopromoter	sugarcane, millets, vegetables	Manidharma Biotech
<i>Serratia plymuthcia</i> HRO-C48	RhizoStar	Strawberries	Prophyta Biologischer Pflanzenschutz
<i>Bacillus subtilis</i> FZB24	TB, WG RhizoPlus	Vegetables, strawberry	AbiTep
<i>Pseudomonas</i> spp.	Proradix	<i>Rhizoctonia solani</i>	Sourcon Padena
<i>Bacillus subtilis</i> strain GB03	Kodiak	Growth promotion, <i>Fusarium</i> spp.	Bayer CropScience
<i>Pseudomonas chlororaphis</i>	Cedomon	Net blotch, leaf spot on barley	BioAgri AB
<i>Bacillus pumilus</i> GB34	YieldShield	Soil-borne pathogens	Bayer CropScience
<i>Delftia acidovorans</i>	BioBoost	Canola	Brett-Young Seeds Limited
<i>Coniothyrium minitans</i>	Contans WG, Intercept WG	<i>Sclerotinia sclerotiorum</i>	Prophyta Biologischer Pflanzenschutz

and depicted in Table 2.

In plants, enhanced production of melatonin is induced as a stress-tolerance mechanism. The melatonin-receptor-mediated mitogen-activated protein kinase cascade is activated in the presence of melatonin leading to the initiation of defense responses against pathogens (38). In response to viral attacks, virus-derived sRNAs are produced and silence viral gene expression. Bacteria, fungi and oomycetes trigger plant defence responses through two different ways: pathogen-associated molecular pattern-triggered immunity and effector-triggered immunity. The nat-siRNAATGB2 is an antisense RNA specifically produced in response to *Pseudomonas syringae* infection and leads to the synthesis of ATGB2 (39). Stress-signaling responses are also specific to plant families and species. In the Nictaba family, Nictaba (*Nicotiana tabacum* agglutinin) forms in response to biotic stress to confer resistance. Several plant families-including Solanaceae, Musaceae, Poaceae, Arecaceae, Fabaceae and Rubiaceae-produce Nictaba-like proteins in response to different biotic stresses. The Nictaba gene family encompasses a wide variety of domains, including a second Nictaba domain, Nictaba-like lectin genes, F-box domains, TIR domains, protein kinase domains, methyltransferase domains, C1 domains, zeta toxin domains, NB-ARC domains and LRRs (40). Herbivore attack affects ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) and Rubisco activase. Under such conditions, the photosynthetic light reaction pathway, starch and sucrose metabolism, carbon fixation and flavonoid biosynthesis are negatively altered and downregulated. These changes result in the suppression of ferredoxin, the chloroplast-encoded D1 protein and ferredoxin NADPH oxidoreductase in plants. In contrast, biotic stress causes the opposite responses of ribulose-phosphate 3-epimerase, fructose-bisphosphate aldolase and ribose-5-phosphate isomerase (41).

The biotic agent and the host plant interact symbiotically and synergistically (13). DNA methylation is a defense mechanism against pathogens, which prevents the leaky expression of genes that enhance salicylic acid-dependent AtPRI and influences callose deposition. Mutations in the genomic DNA affect the efficiency of nitrogen fixation, metabolism and the defense mechanism. The Chromatin Assembly Factor-1 makes the plant resistant to

pathogens by preventing the binding of nucleosomes at transcription start sites. The defense response genes activated include PRI, PR5, WRKY6 and WRKY53. Small RNAs act as both inhibitors and activators (24). Physical barriers like cuticles, cell walls, trichomes, needles and thorns can protect plants from biotic stress. Upon infection, the strengthening of cell walls occurs through callose deposition and lignification. The PR genes get activated and alterations in primary carbon metabolism occur. Phytoalexins are antimicrobial compounds produced during infection, which create adverse conditions for the growth of pathogen. The pathogen recognition receptors (PRRs) in the plant bind to several MAMPs, including flagellin, chitin and lipopolysaccharides of the cell wall of the pathogen (42).

Most pathogens attack plants stealthily, extracting nutrients and gradually leading to host collapse, which results in severe crop losses. However, plants are equipped with a two-tiered defense mechanism (24). In the first layer, MAMPs are recognized and trigger a cascade of responses, including reactive oxygen species (ROS) production and calcium signaling, culminating in pathogen-triggered immunity (PTI). To counteract PTI, pathogens secrete effectors; in response, plants activate effector-triggered immunity (ETI), which constitutes a second, stronger layer of defense against microbial invasion (40).

#### Microbes and plant abiotic stress

Extreme drought, cold, heat and salinity affect plant health and have a devastating effect on metabolism, growth, physiological traits, reproduction, crop quality and yield. Plant responses are specific to the kind of stress; for example, drought causes an increase in the root biomass, reduces plant height and causes high economic loss. Heat stress increases leaf area, decreases kernel weight and increases the number of aborted inflorescences (23). Another example is that germination, growth, development and reproduction are extremely affected by various factors such as salinity, heavy metals, carbon dioxide concentration in the atmosphere and the concentration of poisonous gases like carbon monoxide, hydrogen chloride, benzene, toluene, hydrogen cyanide and oxides of nitrogen. For survival, plants have developed different metabolic pathways, signaling mechanisms and stress-releasing pathways, including components such as hydrodynamic waves,

**Table 3.** Regulation of key metabolites and enhancement of plant tolerance to salinity and drought by plant growth-promoting rhizobacteria

Plant growth-promoting strains	Different stress conditions	Affected plant species	Metabolites produced in plants	References
<i>Pseudomonas fluorescens</i> YX2, <i>Klebsiella variicola</i> F2 and <i>Raoultella planticola</i> YL2	Drought	<i>Zea mays</i> (Maize)	High accumulation of gibberellic acid and choline	(48)
Combined consortia of <i>Pseudomonas synxantha</i> , <i>P. jessenii</i> (strains R62 and R81) and <i>Arthrobacter nitroguajacolicus</i> (strains YB5 and YB3)	Drought	<i>Oryza sativa</i> (Rice)	Accumulation of proline and induces stress-related enzymes	(49)
Different <i>Bacillus</i> spp. including strains of KB142, KB133, KB122 and KB129	Drought	<i>Sorghum bicolor</i>	Carbohydrates and proline	(50)
<i>Pseudomonas oryzihabitans</i> Ep4, <i>Variovorax paradoxus</i> 5C-2 and <i>Achromobacter xylosoxidans</i> Cm4	Drought	<i>Solanum tuberosum</i>	ethylene	(51)
<i>Bacillus</i> sp. RhStr JH5, RhStr 223 and RhStr 71	Salinity	<i>Pisum sativum</i>	Increased phosphate solubilization, siderophore production	(52)
<i>Bacillus amyloliquefaciens</i> and <i>Pseudomonas putida</i>	Drought	<i>Cicer arietinum</i> L.	biofilm formation, minerals solubilization, hormone production	(53)
<i>Pseudomonas putida</i> MTCC5279	Drought	<i>Cicer arietinum</i>	Jasmonate, proline and ethylene	(54)
<i>Phyllobacterium brassicacearum</i> STM196	Drought	<i>Arabidopsis thaliana</i>	Isoprenoid	(55)
<i>Bacillus</i> sp. (strains BST YS1 42 and CHR JH 203)	Salinity	<i>Pisum sativum</i>	Production of ACC deaminase	(56)
<i>Pseudomonas putida</i> Rs-198	Salinity	<i>Gossypium hirsutum</i>	Isoprenoid	(57)
<i>Bacillus megaterium</i> BOFC15	Drought	<i>Arabidopsis thaliana</i>	Spermidine, Isoprenoid, spermine	(58)
<i>Enterobacter ludwigii</i> CL2, <i>Enterobacter asburiae</i> BL	Drought	<i>Triticum aestivum</i>	Amino acid	(59)

electrical signals, calcium and hormones like abscisic acid, jasmonic acid and ethylene. The plant signaling system is activated and develops systemic acquired resistance (SAR), which helps the plant cope with stressful conditions (43).

During high salinity, the PGPR colonizing the roots synthesize extracellular polysaccharides (EPS) and exopolysaccharide (ESP) (Table 1), alter root morphology, produce various osmolytes and maintain ion homeostasis and osmotic balance. Excess stress conditions generate large amounts of reactive oxygen species, leading to impaired ion balance and redox homeostasis. Altered soil chemistry and diffusion rates negatively affect the soil microbiome and reduce bacterial biomass (44). pH and nutrient concentrations are influenced by changes in water content and temperature (45). These changes affect microbial communities in the rhizosphere as well as soil structure, texture and type (46). Prompt inoculation with plant growth-promoting bacteria increases the production of ascorbate peroxidase and glutathione peroxidase, making the plant more tolerant to water stress and enhancing its metabolic activity. Under abiotic stress, plants develop several tolerance mechanisms, such as the upregulation of stress-responsive genes, stabilization of the cellular membrane, activation of ROS scavenging mechanism and production of different metabolic products including proteins and amino acids (47). However, various strains of PGPR produce multiple metabolites, depending on the plant, as a defence mechanism against salinity and drought, as depicted in Table 3.

Salinity and drought affect both the aerial and root systems of plants. The reduction in photosynthesis leads to increased production of reactive oxygen species, higher sodium ion concentration, reduced growth rate, early senescence and downregulated growth processes-these are some of the major changes observed in the aerial parts of the plant (47, 60). In the root system, changes include stunted root growth, deformation of lateral roots, downregulation of branching, large variations in

branching patterns, impaired absorption of water and nutrients, increased uptake of potassium ions, decreased sodium ion uptake, upregulation of ROS and depletion of antioxidant levels (60). Abiotic stress conditions cause a reduction in growth through the regulation of ethylene. Some plant growth-promoting bacteria also produce 1-aminocyclopropane-1-carboxylate deaminase, which cleaves ACC into  $\alpha$ -ketoglutarate and ammonia. This makes the plant more resistant to different stress conditions (61).

Plants develop different tolerance mechanisms against high salinity by changing metabolic pathways through the synthesis of organic solutes and by ion extrusion via vacuolar compartmentalization. This leads to the overexpression of salt-tolerant genes and the production of various protective proteins. The halotolerance genes include proB-74 in prokaryotes and HAL1 in eukaryotes (62). Salt stress exerts an osmotic pressure on plants; ions such as Na, Mg, K, Ca and carbonates, which are soluble in water, have a major impact on salinity. Saline soil contains high levels of soluble salts, forming micro- and macro-phases. The survival of microbes in saline environments is difficult. Halophiles are a specific group of microbes capable of growing under high-salinity conditions; they help maintain plant health and keep the plant alive in stressful conditions (63). P5CS, mod, SOS1, SOS2, SOS3, mt1D and S6PDH are the different genes present in plants for salt tolerance (64–67).

Microbes such as *Funneliformis mosseae*, *Panicum turgidum* and *Rhizophagus intraradices* have been shown to enhance the defence of *P. turgidum* against salinity by increasing the activities of GR, POD, CAT and SOD (antioxidant enzymes), carotenoids, chlorophyll a and b and by improving the absorption of essential elements such as P, K and Ca. Similarly, species such as *Glomus versiforme*, *R. intraradices* and *Funneliformis geosporum* have been shown to enhance defense against drought (68). In another case, *Trichoderma harzianum* improved nutrient absorption, antioxidant activity and oil yield in salinity-stressed *Brassica juncea*, thereby

**Table 4.** Plant growth-promoting microbial strains and their roles

Sl. No.	Microbial strains	Roles	References
1	<i>Azospirillum brasilense</i>	Promote plant growth by upregulating the production of IAA, zeatin (Z), GA <sub>3</sub> , ABA and ethylene	(11)
2	<i>Bacillus</i> spp.	Biocontrol of plant pathogens	(12)
3	<i>Bacillus subtilis</i>	Solubilize the soil phosphate, enhance nitrogen fixation and have antioxidant properties	(13)
4	PS19 strain of <i>Klebsiella</i> sp.	Produces different organic acids which can produce indole compounds, solubilize phosphate in the soil, enhance the production of siderophore and ACC deaminase and nitrogen fixation	(14)
5	IG3 strain	Has a high salt tolerance	(18)
6	<i>Bacillus amyloliquefaciens</i> strain GB03	Make the plant tolerant to drought conditions	(26)
7	<i>Pseudomonas fluorescens</i> YX2	Produce vitamins that can help the plant in better growth and survival in drastic conditions	(48)
8	<i>Rhizophagus irregularis</i> CD1	Promotes plant growth and is shown to make them wilt- resistant after <i>Verticillium</i> infection.	(30, 32)
9	<i>Nictaba</i> or <i>Nicotiana tabacum</i>	Agglutin forms to resist biotic stress	(40)

reducing sodium accumulation. Mutant *Trichoderma* strains further alleviated salinity stress through ACC deaminase production. Likewise, *Streptomyces* spp. enhanced salt tolerance and growth in Micro-Tom tomato and *Burkholderia phytofirmans* strain PsJN alleviated drought stress in wheat and maize (69). These effects are highlighted and summarized in Table 4.

## Conclusion

Plant growth-promoting microbes can be efficiently applied to improve growth, metabolic upregulation, disease resistance and yield in crops. These microbes have multi-faceted roles as biopesticides, phyto-stimulators, plant strengtheners, biofertilizers and stress-tolerance-inducing agents that help plants withstand various stresses such as pathogen attack, salinity, drought, waterlogging, heavy metals and environmental or climatic variations. These stresses negatively affect the quality and quantity of the crop, thereby impacting the economy. The effects on plant growth and development vary depending on the bacterial genera used. Several plant growth-promoting and stress-tolerant strains—such as *Pseudomonas fluorescens* YX2, *Klebsiella variicola* F2, *Raoultella planticola* YL2, *Bacillus* spp. (BST YS1 42 and CHR JH 203), *Enterobacter ludwigii* CL2 and *Enterobacter asburiae* BL—are widely employed in agricultural fields today (Table 4). They provide an eco-friendly and economical approach that is particularly advantageous in integrated pest and nutrient management systems, supporting sustainable agriculture. Their application leads to a reduction in chemical use, thus improving the prominence of the soil microbial diversity and eventually leads to long-term soil health restoration. Furthermore, advances in microbial ecology, genomics and biotechnology have enabled the development of tailored microbial consortia and formulations that target specific crop needs and stress conditions.

## Future perspectives and research gaps

While plant growth-promoting microbes have demonstrated significant potential as microbial biofertilizers, there are certain research gaps that need to be addressed. Future research should emphasize large-scale field validation under multiple climatic

conditions and the optimization of microbial consortia for different crops. Consideration of economic feasibility, ease of formulation, farmer awareness and scalability for real-world applications is also equally important. Addressing these challenges will determine the extent to which microbial biofertilizers can contribute to sustainable agriculture.

## Authors' contributions

DMN was responsible for the investigation and writing of the manuscript. JS contributed to the investigation, editing, formatting, diagram design and table development. PKA provided critical review, corrections and guidance throughout the research process. All authors have read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

## References

- Passioura JB. Soil conditions and plant growth. *Plant Cell Environ.* 2002;25(2):311–8. <https://doi.org/10.1046/j.0016-8025.2001.00802.x>
- Mishra J, Singh R, Arora NK. Plant growth-promoting microbes: diverse roles in agriculture and environmental sustainability. In: Kumar V, Kumar M, Sharma S, Prasad R, editors. *Probiotics plant health*. Singapore: Springer; 2017. p. 71–111. [https://doi.org/10.1007/978-981-10-3473-2\\_4](https://doi.org/10.1007/978-981-10-3473-2_4)
- Ab Rahman SF, Singh E, Pieterse CM, Schenk PM. Emerging microbial biocontrol strategies for plant pathogens. *Plant Sci.* 2018;267:102–11. <https://doi.org/10.1016/j.plantsci.2017.11.012>
- Singh HB. Management of plant pathogens with microorganisms. *Proc Indian Natl Sci Acad.* 2014;80(2):443–54. <https://doi.org/10.16943/ptinsa/2014/v80i2/55120>
- Rani L, Thapa K, Kanojia N, Sharma N, Singh S, Grewal AS, et al. An extensive review on the consequences of chemical pesticides on human health and environment. *J Clean Prod.* 2021;283:124657. <https://doi.org/10.1016/j.jclepro.2020.124657>
- Abdel Bagi AO, Ahmed AA, Elhindi M, Ali AM. Impact of pesticides and other chemicals on the environment. In: *Workshop on Post Conflict National Plan for Environmental Management in Sudan*; 2006. p. 18–

- 20.
7. Pahalvi HN, Rafiya L, Rashid S, Nisar B, Kamili AN. Chemical fertilizers and their impact on soil health. In: Dar GH, Bhat RA, Mehmood MA, Hakeem KR, editors. *Microbiota and biofertilizers*. Vol. 2. Cham.: Springer; 2021. p. 1–20.
  8. Baligar VC, Fageria NK, He ZL. Nutrient use efficiency in plants. *Commun Soil Sci Plant Anal*. 2001;32(7-8):921–50. <https://doi.org/10.1081/CSS-100104098>
  9. Kumar S, Kumar S, Mohapatra T. Interaction between macro- and micro-nutrients in plants. *Front Plant Sci*. 2021;12:665583. <https://doi.org/10.3389/fpls.2021.665583>
  10. Kudoyarova GR, Arkhipova TN, Melent'ev AI. Role of bacterial phytohormones in plant growth regulation. In: Maheshwari D, editor. *Bacterial metabolites sustainable agroecosystem*. Vol. 12. Cham.: Springer; 2015. p. 69–86. [https://doi.org/10.1007/978-3-319-24654-3\\_4](https://doi.org/10.1007/978-3-319-24654-3_4)
  11. Perrig D, Boiero ML, Masciarelli OA, Penna C, Ruiz OA, Cassán FD, et al. Plant-growth-promoting compounds produced by two agronomically important strains of *Azospirillum brasilense*, and implications for inoculant formulation. *Appl Microbiol Biotechnol*. 2007;75:1143–50. <https://doi.org/10.1007/s00253-007-0909-9>
  12. Miljaković D, Marinković J, Balešević-Tubić S. Significance The significance of *Bacillus* spp. in disease suppression and growth promotion of field and vegetable crops. *Microorganisms*. 2020;8(7):1037. <https://doi.org/10.3390/microorganisms8071037>
  13. Hashem A, Tabassum B, Abd\_Allah EF. *Bacillus subtilis*: A plant-growth promoting rhizobacterium that also impacts biotic stress. *Saudi J Biol Sci*. 2019;26(6):1291–7. <https://doi.org/10.1016/j.sjbs.2019.05.004>
  14. Mukherjee T, Banik A, Mukhopadhyay SK. Plant growth-promoting traits of a thermophilic strain of the *Klebsiella* group with its effect on rice plant growth. *Curr Microbiol*. 2020;77(10):2613–22. <https://doi.org/10.1007/s00284-020-02032-0>
  15. Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Gowda CL, Krishnamurthy L. Plant growth promoting rhizobia. 3 *Biotech*. 2015;5:355–77. <https://doi.org/10.1007/s13205-014-0241-x>
  16. Patil A, Kale A, Ajane G, Sheikh R, Patil S. Plant growth-promoting Rhizobium: mechanisms and biotechnological prospective. In: Hansen A, Choudhary D, Agrawal P, Varma A, editors. *Rhizobium biology and biotechnology*. Cham.: Springer; 2017. p. 105–34. [https://doi.org/10.1007/978-3-319-64982-5\\_7](https://doi.org/10.1007/978-3-319-64982-5_7)
  17. Gul N, Wani IA, Mir RA, Nowshahri JA, Aslam S, Gupta R, et al. Plant growth promoting microorganisms mediated abiotic stress tolerance in crop plants: a critical appraisal. *Plant Growth Regul*. 2023;100(1):7–24. <https://doi.org/10.1007/s10725-022-00951-5>
  18. Wei X, Xie B, Wan C, Song R, Zhong W, Xin S, et al. Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. *Agronomy*. 2024;14(3):609. <https://doi.org/10.3390/agronomy14030609>
  19. Prashar P, Kapoor N, Sachdeva S. Rhizosphere: its structure, bacterial diversity and significance. *Rev Environ Sci Biotechnol*. 2014;13:63–77. <https://doi.org/10.1007/s11157-013-9317-z>
  20. Santoyo G, Urdis-Flores CA, Loeza-Lara PD, Orozco-Mosqueda MD, Glick BR. Rhizosphere colonization determinants by plant growth-promoting rhizobacteria (PGPR). *Biology*. 2021;10(6):475. <https://doi.org/10.3390/biology10060475>
  21. Hou J, Liu W, Wang B, Wang Q, Luo Y, Franks AE. PGPR enhanced phytoremediation of petroleum contaminated soil and rhizosphere microbial community response. *Chemosphere*. 2015;138:592–8. <https://doi.org/10.1016/j.chemosphere.2015.07.025>
  22. Hassani MA, Durán P, Hacquard S. Microbial interactions within the plant holobiont. *Microbiome*. 2018;6:1–7. <https://doi.org/10.1186/s40168-018-0445-0>
  23. Berg G. Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture. *Appl Microbiol Biotechnol*. 2009;84(1):11–8. <https://doi.org/10.1007/s00253-009-2092-7>
  24. Amaresan N, Murugesan S, Kumar K, Sankaranarayanan A, editors. *Microbial mitigation of stress response of food legumes*. Boca Raton: CRC Press; 2020. <https://doi.org/10.1201/9781003028413>
  25. Hartmann A, Schmid M, Tuinen DV, Berg G. Plant-driven selection of microbes. *Plant Soil*. 2009;321:235–57. <https://doi.org/10.1007/s11104-008-9814-y>
  26. Schirawski J, Perlin MH. Plant–microbe interaction 2017—the good, the bad and the diverse. *Int J Mol Sci*. 2018;19(5):1374. <https://doi.org/10.3390/ijms19051374>
  27. Nadeem SM, Naveed M, Zahir ZA, Asghar HN. Plant–microbe interactions for sustainable agriculture: fundamentals and recent advances. In: Arora N, editor. *Plant microbe symbiosis: fundamentals and advances*. New Delhi: Springer; 2013. p. 51–103. [https://doi.org/10.1007/978-81-322-1287-4\\_2](https://doi.org/10.1007/978-81-322-1287-4_2)
  28. Niu B, Wang W, Yuan Z, Sederoff RR, Sederoff H, Chiang VL, et al. Microbial interactions within multiple-strain biological control agents impact soil-borne plant disease. *Front Microbiol*. 2020;11:585404. <https://doi.org/10.3389/fmicb.2020.585404>
  29. Ortiz-Castro R, Contreras-Cornejo HA, Macías-Rodríguez L, López-Bucio J. The role of microbial signals in plant growth and development. *Plant Signal Behav*. 2009;4(8):701–12. <https://doi.org/10.4161/psb.4.8.9047>
  30. Baker B, Zambryski P, Staskawicz B, Dinesh-Kumar SP. Signaling in plant-microbe interactions. *Science*. 1997;276(5313):726–33. <https://doi.org/10.1126/science.276.5313.726>
  31. Köhl J, Kolnaar R, Ravensberg WJ. Mode of action of microbial biological control agents against plant diseases. *Front Plant Sci*. 2019;10:845. <https://doi.org/10.3389/fpls.2019.00845>
  32. Balachandran S, Hurry VM, Kelley SE, Osmond CB, Robinson SA, Rohozinski J, et al. Concepts of plant biotic stress. Some insights into the stress physiology of virus-infected plants, from the perspective of photosynthesis. *Physiol Plantarum*. 1997;100(2):203–13. <https://doi.org/10.1111/j.1399-3054.1997.tb04776.x>
  33. Amirsadeghi S, Robson CA, Vanlerberghe GC. The role of the mitochondrion in plant responses to biotic stress. *Physiol Plantarum*. 2007;129(1):253–66. <https://doi.org/10.1111/j.1399-3054.2006.00775.x>
  34. Sergeant K, Renaut J. Plant biotic stress and proteomics. *Curr Proteomics*. 2010;7(4):275–97. <https://doi.org/10.2174/157016410793611765>
  35. Bhar A, Chakraborty A, Roy A. Plant responses to biotic stress: Old memories matter. *Plants*. 2021;11(1):84. <https://doi.org/10.3390/plants11010084>
  36. Zhao D, Wang H, Chen S, Yu D, Reiter RJ. Phytomelatonin: an emerging regulator of plant biotic stress resistance. *Trends Plant Sci*. 2021;26(1):70–82. <https://doi.org/10.1016/j.tplants.2020.08.009>
  37. Ruiz-Ferrer V, Voinnet O. Roles of plant small RNAs in biotic stress responses. *Annu Rev Plant Biol*. 2009;60:485–510. <https://doi.org/10.1146/annurev.arplant.043008.092111>
  38. Miller RN, Costa Alves GS, Van Sluys MA. Plant immunity: unravelling the complexity of plant responses to biotic stresses. *Ann Bot*. 2017;119(5):681–7. <https://doi.org/10.1093/aob/mcw284>
  39. Bilgin DD, Zavala JA, Zhu J, Clough SJ, Ort DR, DeLucia EH. Biotic stress globally downregulates photosynthesis genes. *Plant Cell Environ*. 2010;33(10):1597–613. <https://doi.org/10.1111/j.1365-3040.2010.02167.x>
  40. Zogli P, Libault M. Plant response to biotic stress: Is there a common epigenetic response during plant-pathogenic and symbiotic interactions? *Plant Sci*. 2017;263:89–93. <https://doi.org/10.1016/j.plantsci.2017.07.008>
  41. Großkinsky DK, van der Graaff E, Roitsch T. Regulation of abiotic and biotic stress by plant hormones. In: Collinge DB, editor. *Plant pathogen resistance biotechnology*. Wiley; 2016. p. 131–54. <https://doi.org/10.1002/9781118867716.ch7>
  42. Suzuki N, Rivero RM, Shulaev V, Blumwald E, Mittler R. Abiotic and biotic stress combinations. *New Phytol*. 2014;203(1):32–43. <https://doi.org/10.1111/nph.12797>
  43. Wang L, Ning C, Pan T, Cai K. Role of silica nanoparticles in abiotic and biotic stress tolerance in plants: a review. *Int J Mol Sci*. 2022;23(4):1947. <https://doi.org/10.3390/ijms23041947>
  44. Gupta A, Bano A, Rai S, Mishra R, Singh M, Sharma S, et al. Mechanistic insights of plant-microbe interaction towards drought and salinity stress in plants for enhancing the agriculture productivity. *Plant Stress*. 2022;4:100073. <https://doi.org/10.1016/j.jstress.2022.100073>

45. Pettersson M, Bååth E. Temperature-dependent changes in the soil bacterial community in limed and unlimed soil. *FEMS Microbiol Ecol.* 2003;45(1):13–21. [https://doi.org/10.1016/S0168-6496\(03\)00106-5](https://doi.org/10.1016/S0168-6496(03)00106-5)
46. Khalilpour M, Mozafari V, Abbaszadeh-Dahaji P. Tolerance to salinity and drought stresses in pistachio (*Pistacia vera* L.) seedlings inoculated with indigenous stress-tolerant PGPR isolates. *Sci Hortic.* 2021;289:110440. <https://doi.org/10.1016/j.scienta.2021.110440>
47. Haroim PR, van Overbeek LS, van Elsas JD. Properties of bacterial endophytes and their proposed role in plant growth. *Trends Microbiol.* 2008;16(10):463–71. <https://doi.org/10.1016/j.tim.2008.07.008>
48. Abd El-Ghany TM, Masrahi YS, Mohamed A, Abboud A, Alawlaqi MM, Elhussieny NI. Maize (*Zea mays* L.) growth and metabolic dynamics with plant growth promoting rhizobacteria under salt stresses. *J Plant Pathol Microbiol.* 2015;6(9):305.
49. Gusain YS, Singh US, Sharma AK. Bacterial mediated amelioration of drought stress in drought tolerant and susceptible cultivars of rice (*Oryza sativa* L.). *Afr J Biotechnol.* 2015;14(9):764–73. <https://doi.org/10.5897/AJB2015.14405>
50. Grover M, Madhubala R, Ali SZ, Yadav SK, Venkateswarlu B. Influence of *Bacillus* spp. strains on seedling growth and physiological parameters of sorghum under moisture stress conditions. *J Basic Microbiol.* 2014;54(9):951–61. <https://doi.org/10.1002/jobm.201300250>
51. Belimov AA, Dodd IC, Safronova VI, Shaposhnikov AI, Azarova TS, Makarova NM, et al. Rhizobacteria that produce auxins and contain 1-amino-cyclopropane-1-carboxylic acid deaminase decrease amino acid concentrations in the rhizosphere and improve growth and yield of well-watered and water-limited potato (*Solanum tuberosum*). *Ann Appl Biol.* 2015;167(1):11–25. <https://doi.org/10.1111/aab.12203>
52. Sharma M, Shilpa, Kaur M, Sharma AK, Sharma P. Influence of different organic manures, biofertilizers and inorganic nutrients on performance of pea (*Pisum sativum* L.) in North Western Himalayas. *J Plant Nutr.* 2023;46(4):600–17. <https://doi.org/10.1080/01904167.2022.2071735>
53. Kumar M, Mishra S, Dixit V, Kumar M, Agarwal L, Chauhan PS, et al. Synergistic effect of *Pseudomonas putida* and *Bacillus amyloliquefaciens* ameliorates drought stress in chickpea (*Cicer arietinum* L.). *Plant Signal Behav.* 2016;11(1):e1071004. <https://doi.org/10.1080/15592324.2015.1071004>
54. Tiwari S, Lata C, Chauhan PS, Nautiyal CS. *Pseudomonas putida* attunes morphophysiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery. *Plant Physiol Biochem.* 2016;99:108–17. <https://doi.org/10.1016/j.plaphy.2015.11.001>
55. Bresson J, Varoquaux F, Bontpart T, Touraine B, Vile D. The PGPR strain *Phyllobacterium brassicacearum* STM 196 induces a reproductive delay and physiological changes that result in improved drought tolerance in *Arabidopsis*. *New Phytol.* 2013;200(2):558–9. <https://doi.org/10.1111/nph.12383>
56. Yao L, Wu Z, Zheng Y, Kaleem I, Li C. Growth promotion and protection against salt stress by *Pseudomonas putida* Rs-198 on cotton. *Eur J Soil Biol.* 2010;46(1):49–54. <https://doi.org/10.1016/j.ejsobi.2009.11.002>
57. Zhou C, Ma Z, Zhu L, Xiao X, Xie Y, Zhu J, et al. Rhizobacterial strain *Bacillus megaterium* BOFC15 induces cellular polyamine changes that improve plant growth and drought resistance. *Int J Mol Sci.* 2016;17(6):976. <https://doi.org/10.3390/ijms17060976>
58. Zhang G, Sun Y, Sheng H, Li H, Liu X. Effects of the inoculations using bacteria producing ACC deaminase on ethylene metabolism and growth of wheat grown under different soil water contents. *Plant Physiol Biochem.* 2018;125:178–84. <https://doi.org/10.1016/j.plaphy.2018.02.005>
59. Vafadar F, Amooaghaie R, Otroshy M. Effects of plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungus on plant growth, stevioside, NPK, and chlorophyll content of *Stevia rebaudiana*. *J Plant Interact.* 2014;9(1):128–36. <https://doi.org/10.1080/17429145.2013.779035>
60. Kumar V, Khare T, Sharma M, Wani SH. ROS-induced signaling and gene expression in crops under salinity stress. In: Khan M, Khan N, editors. *Reactive oxygen species and antioxidant systems in plants: role and regulation under abiotic stress.* Singapore: Springer; 2007. [https://doi.org/10.1007/978-981-10-5254-5\\_7](https://doi.org/10.1007/978-981-10-5254-5_7)
61. Glick BR, Cheng Z, Czarny J, Duan J. Promotion of plant growth by ACC deaminase-producing soil bacteria. In: Bakker PAHM, Raaijmakers JM, Bloemberg G, Höfte M, Lemanceau P, Cooke BM, editors. *New perspectives and approaches in plant growth-promoting rhizobacteria research.* Dordrecht: Springer. [https://doi.org/10.1007/978-1-4020-6776-1\\_8](https://doi.org/10.1007/978-1-4020-6776-1_8)
62. Serrano R, Gaxiola R. Microbial models and salt stress tolerance in plants. *Crit Rev Plant Sci.* 1994;13(2):121–38. <https://doi.org/10.1080/07352689409701911>
63. Numan M, Bashir S, Khan Y, Mumtaz R, Shinwari ZK, Khan AL, et al. Plant growth promoting bacteria as an alternative strategy for salt tolerance in plants: a review. *Microbiol Res.* 2018;209:21–32. <https://doi.org/10.1016/j.micres.2018.02.003>
64. Hong Z, Lakkineni K, Zhang Z, Verma DP. Removal of feedback inhibition of  $\Delta$ 1-pyrroline-5-carboxylate synthetase results in increased proline accumulation and protection of plants from osmotic stress. *Plant Physiol.* 2000;122(4):1129–36. <https://doi.org/10.1104/pp.122.4.1129>
65. Chakraborty K, Sairam RK, Bhattacharya RC. Differential expression of salt overly sensitive pathway genes determines salinity stress tolerance in *Brassica* genotypes. *Plant Physiol Biochem.* 2012;51:90–101. <https://doi.org/10.1016/j.plaphy.2011.10.001>
66. Gao M, Tao R, Miura K, Dandekar AM, Sugiura A. Transformation of Japanese persimmon (*Diospyros kaki* Thunb.) with apple cDNA encoding NADP-dependent sorbitol-6-phosphate dehydrogenase. *Plant Sci.* 2001;160(5):837–45. [https://doi.org/10.1016/S0168-9452\(00\)00458-1](https://doi.org/10.1016/S0168-9452(00)00458-1)
67. Abebe T, Guenzi AC, Martin B, Cushman JC. Tolerance of mannitol-accumulating transgenic wheat to water stress and salinity. *Plant Physiol.* 2003;131(4):1748–55. <https://doi.org/10.1104/pp.102.003616>
68. Inbaraj MP. Plant-microbe interactions in alleviating abiotic stress—a mini review. *Front Agron.* 2021;3:667903. <https://doi.org/10.3389/fagro.2021.667903>
69. Munir N, Hanif M, Abideen Z, Sohail M, El-Keblawy A, Radicetti E, et al. Mechanisms and strategies of plant microbiome interactions to mitigate abiotic stresses. *Agronomy.* 2022;12(9):2069. <https://doi.org/10.3390/agronomy12092069>

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