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Sustainable agriculture through rhizosphere bacteria for plant growth promotion, nutrient acquisition, and stress alleviation

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Abstract
Rhizosphere bacteria are attracting a lot of interest in sustainable agriculture because of their capacity to stimulate plant growth, improve nutrient uptake, and reduce stress in plants. A review of recent discoveries in the field of using rhizosphere bacteria for these advantageous agricultural techniques is given in this article. Rhizosphere bacteria facilitate plant growth by solubilizing inaccessible elements like phosphorus, potassium, zinc, and manganese by producing a variety of enzymes and organic acids. Furthermore, these bacteria support plant nutrition by fixing atmospheric nitrogen, a necessary component for plant growth and development. Moreover, some rhizosphere bacterial strains can inhibit plant diseases, which lessen the need for artificial chemical pesticides. Rhizosphere bacteria have improved plant stress tolerance by producing stress-related substances, including phytohormones and osmoprotectants. These bacteria also give rise to systemic resistance in plants, successfully allowing them to survive various biotic and abiotic challenges. Concerning climate change and environmental variations, this rhizosphere bacteria-mediated stress reduction component holds a tremendous potential for sustainable agriculture. But for rhizosphere bacteria-based agricultural techniques to be successfully utilized, a thorough grasp of their variety, ecological relationships, and mode of action are necessary. Optimizing application techniques, formulating bioinoculants, and considering environmental aspects are crucial for consistent and dependable outcomes through rhizosphere bacteria.

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Introduction

Microbial abundance in the soil causes biochemical transformations of nutrients in the presence of

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minerals, air, water, and organic matter (Paul, 2016). Many microorganisms, including bacteria, fungi, protozoa, algae, and actinomycetes, are present in the soil; however, bacteria most commonly influence nutrient transformation and plant growth. Bacteria colonizing in the rhizosphere enhance nutrient availability and soil fertility (De Zelicourt et al., 2013; Zhao et al., 2016). The bacterial assortment is affected by the soil conditions, including the presence of plants in the soil, organic carbon, temperature, moisture, electrical conductivity, and other chemical parameters (Glick, 2012). Many plant species require bacterial association for better growth (Ma et al., 2016). Plants choose the microflora of their own choice and have specific microbes. A balanced assortment of plants and bacterial responses is necessary to maintain mutually beneficial link between plants and soil microorganisms (De et al., 2013). The slow release of chemicals and signals gives plants a better chance to communicate with rhizosphere microflora. By releasing host functional signals, they make an associative symbiosis with plants (Chaparro et al., 2013; Ma et al., 2016). Endophytic bacteria colonize the internal tissues of the plants without degrading the host. Among them, *Rhizobium* spp. is symbiotically associated with the legume and is involved in the fixation of atmospheric nitrogen (Afzal et al., 2019; Lindström and Mousavi, 2020). Free-living bacteria form non-symbiotic associations by colonizing the rhizosphere and root surface.

The bacteria-plant-soil interaction is a complex and dynamic relationship in shaping soil health, plant growth, and ecosystem functioning. Soil is a home to various microorganisms, including bacteria, fungi, archaea, and viruses. There are several billion bacterial cells in a single gram of soil, which are abundant in nature (Ortiz et al*.,* 2021). Organic matter content, moisture temperature, and pH are the soil factors that enhance bacterial abundance and diversity in the rhizosphere (Liu et al., 2020). Several mechanisms are adopted by the plants to interact with the microbes present in the soil (Jayaraman et al., 2021). Some nitrogen-fixing or mineral-solubilizing bacteria are produced by producing several organic acids produced by plants (Fasusi et al*.,* 2021). These bacteria provide essential nutrients to plants, such as nitrogen, phosphorus, potassium, and other micronutrients (Pronk et al*.,* 2022).

The soil nutrient cycle is significantly linked to soil microorganisms, including bacteria, as they convert fixed forms of organic or inorganic minerals into readily available nutrients for plant uptake (Basu et al*.,* 2021). Various rhizobacteria solubilize insoluble minerals, including phosphorus, potassium, zinc, calcium, magnesium, and manganese (Thomas and Singh, 2019). Not all bacteria have symbiotic relations with plants, and some can also harm the growth and production of plants. Soil rotation and cover crops are unique treatments that can improve the proliferation of beneficial microbial communities in soil (Ghani et al*.,* 2022). Thus, in the current review, we discuss how the bacterial-plant-soil interaction is a complex and dynamic process and how does it play a vital role in soil health, plant growth, and ecosystem functioning. It also describes the interactions that are essential for developing sustainable agricultural practices that promote plant growth and soil health while minimizing negative environmental impacts.

Plant growth-promoting bacteria

Some rhizosphere microorganisms may support their host's plant growth, yield, and defense against phytopathogens and abiotic stress tolerance, known as plant growth-promoting bacteria (PGPB). Extracellular plant growth-promoting bacteria located in the rhizosphere and rhizoplane, and intracellular plant growth-promoting bacteria present in the unique structure of root cell nodules are beneficial for the biostimulation of plant growth (Martínez-Viveros et al*.,* 2010). Rhizosphere bacteria are prevalent in soils and help increase nutrient availability, reduce soil-borne diseases, and improve water infiltration into the soil (Abdelaziz et al*.,* 2023). They form a symbiotic relationship with many legumes and other plants, increasing root growth and improving crop yield. Rhizobacteria can also fix atmospheric nitrogen, increasing plant nutrient availability (Sedri, 2022).

Rhizosphere bacteria have been used as a natural fertilizer for years and can be applied to crops directly or incorporated into soils to improve soil health. Rhizosphere bacterial-mediated plant growth promotion is crucial in sustainable agriculture and can increase crop yields and reduce fertilizer input (Sedri et al*.,* 2022). These bacteria can also help restore degraded soils and provide long-term plant benefits. They are eco-friendly substitutes for traditional fertilizers and can sustainably improve crop production (Gupta et al*.,* 2015). Rhizobacteria can colonize the root surface or inside the plant's root and promote plant health through various mechanisms. Rhizobacteria can activate the plant's innate defense mechanisms by inducing systemic resistance. This involves triggering a cascade of signaling pathways within the plant that help it resist diseases and pests (Ding et al*.,* 2022). Rhizobacteria can enhance plant nutrient uptake by solubilizing insoluble nutrients such as phosphorus, iron, and potassium, making them available for plant uptake. They are involved in biological N-fixation and promote N availability for plant growth (Sheoran et al*.,* 2021). Some rhizobacteria take part in the production of phytohormones such as auxins, cytokinins, and gibberellins, which can stimulate plant growth by promoting cell division, elongation, and differentiation (Mekonnen and Kibret, 2021). Rhizobacteria can form biofilms on the root surface, a protective barrier against phytopathogens and abiotic stresses, and they also can compete with pathogenic microorganisms for resources such as nutrients and space, and exclude them from colonizing the root system (Herms et al*.,* 2022). Overall, the mechanistic approach used by rhizospheric bacteria has been summarized in **Figure 1** and discussed in the sections below.

Indole acetic acid-producing bacteria

Phytohormones are essential for controlling several physiological processes in plants. Plants primarily produce phytohormones, although some bacteria have also been found to produce these hormones (Egamberdieva et al*.,* 2017). By producing phytohormones, these bacteria penetrate the rhizosphere and plants' roots and facilitate plant growth (Souza et al*.,* 2015). They generate auxins, cytokinins, gibberellins, and abscisic acid. Indole-3-acetic acid (IAA), an auxin produced by PGPB bacteria, helps to promote root development, lateral root formation, cell elongation, and nutrient absorption (Shah et al*.,* 2022). Bacteria produce zeatin (cytokinins) to encourage bud formation, lateral shoot development, and cell division (Kurepin et al*.,* 2014). Gibberellins produced by bacteria affect flowering, seed germination, and stem length, and endorse plant growth (Olanrewaju et al*.,* 2017). Some bacteria can produce the abscisic acid hormone, which helps plants adapt to abiotic stresses and increase water stress tolerance. Ethylene is involved in aging, leaf abscission, and fruit ripening. It controls growth and development and is also produced in reaction to stress (Chandra-kuntal, 2022).

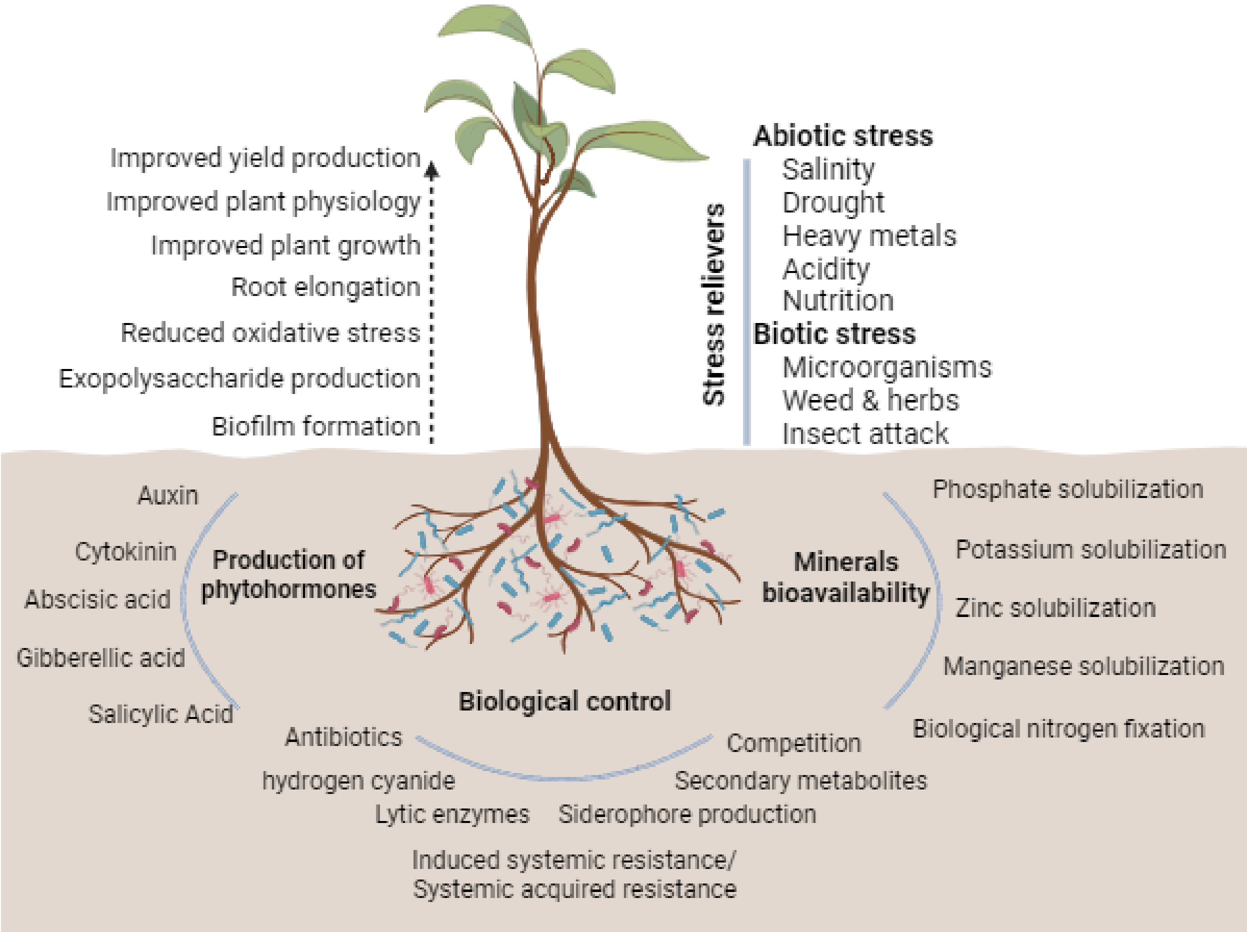

Figure 1. Representation of rhizosphere bacteria-mediated plant growth promotion and alleviation of abiotic and biotic stresses. The model shows promoted plant growth through phytohormone production, mineral solubilization, exopolysaccharides, biofilm production, and induced phytopathogen biocontrol

Auxins are involved in the promotion of plants' growth and development (Gupta et al*.,* 2023). These bacteria interact with the plant in the rhizosphere and promote its growth. These bacteria produce IAA, improving stress tolerance, boosting nutrient absorption, encouraging root development, and protecting plants from infections (Chieb and Gachomo, 2023). IAA-producing bacteria have the potential to enhance crop productivity and general health, which makes them advantageous for agriculture. It leads to sustainable farming techniques by lowering the requirement for chemical fertilizers and synthetic auxins.

Researchers and farmers are investigating the potential of IAA-producing bacteria in agricultural systems to boost yields and plant growth (Prasad, 2023). Several taxonomic groups, including genera like *Bacillus, Pseudomonas, Rhizobium*, *Azospirillum*, and *Enterobacter*, are inhabited by IAA-producing bacteria (War et al., 2023). Numerous environments, including soil, the rhizosphere, and plant tissues, are host to these bacteria.

Bacteria use tryptophan-dependent and tryptophan-independent mechanisms to produce IAA (Naureen et al*.,* 2022). Tryptophan is converted to IAA by bacteria in the tryptophan-dependent pathway (Jahn et al*.,* 2021). Tryptophan decarboxylase catalyzes the decarboxylation of tryptophan, creating tryptamine (Bajguz and Piotrowska, 2023). Tryptamine 2-monooxygenase is often referred to as indole-3-acetamide hydrolase, which converts tryptamine into indole-3-acetamide. Indole-3-acetamide hydrolase hydrolyzes indole-3-acetamide to produce IAA. Tryptophan is a prerequisite for IAA synthesis in this route, and its presence is required (Huang, 2023). Certain bacteria can produce IAA even in the lack of tryptophan. This pathway is called tryptophan-independent pathway. IAA is produced by converting alternate precursors in the tryptophan-independent route (Ortiz-García et al*.,* 2023). Indole-3-pyruvic acid, a frequent precursor in this pathway, is generated by a series of enzymatic processes beginning with intermediates in the shikimate pathway. The indole-3-pyruvate decarboxylase (IPDC) catalyzes the decarboxylation step to generate IAA and then converts indole-3-pyruvic acid into IAA (Xiao et al., 2023). It is pertinent to remember that not all bacteria have both routes, and different bacterial strains may or may not be able to make IAA. Bacteria can create mutualistic interactions with plants and influence numerous physiological processes by generating IAA, which is advantageous to both the bacteria and the host plants (Mazoyon et al., 2023).

Certain bacteria can produce IAA and interact with plants to benefit them in several ways (Tang et al*.,* 2023). They encourage the development of lateral roots, which aid in a plant's ability to search a broader soil region for nutrients and water. IAA production produces more robust and healthier root systems (Das et al*.,* 2022). These bacteria can improve plant nitrogen uptake efficiency. They generate IAA, which helps the root to absorb vital minerals, including potassium, phosphate, and nitrogen. These bacteria lessen the detrimental impacts of environmental conditions on plants, such as desiccation, or high temperatures (Kaushal and Wani, 2016). IAA strengthens plant resilience, enabling them to endure and bounce back from challenging circumstances. Bacterial IAA may also support plant defense mechanisms against diseases (Meena et al*.,* 2020). It increases plant defense against harmful microbes by triggering the plant's immune system. In many plant species, IAA encourages fruit development and flowering. Bacteria can affect these processes by generating IAA, which increases the number of flowers and the yield of high-quality fruits (Duca et al., 2014). Various studies conducted by researchers that elaborate the importance of IAA produced by bacterial species have been summarized in **Table 1**.

Nitrogen-fixing bacteria

Nitrogen (N) is the basis of all life on earth and is necessary for synthesizing nucleic acids, proteins, and enzymes (Raza et al*.,* 2020). A considerable increase in atmospheric N_2 due to the synthesis of chemical fertilizers has caused a shift in emphasis towards biological nitrogen fixation (BNF) by legumes (Soumare et al*.,* 2020). Nitrogen fixation is a crucial mechanism for determining the primary crop yield. The BNF has been widely used as a substitute for chemical N-fertilizers for legume production. The *Rhizobium*-legume association in the BNF process is considered an immensely effective process that can meet the N needs of the host plants (Kebede, 2021). The symbiotic relationship between rhizobia and the legume for biological nitrogen fixation is preferred since it is secure and safe for the environment. For example, like several other legumes, *Sesbania* spp. could employ biologically fixed nitrogen to solve soil problems owing to salt stress and waterlogging (Singh et al*.,* 2021). Low nitrogen fixation and declining soil productivity are usually linked to low productivity of legumes (Slattery et al*.,* 2001).

The inoculation of effective rhizobia can improve the yield production in legumes. Since this approach is mainly limited to leguminous plants in agricultural settings, researchers are very interested in discovering whether comparable symbiosis might also arise in non-legumes to produce the highest possible food yield for humans (Mus et al*.,* 2016). An ancient practice known as "green manuring" with legumes provides physiologically altered N_2 to subsequent crops grown alternately. Legumes' rotation promotes N availability for succeeding cereals (Saadani et al*.,* 2019). *Sesbania* can exchange nitrogen through its aerial parts, including stems, branches, and roots in the soil. Rao and Gill (1993) reported a high nutrient intake in shoots and an increase in nodulation and biomass production in their extensive studies on *Sesbania* species in alkaline stress. In contrast, the Na concentration was low, indicating the plant's value as a source of integrated biofertilizer (Ravshanov et al., 2023). Various roles of nitrogen-fixing rhizosphere and endophytic bacterial strains have been summarized in **Table 2**.

Table 1. The role of indole acetic acid-producing bacteria in plant growth promotion

Bacterial species	Enzymatic mechanisms	Function in plants	References
Burkholderia phytofirmans	ACC-deaminase, 1-aminocyclopropane-1-carboxylate oxidase (ACO)	Regulates ethylene level and takes part in the formation of lateral roots	Kaur et al., 2023
Pseudomonas fluorescens	Chitinase, protease, cellulase, lipase and phytase	Breakdown of chitin, amino acids, carbohydrates, fatty acids, and phytic acid	Kaur and Pandove, 2023
Bacillus amyloliquefaciens	Amylase, cellulase, protease, chitinase, lipase and phytase	Hydrolyze starch into glucose and maltose; breakdown of cellulose, proteins, lipids, and chitin	Liu and Kokare, 2023
Azospirillum irakense	Nitrogenase enzymes	Biological nitrogen fixation	Nair, 2023
Burkholderia spp.	1-aminocyclopropane-1-carboxylate (ACC) deaminase	Cell elongation and root development	Orozco-Mosqueda et al., 2023
Azospirillum picis	Nitrogenase enzymes	Biological nitrogen fixation	Rabara et al., 2023
Azospirillum melinis	Nitrogenase enzymes	Protein synthesis, chlorophyll production, and biological nitrogen fixation	Rana et al., 2023
Pseudomonas putida	Oxidase, chitinase, cellulase, protease and lipase	Root initiation and elongation, breakdown of chitin, cellulose protein, and lipids.	Rani et al., 2023
Pseudomonas aeruginosa	ACC deaminase	Promotes plant growth under stressful conditions	Ratnaningsih et al., 2023
Bacillus spp.	Indole-3-acetate hydrolase, indole-3-acetyl-amide hydrolase, isopentenyl transferase, and cytokinin oxidase	Stress tolerance	Roy et al., 2023a
Burkholderia gladioli	Oxidase and chitinase	Cell elongation, root initiation, flowering, protection of plants from fungal pathogens, and biological nitrogen fixation	Shahid et al., 2023
Azospirillum orayzae	Nitrogenase enzymes, reductases, and hydrogenases	Biological nitrogen fixation	Tokas et al., 2023
Pseudomonas spp.	Indole acetyltransferase, gibberellin oxidase, and jasmonate carboxyl methyltransferase	Defense response against pathogens	Vanková et al., 2023
Rhizobium spp., *Bradyrhizobium* spp.	Oxidase, and isopentenyl transferase	Root development and nodulation, and cytokinin production	Wang et al., 2023
Bacillus pumilus	Cellulase acetyl esterase	Cellulose degradation	Yang et al., 2023
Azospirillum brasilense	ACC deaminase, nitrogenase, and phosphate solubilizing enzymes	N_2 fixation, phosphate solubilization and lowering of the ethylene level	Zamanzadeh-Nasrabadi et al., 2023
Bacillus subtilis	Amylase, protease, cellulase, chitinase, and lipase	Hydrolysis of starch into simple sugars, and breakdown of proteins, cellulose, chitin & lipids	Zhou et al., 2023
Azospirillum lipoferum	Nitrogenase enzyme	Biological nitrogen fixation	Lee et al., 2021
Streptomyces spp.	Indole-3-acetate hydrolase, isopentenyl transferase and gibberellin 3-oxidase	Resistance against diseases	Vurukonda et al., 2018
Azospirillum spp.	Oxidase, indole-3-acetamide (IAM) hydrolase	Promotion of root growth and nutrient absorption	Duca et al., 2014

To increase soil biodiversity conservation, it is therefore preferable to apply native rhizobial strains as biofertilizers (De Mandal and Bhatt, 2020). The detrimental properties of chemical fertilizers on biodiversity are minimized by biofertilization. Rhizobia are not highly mobile in soil; hence, the point at which they are introduced into the soil determines the nodulation pattern (Otaiku et al., 2022). Farmers can use rhizobial inoculation to maximize grain legume yields with suitable and appropriate rhizobia where a low population of local rhizobial strains predominates. Debela et al. (2021) reported increased plant growth and nodulation efficiency by 80-90% through inoculation with abiotic stress-tolerant cluster

Table 2. An overview of nitrogen-fixing bacteria and their role in plant growth promotion

Microorganisms	Interaction	Findings	References
Bradyrhizobium sp.	Symbiotic	Enhanced guar growth attributes and seed yield	El-Sawah et al. (2021)
Bacillus xiamenesis PM14	Non-symbiotic	Strain PM14 promoted plant growth and metal accumulation in *Sesbania sesban*	Din et al., 2020
Pasteuria penetrans	Non-symbiotic	Increased marketable yield of sweet potato	Subedi et al., 2020
Azorhizobium caulinodans ORS571	Symbiotic	Strain ORS571 showed its ability for atmospheric nitrogen fixation in free-living and symbiotic association	Liu et al., 2019
Rhizobium sp. (strain NEPMR1, NETBR1)	Symbiotic	Promoted tolerance against salt and temperature stress	Nohwar et al., 2019
Lactobacillus plantarum PM411	Non-symbiotic	Increased survival on plant surfaces and overexpression of stress-related genes	Daranas et al., 2018
Sinorhizobium saheli, Ensifer sp. AC01b	Symbiotic	Bioremediated the glyphosate toxicity	Chauhan et al., 2017
Agrobacterium salinitolerance	Symbiotic	Improved salt stress tolerance in host plant	Yan et al., 2017
Pseudomonas fluorescens DACG3, *Burkholderia* sp. DACG1	Non-symbiotic	Promoted biomass and root and shoot growth of chickpea	Dasgupta et al., 2015
Bacillus amyloliquefaciens BZ6-1	Non-symbiotic	Production of antimicrobial compounds	Wang and Liang, 2014
Burkholderia spp. KJ006	Symbiotic	KJ006 was involved in *Nif* gene cluster and antifungal activity	Kwak et al., 2012
Enterobacter cloacae ENHKU01	Non-symbiotic	This strain promoted plant growth	Liu et al., 2012
Pseudomonas fluorescens EB69	Non-symbiotic	Produced siderophores and inhibitory compounds	Ramesh and Phadke, 2012
Burkholderia phytofirmans PsJN	Symbiotic	IAA synthesis, ACC deaminase acctivation	Weilharter et al., 2011
Azospirillum lipoferum 4B	Symbiotic	Strain 4B was involved in nitrogen fixation and production of phytohormones	Wisniewski-Dye et al., 2011
Azospirillum sp. B510	Symbiotic	Strain B510 produced IAA and was involved in BNF	Kaneko et al., 2010
Bacillus amyloliquefaciens Bg-C31	Non-symbiotic	Production of anti-microbial proteins	Hu et al., 2010
Rhizobium strain IRBG74	Symbiotic	This strain facilitated nodulation and biomass production	Cummings et al., 2009
Serratia plymuthica HRO-C48	Non-symbiotic	Quorum sensing, and growth promotion	Müller et al., 2009
Enterobacter sp. 638	Non-symbiotic	Produces siderophores, IAA, 2,3-butanediol, and acetoin	Taghavi et al., 2009
Methylobacterium sp. Strain NPFM-SB3	Symbiotic	This strain produced IAA, cytokinins, and promoted lateral roots in rice seedlings	Senthilkumar et al., 2009
Azorhizobium doebereinerae, *Rhizobium etli*	Symbiotic	Increased dry matter production	Blanco et al., 2008
Klebsiella pneumoniae 342	Symbiotic	Nitrogen fixation	Fouts et al., 2008
Serratia marcescens UPM39B3	Non-symbiotic	Growth promotion	Ting et al., 2008
Pseudomonas stutzeri A1501	Symbiotic	N_2-fixation	Yan et al., 2008
Rhizobium sp.	Symbiotic	Synthesis of IAA	Sridevi and Mallaiah, 2007
Rhizobium sp. U9709-SC	Symbiotic	Solubilization of insoluble phosphate	Daimon et al., 2006
Pantoea agglomerans EPS125	Non-symbiotic	Accumulation of trehalose & glycinebetaine for desiccation tolerance	Bonaterra et al., 2005
Paenibacillus sp. K165	Non-symbiotic	Induced systematic resistance	Tjamos et al., 2005

bean rhizobial isolates. However, there are two most popular methods for utilizing BNF: the first is improved crop, soil, and water management to maximize BNF potential; the second is *Rhizobium* inoculation or host genotype selection to ensure increased nitrogen fixation in the plant (Pankievicz et al*.,* 2019). The rhizobia-legume symbiosis accounts for a significant amount of the nitrogen available to the leguminous crops. Among these, the most sustainable agricultural technique is the use of efficient rhizobial strains as biofertilizers to increase the output of legumes (Saharan and Nehra, 2011). It becomes necessary to improve rhizobia to increase their symbiotic efficiency and a wide range of host options (Gopalakrishnan et al*.,* 2015). Recent developments in high-throughput next-generation technology make it possible to investigate the depth of biological nitrogen fixation. For improving nitrogen fixation in legumes, omics-based approaches are very effective and instructive (Qi et al*.,* 2023).

Mineral solubilizing bacteria

Microorganisms that can increase the solubility and bioavailability of various minerals in their natural surroundings are called mineral-solubilizing microorganisms. Mineral-solubilizing bacteria play a critical role in biogeochemical cycles by releasing vital nutrients from minerals and making them available for plant uptake and other biological activities (Etesami and Adl, 2020). Mineral-solubilizing bacteria use a variety of techniques to make minerals accessible. Producing organic acids like gluconic acid, oxalic acid, and citric acid is one of the main strategies bacteria use to solubilize insoluble minerals (Bhadrecha et al., 2023). The bacterial strains produce these organic acids, which have chelating properties. They bond to metal ions in minerals to promote their breakdown. Bacteria also produce siderophores and various enzymes participating in mineral solubilization (Walpola et al., 2022). Phosphate-containing minerals are hydrolyzed with enzymes like phosphatases, which release soluble phosphate ions. Bacterial siderophores attach to ferric ions and help in their breakdown to be readily available for plant uptake (Cui et al., 2023). Mineral solubilization by these bacteria has significant consequences for both farming and the restoration of the environment. In nutrient-deficient soils, mineral-solubilizing bacteria increase plant growth and production by increasing the availability of vital minerals. Furthermore, their capacity to extract heavy metals from minerals and detoxify them, can support bioremediation processes, which clean up contaminated areas to lower contamination levels (Timofeeva et al., 2022). Mineral solubilizing bacteria can promote the release and breakdown of vital nutrients from minerals via various processes, such as the synthesis of organic acids, the secretion of enzymes, and siderophore-mediated solubilization.

Table 3. Mechanisms of mineral solubilizing bacteria through enzymolysis and production of organic acids

Mineral solubilization	Bacteria	Enzyme produced	Organic acid produced	References
Phosphate solubilization	*Pseudomonas fluorescens*	Gluconate dehydrogenase	Gluconic acid	Cheng et al., 2023
	Bacillus subtilis	Phosphatase	Citric acid	Cheng et al., 2023
	Burkholderia cepacia	Malate dehydrogenase	Malic acid	Espinosa-Hernández et al., 2023
	Pantoea agglomerans	Citrate synthase	Citric acid	Maldani et al., 2023
	Rhizobium leguminosarum	Nitrogenase	Citric acid and Malic acid	Rabani et al., 2023
	Enterobacter cloacae	Pyruvate carboxylase, Phosphatase	Citric acid	Wang et al., 2023
	Klebsiella pneumoniae	Phosphatases and Proteases	Acetic acid, Lactic acid	Gupta et al., 2021
	Serratia marcescens	Phosphatases and Proteases	Gluconic acid	Mulani et al., 2021
	Pseudomonas fluorescens	Phosphatases and Proteases	Gluconic acid and Oxalic acid	Rawat et al., 2021
	Microbacterium arborescens	Proteases	Citric acid and Malic acid	Bhagat et al., 2021
	Burkholderia cepacia	Phosphatases and Proteases	Gluconic acid and Oxalic acid	Chawngthu et al., 2020
	Enterobacter spp.	Phosphatases and Proteases	Gluconic acid	Kour et al., 2020
	Azospirillum lipoferum	Phosphatases and Nitrogenase	Gluconic acid and Malic acid	Ayyaz et al., 2016

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	Azotobacter chroococcum	Nitrogenase	Gluconic acid and Keto-gluconic acid	Kumar et al., 2016
Potassium solubilization	*Pseudomonas putida*	Oxalate decarboxylase	Oxalate	Shahid et al., 2023
	Burkholderia gladioli	Succinate dehydrogenase	Succinic acid	Silva et al., 2023
	Enterobacter asburiae	Citrate synthase	Citric acid	Jini et al., 2023
	Pantoea dispersa	Malate dehydrogenase	Malic acid	Singh et al., 2023
	Rhizobium leguminosarum	Nitrogenase	Citric acid and Malic acid	Ghorai and Ghosh, 2022
	Klebsiella pneumoniae	Phosphatases and Proteases	Acetic acid and Lactic acid	Gupta et al., 2021
	Bacillus megaterium	Gluconic dehydrogenase, Phosphatases and Proteases	Gluconic acid, Citric acid and Lactic acid	Mei et al., 2021
	Serratia marcescens	Phosphatases and Proteases	Gluconic acid	Mulani et al., 2021
	Pseudomonas fluorescens	Phosphatases and Proteases	Gluconic acid and Oxalic acid	Rawat et al., 2021
	Burkholderia cepacia	Phosphatases and Proteases	Gluconic acid and Oxalic acid	Chawngthu et al., 2020
	Azotobacter chroococcum	Nitrogenase	Gluconic acid and Keto-gluconic acid	Jin et al., 2020
	Enterobacter spp.	Phosphatases and Proteases	Gluconic acid	Kour et al., 2020
	Bacillus subtilis	Phosphatases	Citric acid and Malic acid	Behera et al., 2017
	Azospirillum lipoferum	Phosphatases and Nitrogenase	Malic acid and Succinic acid	Ayyaz et al., 2016
Zinc solubilization	*Pseudomonas putida*	Glucose dehydrogenase	Gluconic acid	Joshi et al., 2023
	Pantoea dispersa	Lactate dehydrogenase	Lactic acid	Ma et al., 2023
	Pantoea dispersa	Proteases and Phosphatases	Citric acid and Gluconic acid	Mondal et al., 2023
	Acinetobacter sp.	Malate dehydrogenase	Malic acid	Singh et al., 2023
	Bacillus megaterium	ACC deaminase	Gluconic acid	Wang et al., 2023
	Burkholderia vietnamiensis	Citrate synthase	Citric acid	Ghorai and Ghosh, 2022
	Enterobacter cloacae, Bacillus aryabhattai	Proteases and Phosphatases	Citric acid and Oxalic acid	Hakim et al., 2021
	Burkholderia cepacia	Proteases and Phosphatases	Gluconic acid and Itaconic acid	Seenivasagan and Babalola, 2021
	Rhizobium leguminosarum	Proteases and Phosphatases	Citric acid and Malic acid	Kour et al., 2020
	Bacillus subtilis	Proteases and Phosphatases	Citric acid and Malic acid	Dash and Dangar, 2019
	Pseudomonas fluorescens	Proteases and Phosphatases	Gluconic acid and Succinic acid	Kumawat et al., 2019
	Bacillus licheniformis	Proteases and Phosphatases	Citric acid and Malic acid	Kumar et al., 2014
Manganese solubilization	*Burkholderia cepacia*	Manganese oxidase and Laccase	Gluconic acid and Itaconic acid	Dudhagara et al., 2023
	Rhizobium leguminosarum	Manganese oxidase and Laccase	Gluconic acid and Oxalic acid	Devi et al., 2022
	Enterobacter cloacae	Manganese oxidase and Laccase	Citric acid and Oxalic acid	Athukorala, 2021
	Bacillus subtilis	Manganese oxidase and Laccase	Gluconic acid and Malic acid	Athukorala, 2021

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Agrobacterium tumefaciens	Manganese oxidase and Laccase	Gluconic acid and Succinic acid	Devi et al., 2020
Pseudomonas aeruginosa	Manganese oxidase and Laccase	Gluconic acid and Oxalic acid	Kumar and Chandra, 2020
Azotobacter chroococcum	Manganese oxidase and Laccase	Gluconic acid and Itaconic acid	Mahala et al., 2020
Pseudomonas putida	Manganese oxidase and Laccase	Citric acid and Malic acid	Wan et al., 2020
Bacillus cereus	Manganese oxidase and Laccase	Gluconic acid and Itaconic acid	Javaid et al., 2019
Arthrobacter globiformis	Manganese oxidase and Laccase	Citric acid and Malic acid	Rahi and Soni, 2007

Microorganisms involved in solubilizing insoluble phosphate are termed phosphate solubilizing bacteria (PSB) and are significantly present in many habitats. The primary function of these bacteria is to solubilize insoluble forms of phosphorus and ensure its availability to plants and microbes (Kafle et al., 2019). The PSB perform various actions and mechanisms to solubilize insoluble minerals, including organic acids. These organic acids produced by bacteria in phosphate solubilization are citric acid, gluconic acid, oxalic acid, and malic acid, which can act as chelating agents. These organic acids help break down mineral phosphate by adhering to the metal ions of those minerals (Chai et al., 2023).

Along with organic acids, enzymes also facilitate phosphate solubilization. Phosphatases are one of the significant enzymes that take part in this process. PSB produce alkaline and acidic phosphatases, which ensure the availability of soluble phosphate by reacting with phosphate-containing minerals and esters (Peng et al., 2023). Microorganisms, including *Bacillus megaterium, Pseudomonas fluorescens, Burkholderia* spp., *Enterobacter* spp., and *Azotobacterium chlorococcum,* are involved in phosphate solubilization (Sharma et al., 2023). PSB are an essential research subject due to their phosphorus restriction capacity and helping in improving and developing several agricultural and environmental scenarios (Ramirez-Gil et al., 2023).

The rhizobacteria involved in solubilizing insoluble potassium and ensuring potassium availability in the rhizosphere are termed potassium solubilizing bacteria (KSB) (Etesami and Adl, 2020). To solubilize the insoluble form of potassium, these bacteria use several techniques; one is the production of organic acids that can act as chelating agents. By forming complexes with potassium ions, organic acids production by KSB, including citric acid, malic acid, oxalic acid, and gluconic acid, assist in solubilizing insoluble potassium compounds (Sindhu et al., 2022). In addition, KSB-produced enzymes are essential for the solubilization of potassium. Potassium is released from organic materials and minerals via phosphatases, specifically acid phosphatases and alkaline phosphatases (Kumar et al., 2022). These enzymes catalyze the release of soluble potassium ions by hydrolyzing phosphorus molecules. Among the bacteria recognized for their capacity to solubilize potassium are *Bacillus subtilis, Burkholderia cepacia, Pseudomonas* spp., *Azospirillum* spp., and *Enterobacter* spp. (Devi et al., 2022). Several studies focus on the capacity of these bacteria, among others, to solubilize potassium and encourage plant development. The ability of KSB to enhance plant uptake of potassium renders them advantageous in the context of sustainable agriculture and nutrient management approaches (Sarkar et al., 2021).

A category of microorganisms known as zinc solubilizing bacteria (ZSB) assists in releasing zinc from the soil, so plants can absorb it more easily. These bacteria increase zinc availability in the rhizosphere by solubilizing zinc from insoluble sources in multiple processes (Khoshru et al., 2020). One method that ZSB use for zinc solubilization is the synthesis of organic acids. Organic acids secreted by ZSB, including acetic, citric, gluconic, and oxalic acids, function as chelators by forming compounds with zinc ions and promoting their solubility (Khoshru et al., 2023). Enzymes also play a crucial role in zinc solubilization by ZSB. Acid phosphatases and alkaline phosphatases release zinc from organic matter and minerals. These enzymes release soluble zinc ions by catalyzing the hydrolysis of substances containing phosphorus (Chen and Arai, 2023). The few examples of bacteria well-known for their capacity to solubilize zinc are *Bacillus cereus, Pseudomonas fluorescens, Agrobacterium* spp., *Enterobacter* spp., and *Gluconacetobacter diazotrophicus* (Mehmood et al., 2023). Various microbes have also been examined for their ability to solubilize zinc and encourage plant development. By absorbing zinc, these bacteria have become significant in sustainable agriculture and nutrient management (Gauba et al., 2023).

A group of bacteria that takes part in solubilizing the insoluble form of manganese is called manganese solubilizing bacteria (MSB). They also ensure the Mn absorption in plants (Khoshru et al., 2023). Manganese solubilizing bacteria perform organic acids and enzyme production processes. Organic acids, including citric acid, oxalic acid, malic acid, and gluconic acid, convert insoluble manganese into soluble nutrients; they act as chelating agents by forming mineral complexes (Ijaz et al., 2021). The production of enzymes by MSB also helps in manganese solubilization. For example, acid phosphatases release manganese, and phytases remove organic matter (Lall and Dumas, 2022). When these phosphate-containing molecules break down, a soluble form of manganese is released. *Bacillus subtilis, Pseudomonas putida, Arthrobacter* spp., *Cellvibrio* spp., and *Streptomyces* spp. are some of the main bacteria species that are known for their manganese solubilizing potential (Shinde et al., 2022). These microbes ensure the availability of manganese to plants. With the help of MSB, manganese uptake in plants is increased, which is vital for plant growth and nutrient uptake.

The breakdown of complex organic compounds with phosphate-solubilizing bacteria releases soluble orthophosphate ions by producing citric acid and gluconic acid. They also secrete phosphatases (Cheng et al., 2023). By proton extrusion, they also decrease pH and increase phosphate solubility. Potassium solubilization occurs when bacteria create organic acids, such as acetic and oxalic acids, which chelate potassium ions and make them more soluble (Setiawati et al., 2022). They might also produce siderophores, iron-chelating substances that indirectly increase potassium availability by relocating potassium ions from clay minerals (Potysz and Bartz, 2023). Zinc solubilizing bacteria use the secretion of organic acids (such as malic and citric acids) to chelate zinc ions and help release them from insoluble forms. They produce enzymes that degrade organic materials and release bound zinc, including proteases and organic acid decarboxylases (Singh et al., 2023). By separating manganese from mineral complexes, bacteria solubilize it by using organic acids as chelating agents. Manganese ions are released during the breakdown of organic matter by enzymes produced by bacteria, such as phytase and acid phosphatase (Mondal et al., 2023). Microorganisms use a variety of approaches to solubilize minerals, including phosphate, potassium, zinc, and manganese, including the secretion of organic acids, the synthesis of enzymes, and pH regulation (Khoshru et al., 2023) are summarized in **Table 3**. Ultimately, these processes improve the accessibility and uptake of these vital nutrients, which is advantageous for plant development and the environment's nutrient cycle.

ACC deaminase-producing bacteria

Certain bacteria produce the ACC (1-aminocyclopropane-1-carboxylate) deaminase enzyme, especially under stress conditions. ACC deaminase-producing bacteria favor plant development and growth (Singh *et al.,* 2022). Under stressful environmental conditions such as salinity, drought, temperature, and heavy metal toxicity, ACC deaminase production by bacteria can mitigate these stresses, and is pivotal for plant-microbe interaction (Chandwani and Amaresan, 2022).

Ethylene is involved in various physiological processes because it is a naturally occurring plant hormone. In ethylene biosynthesis, ACC is a critical precursor. Plants produce a surplus of ethylene under stressful environmental conditions, inhibiting growth, reducing cell integrity, and lowering yield (Khan et al*.,* 2017). To alleviate the effect of these stresses, ACC deaminase catalyzes the conversion of ACC into α-ketobutyrate and ammonia thereby lowering down ethylene production in plants (Jha et al*.,* 2021). Several investigations have shown that ACC deaminase-producing bacteria have enhanced plant ability to tolerate various abiotic stresses, such as salinity, heavy metals, drought, and high temperature, that improve plant growth and development by increasing protein content, seed germination, root elongation, and biomass production in the plant (Gowtham et al., 2020; Han et al., 2021; Naing et al*.,* 2021).

ACC deaminase-producing bacteria colonize plant roots and form a symbiotic association with the host plant (Roy et al*.,* 2023b). These bacteria predominantly interact with the plant and initiate a series of beneficial effects. In return, plants provide the bacteria nutrients and a protected niche to grow and survive. ACC deaminase-producing bacteria help plants to overcome stress by decreasing ethylene levels, as summarized in **Figure 2** (Bittencourt et al., 2023). Metabolizing ACC lowers ethylene production and mitigates the adverse effects of stress-induced ethylene accumulation (Etesami et al., 2020). ACC deaminase-producing bacteria exhibit another attractive characteristic, i.e, the ability to modulate plant stress-responsive genes directly. By eliciting changes in gene expression, these bacteria help plants to activate stress-responsive pathways, reinforce their defense mechanisms, and adapt to adverse environmental conditions (Ali et al., 2022; Naing et al*.,* 2021). The bacterial ACC deaminase activity could be due to the *acdS* gene broadly distributed in most soil microorganisms (Gupta et al*.,* 2021). For example, Nascimento et al. (2014) reported the presence of this gene in a diverse group of bacteria, including Actinobacteria, Deinococcus, α-Proteobacteria, β-Proteobacteria, γ-Proteobacteria, and Firmicutes. The Lrp-like regulatory proteins, such as AcdR, regulate the expression of *acdS* genes in proteobacteria (Ekimova et al*.,* 2022). This gene is also found in the fungus *Trichoderma asperellum,* which showed plant growth promotion characteristics and biocontrol of phytopathogenic microorganisms (Rauf et al., 2021).

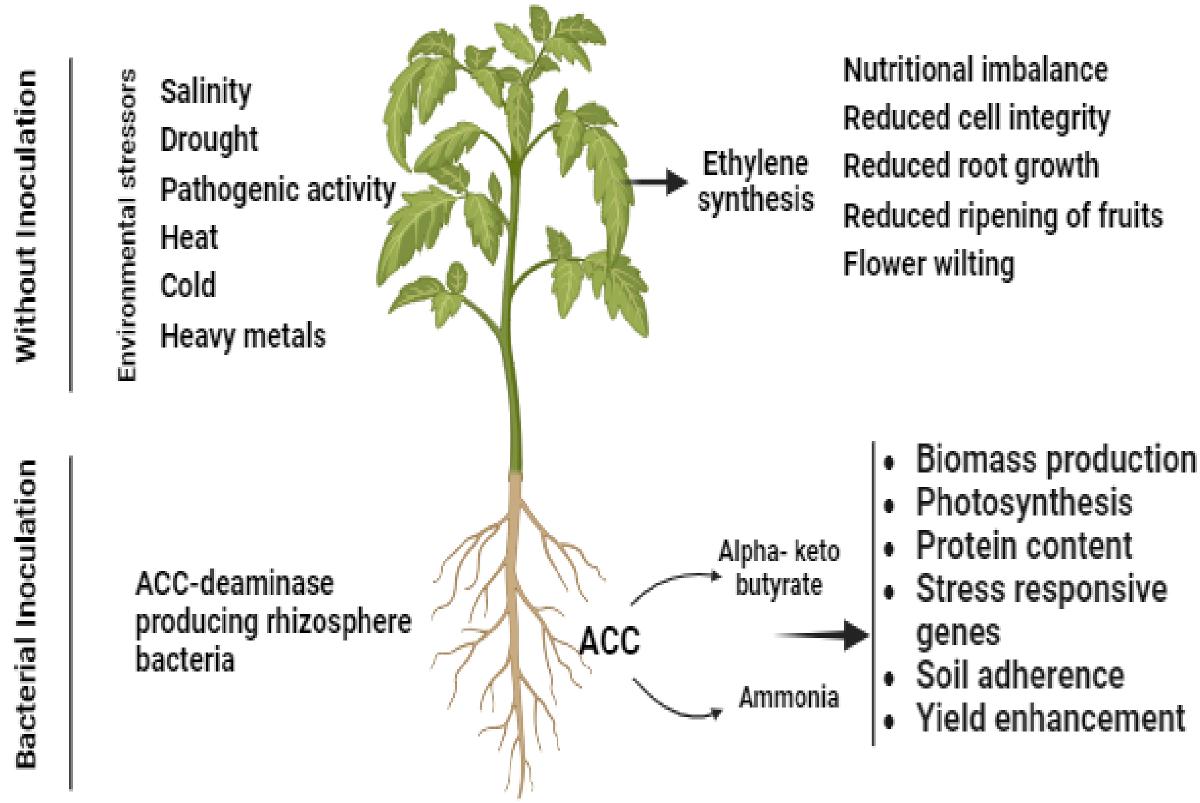

Figure 2. A schematic representation of ACC deaminase-producing bacteria involved in stress alleviation through reducing alleviated ethylene level

The range of stress conditions that ACC deaminase-producing bacteria address is nothing short of remarkable. These bacteria alleviate water stress in drought-stricken environments by maintaining root growth and inhibiting ethylene-triggered growth (Yavuz et al*.,* 2023). Salinity stress is a challenge that disrupts nutrient uptake and cellular processes, which can be managed through the exact ethylene-regulating mechanism. ACC deaminase-producing bacteria help plants to adapt to saline conditions without compromising growth (Misra and Chauhan, 2020). The role of these bacteria in combatting pathogen attacks is equally significant. When plants encounter pathogens, ethylene production surges as part of the defense response (Tyśkiewicz et al*.,* 2022). However, excessive ethylene can lead to tissue damage and inhibit growth. ACC deaminase-producing bacteria fine-tune this ethylene response, enabling a balanced defense reaction without causing harm to the plant (Katiyar et al*.,* 2021). Temperature extremes, heavy metal exposure, nutrient deficiencies, and even the transplant shock experienced during replanting, are all challenges that these bacteria assist plants in surmounting. By reducing ethylene accumulation, these microorganisms facilitate stress tolerance across a spectrum of adverse conditions (Chandwani and Amaresan, 2022). This adaptability highlights the versatility of ACC deaminase-producing bacteria and their potential to reshape our environmental sustainability and ecosystem restoration strategies.

Table 4. Role of ACC deaminase-producing rhizosphere bacteria in alleviating stress in host plants

Stress	Organism	Host plant	Findings	References
Salt stress	*Pantoea agglomerans* R1, *Pseudomonas fragi* R4	French bean (*Phaseolus vulgaris*)	These strains improved root architecture, plant growth, and micronutrient uptake under salt-stressed conditions	Gupta et al., 2023
	Aneurinibacillus aneurinilyticus AIOA1, *Paenibacillus* sp. SG_AIOA2	Common bean (*Phaseolus vulgaris*)	These strains mitigated the negative impact of salt stress on plants	Gupta et al., 2021
	Bacillus marisflavi (CHR JH 203), *Bacillus cereus* (BST YS1_42)	Pea *(Pisum sativum)*	These strains possessing PGP traits promoted plant growth under saline stress	Gupta et al., 2021

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	Bacillus subtilis (NBRI 28B, NBRI 33 N), *B. safensis* (NBRI 12 M)	Maize (*Zea mays*)	These strains exhibiting multiple PGP attributes alleviated salt stress by reducing ethylene levels in the host plant	Misra and Chauhan, 2020
	Methylobacterium oryzae CBMB20	Rice (*Oryza sativa*)	Strain CBMB20 promoted cell viability of roots by regulating the ethylene emission pathway under salt stress	Choudhury et al., 2020
	Bacillus siamensis (PM13), *Bacillus* sp. (PM15), *Bacillus methylotrophicus* (PM19)	Wheat (*Triticum aestivum*)	These bacterial strains efficiently reduced the impact of salinity on wheat growth	Din et al., 2019
	Aneurinibacillus aneurinilyticus ACC02, *Paenibacillus* sp. ACC06	French bean (*Phaseolus vulgaris*)	Bacterial consortia alleviated the negative effects of salinity stress and promoted plant growth	Gupta and Pandey, 2019
Drought stress	*Pseudomonas* sp. MRBP4, *Pseudomonas* sp. MRBP13, *Bacillus* sp. MRBP10	Maize (*Zea mays*)	The synergistic effect of the bacterial strains was observed in maize in terms of biochemical and physiological attributes under drought stress in arid regions	Ojuederie and Babalola, 2023
	Pseudomonas stutzeri AK17, *Paenibacillus polymyxa* KM6	Cluster bean (*Cyamopsis tetragonoloba*)	These bacteria improved drought tolerance in cluster bean seedlings	Jain and Saraf, 2023
	Serratia marcescens RRN II 2, *Pseudomonas* sp. RRC I 5	Wheat (*Triticum aestivum*)	These bacteria improved the physiological traits, productivity, and nutrient status in wheat during drought stress	Khan and Singh, 2021
	Variovorax paradoxus RAA3, *Pseudomonas* sp. DPC12, *Achromobacter* spp. PSA7, *Ochrobactrum anthropi* DPC9	Wheat (*Triticum aestivum*)	These bacteria were effective inoculants to improve the growth of wheat plants in water-stressed rain-fed environments	Chandra et al., 2019
	Bacillus subtilis Rhizo SF 48	Tomato (*Solanum lycopersicum*)	Rhizo SF 48 served as a useful bioinoculant for sustainable tomato production in arid and semi-arid regions with water deficit	Gowtham et al., 2019
	Pseudomonas fluorescens DPB15, *P. palleroniana* strain DPB16	Wheat (*Triticum aestivum*)	Bacterial inoculation enhanced the growth of wheat in terms of root and shoot biomass, height, and foliar nutrient content	Chandra et al., 2018
	Pseudomonas sp. RJ15, *Bacillus subtilis* RJ46	*Vigna mungo*, *Pisum sativum*	Bacterial application improved crop health in drought-affected acidic agricultural fields	Saikia et al., 2018
Heavy metal stress	*Burkholderia pyrrocinia* LWK2	Katsura tree (*Cercidiphyllum japonicum*)	LWK2 was resistant to Cu, Zn, Cd, and Co, with maximum tolerance to 4 mM, 10 mM, 3 mM, and 1 mM, respectively.	Jin et al., 2023
	Sphingomonas sp. PbM2	Maize (*Zea mays*)	PbM2 remediated the contaminated soil,	Lee et al., 2023
	Enterobacter cloacae (ZNP-4)	Wheat (*Triticum aestivum*)	ZNP-4 alleviated the heavy metal stress and improved wheat production	Singh et al., 2022
	Pseudomonas sp. TR15a, *Bacillus aerophilus* TR15c	Sunflower (*Helianthus annuus*)	Bacterial strains enhanced Cu uptake and improved biomass production, and decontaminated Cu-contaminated natural ecosystems	Kumar et al., 2021

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Achromobacter sp. A1	Maize (*Zea mays*)	A1 had a great potential to immobilize Cd and reduce its uptake in maize in Cd-contaminated environments	Sun et al., 2022
Bacillus gibsonii (PM11), *Bacillus xiamenensis* (PM14)	Flax plant (*Linum usitatissimum*)	These bacterial strains elevated phytoextraction of multi-metals from industrially contaminated soils	Zainab et al., 2020
Agrobacterium fabrum, *Leclercia adecarboxylata*	Maize (*Zea mays*)	Inoculation of these bacterial strains alleviated chromium toxicity and promoted plant growth in maize	Danish et al., 2019

The mechanisms by which ACC deaminase-producing bacteria positively affect plants are not fully understood. However, the bacteria are believed to decrease ethylene levels, stimulate plant growth-promoting hormones, enhance nutrient availability, and induce systemic resistance against pathogens (Han et al*.,* 2021; Baslam et al., 2023). These multifaceted interactions demonstrate the complex nature of the plant-microbe relationship and highlight the potential of ACC deaminase-producing bacteria as biofertilizers and biocontrol agents in agriculture (Baslam, 2023). The crop inoculation with ACC deaminase-producing bacteria leads to enhanced root elongation, improved nutrient uptake, and plant growth promotion. Moreover, these bacteria enhance plant resilience by producing PGP substances, such as IAA, gibberellins, and cytokinins. They can modulate the levels of these phytohormones, which play critical roles in plant development and stress tolerance (Kaur and Karnwal, 2023). Chandra et al. (2019) reported that ACC deaminase-producing *Variovorax paradoxus* RAA3, *Pseudomonas* spp. DPC12, *Achromobacter* spp. PSA7 and *Ochrobactrum anthropi* DPC9 promoted wheat growth under water-stressed rain-fed environments. Similarly, Gupta and Pandey (2019) reported the alleviation of the negative effects of drought and salt stress in *Phaseolus vulgaris* by inoculating with ACC deaminase-producing bacteria. The findings of other researchers in salinity, heavy metals, and drought stress alleviation through ACC deaminase-producing bacteria are summarized in **Table 4**.

Biological control of phytopathogens

The significance of developing ecologically acceptable alternatives to the heavy use of chemical pesticides for managing crop diseases has spurred interest in the biological control of plant pathogens during the past ten years (Heydari and Pessarakli, 2010). One of the most promising approaches to safer and more sensible crop management is the employment of helpful microorganisms (biopesticides) (Dlamini et al*.,* 2022). In the past ten years, interest in the biological management of plant pathogens has increased due to the importance of environment-friendly alternatives to the extensive use of chemical pesticides for managing crop diseases (Ab Rahman et al*.,* 2018).

Biocontrol of plant diseases may be able to deal with conditions that are wholly or partially resistant to current control approaches in addition to acting as a replacement for chemical pesticides (Bardin et al*.,* 2015). Using beneficial microorganisms (biopesticides) is one of the most promising strategies for safer and more reasonable crop management. The suppression of plant pathogen populations by living organisms is known as the biological control of plant diseases (Heimpel and Mills, 2017). It is possible to choose isolates of helpful microorganisms that are very powerful against infections and can grow on artificial media. Augmentative biological control applies carefully selected and mass-produced antagonists once or multiple times throughout a growing season (Eilenberg et al., 2001; Van Lenteren et al., 2018).

Growers employ microbial biological control agents (MBCAs), living microorganisms that are commercially augmentative for the biological control of diseases (Sabbahi et al*.,* 2022). Other products contain antimicrobial metabolites produced by specific microbial species, and other items even contain only antimicrobial metabolites without living organisms. These substances are regarded as chemical actives legally (Kohl et al., 2019). Additionally, bacteriophages and mycoviruses have the potential to operate as MBCAs against plant diseases (Van Lenteren et al*.,* 2018). These MBCAs use various modes of action to shield crops from disease damage. Without direct antagonistic contact with the pathogen, they may produce resistance against infections by a pathogen in plant tissues (Pieterse et al., 2014; Conrath et al*.,* 2015). Competition for nutrients and available space is another indirect interaction with pathogens (Spadaro and Droby, 2016). MBCAs can interact with the pathogen directly through antibiosis or hyperparasitism. Ghorbanpour et al. (2018) reported that hyperparasites infect host cells and bacterial pathogens' mycelium, spores, and resting structures. Another direct route of action is the generation of antimicrobial secondary metabolites that have inhibitory effects against infections (Raaijmakers and Mazzola, 2012).

Bacteria and plants coexist closely within agricultural environments. Bacteria may create symbiotic associations with plants by adhering to the root surface or phyllosphere or surviving in soils as free-living organisms (Ayangbenro and Babalola, 2021). Secondary metabolites secreted *in situ* in small amounts increase antagonists' competitive advantage (Grandlic et al., 2009). For the control of nematodes, bacteria species from the genera *Agrobacterium, Arthrobacter, Azotobacter, Clostridium, Desulfovibrio, Serratia, Burkholderia, Azospirillum, Bacillus*, *Chromobacterium,* and *Corynebacterium* have been reported for their biocontrol role (Tapia-Vázquez et al*.,* 2022). The ability of microorganisms to efficiently compete for ecological niches, colonize plant surfaces, and create nematicidal and antimicrobial chemicals (antibiotics, toxins, siderophores, hydrolytic enzymes, etc.) allows bacteria to suppress plant-parasitic nematodes in various ways (Lahlali et al., 2022). Competition for resources or infection sites, parasitism, antibiosis, or other mechanisms can all produce a direct antagonistic effect. Bacteria may indirectly strengthen the host's defenses, leading to induced systemic resistance (ISR) (Prajapati et al*.,* 2020). The *Bacillaceae* and *Pseudomonadaceae* members are given special consideration, emphasizing how they can control the nematode of the *Meloidogyne* genus (Berlanga et al*.,* 2020). Bacterial endophytes are advantageous as possible biocontrol agents against wilt diseases because they can occupy an ecological niche comparable to that of vascular wilt pathogens (Kavino and Manoranjitham, 2018). Beneficial bacteria have been linked to many potential disease-suppressing processes, including the induction of systemic resistance, growth promotion, and competition (Kolytaitė et al., 2022; Fadiji and Babalola, 2020).

Conclusion

Rhizosphere bacteria have enormous potential for sustainable agriculture by encouraging plant growth, improving nutrient uptake, and reducing plant stress. The information in this review shows how important rhizosphere bacteria are beneficial to agricultural sustainability and provide encouraging solutions to current and upcoming problems. Rhizosphere bacteria significantly improve plant nutrition by solubilizing essential minerals, fixing nitrogen, and suppressing plant diseases. This biological intervention minimizes environmental pollution and ecosystem damage and increases crop production while reducing reliance on chemical pesticides and synthetic fertilizers. Furthermore, in considering climate change and uncertain climatic conditions, the capacity of rhizosphere bacteria to minimize plant stress and confer resistance to biotic and abiotic stresses is crucial. The utilization of rhizosphere bacteria presents a viable approach to sustainable agriculture. By acknowledging and investigating the capabilities of these advantageous microbes, we can create a more resilient and eco-friendly agricultural system that guarantees nutrition, preserves natural resources, and lessens the effects of climate change.

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References

Ab Rahman, S.F.S., Singh, E., Pieterse, C.M., Schenk, P.M. (2018). Emerging microbial biocontrol strategies for plant pathogens. *Plant Science* 267:102-111.

Abdelaziz, A.M., Hashem, A.H., El-Sayyad, G.S., El-Wakil, D.A., Selim, S., Alkhalifah, D.H., Attia, M.S. (2023). Biocontrol of soil borne diseases by plant growth promoting rhizobacteria. *Tropical Plant Pathology* 48:105–127.

Afzal, I., Shinwari, Z.K., Sikandar, S., Shahzad, S. (2019). Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants. *Microbiological Research* 221:36-49.

Ali, B., Wang, X., Saleem, M.H., Sumaira, Hafeez, A., Afridi, M.S., Ali, S. (2022). PGPR-mediated salt tolerance in maize by modulating plant physiology, antioxidant defense, compatible solutes accumulation and bio-surfactant producing genes. *Plants* 11(3):345.

Athukorala, A.D.S.N.P. (2021). Solubilization of micronutrients using indigenous microorganisms. *In* "Microbial Technology for Sustainable Environment", (P. Bhatt, S. Gangola, D. Udayanga, G. Kumar, eds.). pp. 365-417. Springer, Singapore. https://doi.org/10.1007/978-981-16-3840-4_21

Ayangbenro, A.S., Babalola, O.O. (2021). Reclamation of arid and semi-arid soils: The role of plant growth-promoting archaea and bacteria. *Current Plant Biology* 25:100173.

Ayyaz, K., Zaheer, A., Rasul, G., Mirza, M.S. (2016). Isolation and identification by 16S rRNA sequence analysis of plant growth-promoting *Azospirilla* from the rhizosphere of wheat. *Brazilian Journal of Microbiology* 47:542-550.

Bajguz, A., Piotrowska-Niczyporuk, A. (2023). Biosynthetic pathways of hormones in plants. *Metabolites* 13(8):884.

Bardin, M., Ajouz, S., Comby, M., Lopez-Ferber, M., Graillot, B., Siegwart, M., Nicot, P.C. (2015). Is the efficacy of biological control against plant diseases likely to be more durable than that of chemical pesticides? *Frontiers in Plant Science* 6:566.

Baslam, M., (2023). Advances and new perspectives in plant-microbe interactions. *International Journal of Molecular Sciences* 24(6):5143.

Basu, S., Kumar, G., Chhabra, S., Prasad, R. (2021). Role of soil microbes in biogeochemical cycle for enhancing soil fertility. *In* "New and Future Developments in Microbial Biotechnology and Bioengineering" (J.P. Verma, C.A. Macdonald, V.K. Gupta, A.R. Podile, eds.). pp. 149-157. Elsevier. doi.org/10.1016/B978-0-444-64325-4.00013-4

Behera, B.C., Yadav, H., Singh, S.K., Sethi, B.K., Mishra, R.R., Kumari, S., Thatoi, H. (2017). Alkaline phosphatase activity of a phosphate solubilizing *Alcaligenes faecalis*, isolated from mangrove soil. *Biotechnology Research and Innovation* 1(1):101-111.

Berlanga-Clavero, M.V., Molina-Santiago, C., de Vicente, A., Romero, D. (2020). More than words: the chemistry behind the interactions in the plant holobiont. *Environmental Microbiology* 22(11):4532-4544.

Bhadrecha, P., Singh, S., Dwibedi, V. (2023). 'A plant's major strength in rhizosphere': the plant growth promoting rhizobacteria. *Archives of Microbiology* 205(5):165.

Bhagat, N., Raghav, M., Dubey, S., Bedi, N. (2021). Bacterial exopolysaccharides: Insight into their role in plant abiotic stress tolerance. *Journal of Microbiology and Biotechnology* 31(8):1045–1059.

Bittencourt, P.P., Alves, A.F., Ferreira, M.B., da Silva Irineu, L.E.S., Pinto, V.B., Olivares, F.L. (2023). Mechanisms and applications of bacterial inoculants in plant drought stress tolerance. *Microorganisms* 11(2):502.

Blanco, A.R., Csukasi, F., Abreu, C., Sicardi, M. (2008). Characterization of rhizobia from *Sesbania* species native to seasonally wetland areas in Uruguay. *Biology and Fertility of Soils* 44(7):925–932

Bonaterra, A., Camps, J., Montesinos, E. (2005). Osmotically induced trehalose and glycine betaine accumulation improves tolerance to desiccation, survival and efficacy of the postharvest biocontrol agent *Pantoea agglomerans* EPS125. *FEMS Microbiology Letters* 250:1–8.

Chai, X., Cao, F., Zhang, C., Zhong, K., Jiang, L. (2023). Investigating the use of *Aspergillus niger* fermentation broth as a washing treatment for arsenic and antimony co-contaminated soil. *Environmental Science and Pollution Research* 30:82866–82877

Chan, G.Y., Zhi, H.Y., Wong, M.H. (2003) Comparison of four *Sesbania* species to remediate Pb/Zn and Cu mine tailings. *Environmental Management* 32(2):246–251

Chandra, D., Srivastava, R., Sharma, A.K. (2018). Influence of IAA and ACC deaminase producing fluorescent pseudomonads in alleviating drought stress in wheat (*Triticum aestivum). Agricultural Research* 7:290-299.

Chandra, D., Srivastava, R., Gupta, V.V., Franco, C.M., Sharma, A.K. (2019). Evaluation of ACC-deaminase-producing rhizobacteria to alleviate water-stress impacts in wheat (*Triticum aestivum* L.) plants. *Canadian Journal of Microbiology* 65(5):387-403.

Chandra-kuntal, K. (2022). Ethylene and ROS crosstalk in plant developmental processes. *In* "Ethylene in Plant Biology*"* (S. Singh, T. Husain, V.P. Singh, D.K. Tripathi, S.M. Prasad, N.K. Dubey, eds.). pp. 125-177. Wiley.

Chandwani, S., Amaresan, N. (2022). Role of ACC deaminase producing bacteria for abiotic stress management and sustainable agriculture production. *Environmental Science and Pollution Research* 29(16):22843-22859.

Chaparro, J.M., Badri, D.V., Bakker, M.G., Sugiyama, A., Manter, D.K., Vivanco, J.M. (2013). Root exudation of phytochemicals in Arabidopsis follows specific patterns that are developmentally programmed and correlate with soil microbial functions. *PLOS One* 8(2):e55731.

Chauhan, M.P., Singh, N.K., Chaudhary, A.K., Shalini, R. (2017). Characterization of rhizobium isolates from *Sesbania* rhizosphere and their role in bioremediation of glyphosate and Monocrotophos. *International Journal of Applied and Natural Sciences* 6 (4):11-22.

Chawngthu, L., Hnamte, R., Lalfakzuala, R. (2020). Isolation and characterization of rhizospheric phosphate solubilizing bacteria from wetland paddy field of Mizoram, India. *Geomicrobiology Journal* 37(4):366-375.

Chen, A., Arai, Y. (2023). A review of the reactivity of phosphatase controlled by clays and clay minerals: Implications for understanding phosphorus mineralization in soils. *Clays and Clay Minerals* 71:119-142.

Cheng, Y., Narayanan, M., Shi, X., Chen, X., Li, Z., Ma, Y. (2023). Phosphate-solubilizing bacteria: Their agroecological function and optimistic application for enhancing agro-productivity. *Science of The Total Environment* 901:166468. doi.org/10.1016/j.scitotenv.2023.166468.

Chieb, M., Gachomo, E.W. (2023). The role of plant growth promoting rhizobacteria in plant drought stress responses. *BMC Plant Biology* 23(1):407.

Choudhury, A.R., Trivedi, P., Madhaiyan, M., Choi, J., Choi, W., Park, J.H., Sa, T. (2023). ACC deaminase producing endophytic bacteria enhances cell viability of rice (*Oryza sativa* L.) under salt stress by regulating ethylene emission pathway. *Environmental and Experimental Botany* 213:105411. doi.org/10.1016/j.envexpbot.2023.105411.

Conrath, U., Beckers, G.J., Langenbach, C.J., Jaskiewicz, M.R. (2015). Priming for enhanced defense. *Annual Review of Phytopathology* 53:97-119.

Cui, Q., Zhang, Z., Beiyuan, J., Cui, Y., Chen, L., Chen, H., Fang, L. (2023). A critical review of uranium in the soil-plant system: Distribution, bioavailability, toxicity, and bioremediation strategies. *Critical Reviews in Environmental Science and Technology* 53(3):340-365.

Cummings, S.P., Gyaneshwar, P., Vinuesa, P., Farruggia, F.T., Andrews, M., Humphry, D. et al. (2009). Nodulation of *Sesbania* species by *Rhizobium* (*Agrobacterium*) strain IRBG74 and other rhizobia. *Environmental Microbiology* 11(10):2510–2525

Daimon, H., Nobuta, K., Ohe, M., Harada, J., Nakayama, Y. (2006). Tricalcium phosphate solubilization by root nodule bacteria of *Sesbania cannabina* and *Crotalaria juncea*. *Plant Production Science* 9(4):388–389.

Danish, S., Kiran, S., Fahad, S., Ahmad, N., Ali, M.A., Tahir, F.A., Nasim, W. (2019). Alleviation of chromium toxicity in maize by Fe fortification and chromium tolerant ACC deaminase producing plant growth promoting rhizobacteria. *Ecotoxicology and Environmental Safety* 185:109706.

Daranas, N., Badosa, E., Frances, J., Montesinos, E., Bonaterra, A. (2018). Enhancing water stress tolerance improves fitness in biological control strains of *Lactobacillus plantarum* in plant environments. *PLOS One* 13:e0190931

Das, P.P., Singh, K.R., Nagpure, G., Mansoori, A., Singh, R.P., Ghazi, I.A., Singh, J. (2022). Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices. *Environmental Research* 214:113821.

Dasgupta, D., Ghati, A., Sarkar, A., Sengupta, C., Paul, G. (2015). Application of plant growth promoting rhizobacteria (PGPR) isolated from the rhizosphere of *Sesbania bispinosa* on the growth of chickpea (*Cicer arietinum* L.). *International Journal of Current Microbiology and Applied Sciences* 4(5):1033–1042.

Dash, N., Dangar, T.K. (2019). Phosphate mineralization by a rice (*Oryza sativa* L.) rhizoplanic *Enterobacter* sp. *American-Eurasian Journal of Sustainable Agriculture* 13(4):1-18.

De Mandal, S., Bhatt, P. (Eds.). (2020). "Recent Advancements in Microbial Diversity". Academic Press.

De Zelicourt, A., Al-Yousif, M., Hirt, H. (2013). Rhizosphere microbes as essential partners for plant stress tolerance. *Molecular Plant* 6(2):242-245.

Debela, C., Tana, T. Wogi, L. (2021). Effect of *Rhizobium* inoculation, NPS fertilizer and vermicompost on nodulation and yield of soybean (*Glycine max* (L.). Merrill) at Bako, Western Ethiopia. *Journal of Chemical, Environmental and Biological Engineering* 5:49-61.

Devi, R., Kaur, T., Kour, D., Rana, K.L., Yadav, A., Yadav, A.N. (2020). Beneficial fungal communities from different habitats and their roles in plant growth promotion and soil health. *Microbial Biosystems* 5(1):21-47.

Devi, R., Kaur, T., Kour, D., Yadav, A., Yadav, A.N., Suman, A., Saxena, A.K. (2022). Minerals solubilizing and mobilizing microbiomes: A sustainable approach for managing minerals' deficiency in agricultural soil. *Journal of Applied Microbiology* 133(3):1245-1272.

Din, B.U., Rafque, M., Javed, M.T., Kamran, M.A., Mehmood, S., Khan, M., Sultan, T., Munis, M.F.H., Chaudhary, H.J. (2020). Assisted phytoremediation of chromium spiked soils by *Sesbania sesban* in association with *Bacillus xiamenensis* PM14: a biochemical analysis. *Plant Physiology and Biochemistry* 146:249–258

Din, B.U., Sarfraz, S., Xia, Y., Kamran, M.A., Javed, M.T., Sultan, T., Chaudhary, H.J. (2019). Mechanistic elucidation of germination potential and growth of wheat inoculated with exopolysaccharide and ACC-deaminase producing *Bacillus* strains under induced salinity stress. *Ecotoxicology and Environmental Safety* 183:109466.

Ding, L.N., Li, Y.T., Wu, Y.Z., Li, T., Geng, R., Cao, J., Tan, X.L. (2022). Plant disease resistance-related signaling pathways: Recent progress and future prospects. *International Journal of Molecular Sciences* 23(24):16200.

Dlamini, S.P., Akanmu, A.O., Babalola, O.O. (2022). Rhizospheric microorganisms: The gateway to a sustainable plant health. *Frontiers in Sustainable Food Systems* 6:925802.

Duca, D., Lorv, J., Patten, C.L., Rose, D., Glick, B.R. (2014). Indole-3-acetic acid in plant–microbe interactions. *Antonie Van Leeuwenhoek* 106:85-125.

Dudhagara, D.R., Javia, B.M., Vala, A.K. (2023). Exploiting marine fungi in the removal of hazardous pollutants and biomass valorisation. *In* "Marine Organisms: A Solution to Environmental Pollution? Uses in Bioremediation and in Biorefinery" (T. Encarnação, A.C. Pais, eds.). pp. 117-146. Springer, Cham.

Egamberdieva, D., Wirth, S.J., Alqarawi, A.A., Abd_Allah, E.F., Hashem, A. (2017). Phytohormones and beneficial microbes: essential components for plants to balance stress and fitness. *Frontiers in Microbiology* 8:2104.

Eilenberg, J., Hajek, A., Lomer, C. (2001). Suggestions for unifying the terminology in biological control. *Biocontrol* 46:387-400.

Ekimova, G.A., Fedorov, D.N., Doronina, N.V., Khmelenina, V.N., Mustakhimov, I.I. (2022). AcdR protein is an activator of transcription of 1-aminocyclopropane-1-carboxylate deaminase in *Methylobacterium* radiotolerans JCM 2831. *Antonie van Leeuwenhoek* 115(9):1165-1176.

El-Sawah, A.M., El-Keblawy, A., Ali, D.F.I., Ibrahim, H.M., El-Sheikh, M.A., Sharma, A. et al. (2021). Arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria enhance soil key enzymes, plant growth, seed yield, and qualitative attributes of guar. *Agriculture* 11(3):194.

Espinosa-Hernández, V., Gonzalez, J.E., Trejo, E.O., Martinez, J.D., Moreno, J.C.M. (2023). Assessing the nutritional effect of *Lupinus montanus* on *Zea mays* sp. through the Use of Rhizotrons. *International Journal of Plant Biology* 14:910-921.

Etesami, H., Adl, S.M. (2020). Plant growth-promoting rhizobacteria (PGPR) and their action mechanisms in availability of nutrients to plants. *In* "Phyto-Microbiome in Stress Regulation. Environmental and Microbial Biotechnology" (M. Kumar, V. Kumar, R., Prasad, eds.). pp. 147-203. Springer, Singapore.

Etesami, H., Noori, F., Ebadi, A., Reiahi Samani, N. (2020). Alleviation of stress-induced ethylene-mediated negative impact on crop plants by bacterial ACC deaminase: perspectives and applications in stressed agriculture management. *In* "Plant Microbiomes for Sustainable Agriculture, Sustainable Development and Biodiversity", (A. Yadav, J. Singh, A. Rastegari, N. Yadav, eds.). pp. 287-315. Springer, Chan.

Fadiji, A.E., Babalola, O.O. (2020). Exploring the potentialities of beneficial endophytes for improved plant growth. *Saudi Journal of Biological Sciences* 27(12):3622-3633.

Fasusi, O.A., Cruz, C., Babalola, O.O. (2021). Agricultural sustainability: microbial biofertilizers in rhizosphere management. *Agriculture* 11(2):163.

Fouts, D.E., Tyler, H.L., DeBoy, R.T., Daugherty, S., Ren, Q., Badger, J.H. et al. (2008). Complete genome sequence of the N_2-fixing broad host range endophyte *Klebsiella pneumoniae* 342 and virulence predictions verified in mice. *PLOS Genetics* 4:e1000141.

Gauba, A., Hari, S.K., Ramamoorthy, V., Vellasamy, S., Govindan, G., Arasu, M.V. (2023). The versatility of green synthesized zinc oxide nanoparticles in sustainable agriculture: A review on metal-microbe interaction that rewards agriculture. *Physiological and Molecular Plant Pathology* 125:102023.

Ghani, M.I., Ali, A., Atif, M.J., Pathan, S.I., Pietramellara, G., Ali, M., Cheng, Z. (2022). Diversified crop rotation improves continuous monocropping eggplant production by altering the soil microbial community and biochemical properties. *Plant and Soil* 480:603–624.

Ghorai, P., Ghosh, D. (2022). Ameliorating the performance of NPK biofertilizers to attain sustainable agriculture with special emphasis on bioengineering. *Bioresource Technology Reports* 19:101117.

Ghorbanpour, M., Omidvari, M., Abbaszadeh-Dahaji, P., Omidvar, R., Kariman, K. (2018). Mechanisms underlying the protective effects of beneficial fungi against plant diseases. *Biological Control* 117:147-157.

Glick, B.R. (2012). Plant growth-promoting bacteria: mechanisms and applications. *Scientifica* 2012:963401. doi.org/10.6064/2012/963401.

Gopalakrishnan, S., Sathya, A., Vijayabharathi, R., Varshney, R.K., Gowda, C.L., Krishnamurthy, L. (2015). Plant growth promoting rhizobia: challenges and opportunities. *3 Biotech* 5:355-377.

Gowtham, H.G., Singh, B., Murali, M., Shilpa, N., Prasad, M., Aiyaz, M., Niranjana, S.R. (2020). Induction of drought tolerance in tomato upon the application of ACC deaminase producing plant growth promoting rhizobacteriumm *Bacillus subtilis* Rhizo SF 48. *Microbiological Research* 234:126422.

Grandlic, C.J., Palmer, M.W., Maier, R.M. (2009). Optimization of plant growth-promoting bacteria-assisted phytostabilization of mine tailings. *Soil Biology and Biochemistry* 41(8):1734-1740.

Gupta, A., Bano, A., Rai, S., Kumar, M., Ali, J., Sharma, S., Pathak, N. (2021). ACC deaminase producing plant growth promoting rhizobacteria enhance salinity stress tolerance in *Pisum sativum*. *3 Biotech* 11(12):514.

Gupta, G., Parihar, S.S., Ahirwar, N.K., Snehi, S.K., Singh, V. (2015). Plant growth promoting rhizobacteria (PGPR): Current and future prospects for development of sustainable agriculture. *Journal of Microbial Biochemistry and Technology* 7(2):096-102.

Gupta, P., Trivedi, M., Soni, H. (2021). Isolation, identification and evaluation of indigenous plant growth promoting bacterium *Klebsiella pneumoniae* PNE1. *International Journal for Research in Applied Sciences and Biotechnology* 8(6):47-56.

Gupta, R., Anand, G., Bar, M. (2023). Developmental phytohormones: key players in host-microbe interactions. *Journal of Plant Growth Regulation* doi.org/10.1007/s00344-023-11030-y

Gupta, S., Pandey, S. (2019). ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (*Phaseolus vulgaris*) plants. *Frontiers in Microbiology* 10:1506.

Gupta, S., Pandey, S., Kotra, V., Kumar, A. (2023). Assessing the role of ACC deaminase-producing bacteria in alleviating salinity stress and enhancing zinc uptake in plants by altering the root architecture of French bean (*Phaseolus vulgaris*) plants. *Planta* 258(1):3.

Hakim, S., Naqqash, T., Nawaz, M.S., Laraib, I., Siddique, M.J., et al. (2021). Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability. *Frontiers in Sustainable Food Systems* 5:617157.

Han, L., Zhang, H., Xu, Y., Li, Y., Zhou, J. (2021). Biological characteristics and salt-tolerant plant growth-promoting effects of an ACC deaminase-producing *Burkholderia pyrrocinia* strain isolated from the tea rhizosphere. *Archives of Microbiology* 203:2279-2290.

Heimpel, G.E., Mills, N.J. (2017). “Biological Control”. Cambridge University Press.

Herms, C.H., Hennessy, R.C., Bak, F., Dresbøll, D.B., Nicolaisen, M.H. (2022). Back to our roots: exploring the role of root morphology as a mediator of beneficial plant–microbe interactions. *Environmental Microbiology* 24(8):3264-3272.

Heydari, A., Pessarakli, M. (2010). A review on biological control of fungal plant pathogens using microbial antagonists. *Journal of Biological Sciences* 10(4):273-290.

Hu, H.Q., Li, X.S., He, H. 2010. Characterization of an antimicrobial material from a newly isolated *Bacillus amyloliquefaciens* from mangrove for biocontrol of *Capsicum* bacterial wilt. *Biological Control* 54:359–365.

Huang, Z. (2023). “Tryptophan catabolism by gut microbiota: A bridge connecting food science and Human Nutrition”, PhD Thesis, Wageningen University, Wageningen. 228 p.

Ijaz, A., Mumtaz, M.Z., Wang, X., Ahmad, M., Saqib, M., Maqbool, H., Mustafa, A. (2021). Insights into manganese solubilizing *Bacillus* spp. for improving plant growth and manganese uptake in maize. *Frontiers in Plant Science* 12:719504.

Jahn, L., Hofmann, U., and Ludwig-Müller, J. (2021). Indole-3-acetic acid is synthesized by the endophyte *Cyanodermella asteris* via a tryptophan-dependent and-independent way and mediates the interaction with a non-host plant. *International Journal of Molecular Sciences* 22(5):2651.

Jain, R., Saraf, M. (2023). ACC deaminase producing PGPR modulates nutrients uptake, soil properties and growth of cluster bean (*Cyamopsis tetragonoloba* L.) under deficit irrigation. *Biologia* 78:2303–2316

Javaid, R., Sabir, A., Sheikh, N., Ferhan, M. (2019). Recent advances in applications of acidophilic fungi to produce chemicals. *Molecules* 24(4):786.

Jayaraman, S., Naorem, A.K., Lal, R., Dalal, R.C., Sinha, N.K., Patra, A.K., Chaudhari, S.K. (2021). Disease-suppressive soils—beyond food production: a critical review. *Journal of Soil Science and Plant Nutrition* 21:1437-1465.

Jha, C.K., Sharma, P., Shukla, A., Parmar, P., Patel, R., Goswami, D., Saraf, M. (2021). Microbial enzyme, 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase: an elixir for plant under stress. *Physiological and Molecular Plant Pathology* 115:101664.

Jin, H., Wang, H., Zhang, Y., Hu, T., Lin, Z. et al. (2020). Description of *Azotobacter chroococcum* subsp. *isscasi* subsp. nov. isolated from paddy soil and establishment of *Azotobacter chroococcum* subsp. *chroococcum* subsp. nov. *International Journal of Systematic and Evolutionary Microbiology I*70(3):2124-2131.

Jin, T., Cao, Y., Li, Y., Bai, F., Bai, B., Ren, B., Ren, J., Meng, J., Li, L., Wang, Y. (2023). Isolation, identification, and whole-genome sequence analysis of a plant growth-promoting bacterium LWK2 from *Cercidiphyllum japonicum* rhizosphere. *Microbiology China* 50(5):1917-1940.

Jini, D., Ganga, V.S., Greeshma, M.B., Sivashankar, R., Thirunavukkarasu, A. (2023). Sustainable agricultural practices using potassium-solubilizing microorganisms (KSMs) in coastal regions: a critical review on the challenges and opportunities. *Environment, Development and Sustainability* doi.org/10.1007/s10668-023-03199-9.

Joshi, S., Gangola, S., Jaggi, V., and Sahgal, M. (2023). Functional characterization and molecular fingerprinting of potential phosphate solubilizing bacterial candidates from Shisham rhizosphere. *Scientific Reports* 13(1):7003.

Kafle, A., Cope, K.R., Raths, R., Krishna Yakha, J., Subramanian, S., Bücking, H., Garcia, K. (2019). Harnessing soil microbes to improve plant phosphate efficiency in cropping systems. *Agronomy* 9(3):127.

Kaneko, T., Minamisawa, K., Isawa, T., Nakatsukasa, H., Mitsui, H., Kawaharada, Y. et al. (2010). Complete genomic structure of the cultivated rice endophyte *Azospirillum* sp. B510. *DNA Research* 17(1):37-50.

Katiyar, P., Dubey, R.C. Maheshwari, D.K. (2021). ACC deaminase-producing Ensifer adhaerens KS23 enhances proximate nutrient of *Pisum sativum* L. cultivated in high altitude. *Archives of Microbiology* 203(5):2689-2698.

Kaur, G., Patel, A., Dwibedi, V., Rath, S.K. (2023). Harnessing the action mechanisms of microbial endophytes for enhancing plant performance and stress tolerance: current understanding and future perspectives. *Archives of Microbiology* 205(9):303.

Kaur, J., Pandove, G. (2023). Understanding the beneficial interaction of plant growth promoting rhizobacteria and endophytic bacteria for sustainable agriculture: a bio-revolution approach. *Journal of Plant Nutrition* 46(14):3569-3597.

Kaur, M., Karnwal, A. (2023). Screening of endophytic bacteria from stress-tolerating plants for abiotic stress tolerance and plant growth-promoting properties: Identification of potential strains for bioremediation and crop enhancement. *Journal of Agriculture and Food Research* 14:100723.

Kaushal, M., Wani, S.P. (2016). Plant-growth-promoting rhizobacteria: drought stress alleviators to ameliorate crop production in drylands. *Annals of Microbiology* 66:35-42.

Kavino, M., Manoranjitham, S.K. (2018). *In vitro* bacterization of banana (*Musa* spp.) with native endophytic and rhizospheric bacterial isolates: novel ways to combat *Fusarium* wilt. *European Journal of Plant Pathology* 151:371-387.

Kebede, E. (2021). Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. *Frontiers in Sustainable Food Systems* 5:767998.

Khan, A., Singh, A.V. (2021). Multifarious effect of ACC deaminase and EPS producing *Pseudomonas* sp. and *Serratia marcescens* to augment drought stress tolerance and nutrient status of wheat. *World Journal of Microbiology and Biotechnology* 37:1-17.

Khan, N.A., Khan, M.I.R., Ferrante, A., Poor, P. (2017). Ethylene: a key regulatory molecule in plants. *Frontiers in Plant Science* 8:1782.

Khatoon, Z., Huang, S., Rafique, M., Fakhar, A., Kamran, M.A., Santoyo, G. (2020). Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. *Journal of Environmental Management* 273:111118.

Khoshru, B., Mitra, D., Mahakur, B., Sarikhani, M.R., Mondal, R., Verma, D., Pant, K. (2020). Role of soil rhizobacteria in utilization of an indispensable micronutrient zinc for plant growth promotion. *Journal of Critical Reviews* 21:4644-4654.

Khoshru, B., Mitra, D., Nosratabad, A.F., Reyhanitabar, A., Mandal, L., Farda, B., Mohapatra, P.K.D. (2023). Enhancing manganese availability for plants through microbial potential: a sustainable approach for improving soil health and food security. *Bacteria* 2(3):129-141.

Khoshru, B., Sarikhani, M.R., Reyhanitabar, A., Oustan, S., Malboobi, M.A. (2023). Evaluation of the potential of rhizobacteria in supplying nutrients of *Zea mays* L. plant with a focus on zinc. *Journal of Soil Science and Plant Nutrition* 23:1816–1829.

Köhl, J., Kolnaar, R., Ravensberg, W.J. (2019). Mode of action of microbial biological control agents against plant diseases: relevance beyond efficacy. *Frontiers in Plant Science* 10:doi.org/10.3389/fpls.2019.00845.

Kolytaitė, A., Vaitiekūnaitė, D., Antanynienė, R., Baniulis, D., Frercks, B. (2022). *Monilinia fructigena* suppressing and plant growth promoting endophytic *Pseudomonas* spp. bacteria isolated from plum. *Microorganisms* 10(12):2402.

Kour, D., Rana, K.L., Kaur, T., Yadav, N., Halder, S.K., Yadav, A.N. et al. (2020). Potassium solubilizing and mobilizing microbes: biodiversity, mechanisms of solubilization, and biotechnological implication for alleviations of abiotic stress. *In* “New and Future Developments in Microbial Biotechnology and Bioengineering” (A.A. Rastegari, A.N. Yadav, N. Yadav eds.). pp. 177-202. Elsevier.

Kumar, A., Chandra, R. (2020). Ligninolytic enzymes and its mechanisms for degradation of lignocellulosic waste in environment. *Heliyon* 6(2):e03170.

Kumar, A., Maleva, M., Bruno, L.B., Rajkumar, M. (2021). Synergistic effect of ACC deaminase producing *Pseudomonas* sp. TR15a and siderophore producing *Bacillus aerophilus* TR15c for enhanced growth and copper accumulation in *Helianthus annuus* L. *Chemosphere* 276:130038.

Kumar, C., Wagh, J., Archana, G., Naresh Kumar, G. (2016). Sucrose dependent mineral phosphate solubilization in *Enterobacter asburiae* PSI3 by heterologous overexpression of periplasmic invertases. *World Journal of Microbiology and Biotechnology* 32:194. https://doi.org/10.1007/s11274-016-2153-x.

Kumar, S., Sindhu, S.S., Kumar, R. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Current Research in Microbial Sciences* 3:100094.

Kumar, V., Sangwan, P., Verma, A.K., Agrawal, S. (2014). Molecular and biochemical characteristics of recombinant β-propeller phytase from *Bacillus licheniformis* strain PB-13 with potential application in aquafeed. *Applied Biochemistry and Biotechnology* 173:646-659.

Kumawat, K.C., Sharma, P., Sirari, A., Singh, I., Gill, B.S., Singh, U., Saharan, K. (2019). Synergism of *Pseudomonas aeruginosa* (LSE-2) nodule endophyte with *Bradyrhizobium* sp. (LSBR-3) for improving plant growth, nutrient acquisition and soil health in soybean. *World Journal of Microbiology and Biotechnology* 35(3):47. .

Kurepin, L.V., Zaman, M., Pharis, R.P. (2014). Phytohormonal basis for the plant growth promoting action of naturally occurring biostimulators. *Journal of the Science of Food and Agriculture* 94(9):1715-1722.

Kwak, M.J., Song, J.Y., Kim, S.Y., Jeong, H., Kang, S.G., Kim, B.K., Kwon, S.K., Lee, C.H., Yu, D.S., Park, S.H., Kim, J.F., 2012. Complete genome sequence of the endophytic bacterium *Burkholderia* sp. strain KJ006. *Journal of Bacteriology* 194:4432–4433.

Lahlali, R., Ezrari, S., Radouane, N., Kenfaoui, J., Esmaeel, Q., El Hamss, H., Barka, E.A. (2022). Biological control of plant pathogens: A global perspective. *Microorganisms*10(3):596.

Lall, S.P., Dumas, A. (2022). Nutritional requirements of cultured fish: Formulating nutritionally adequate feeds. *In* “Feed and Feeding Practices in Aquaculture”, (D.A. Davis, ed.). pp. 65-132. Woodhead Publishing.

Lee, S.K., Lur, H.S., Liu, C.T. (2021). From lab to farm: Elucidating the beneficial roles of photosynthetic bacteria in sustainable agriculture. *Microorganisms* 9:2453.

Lee, S.Y., Lee, Y.Y., Cho, K.S. (2023). Inoculation effect of heavy metal tolerant and plant growth promoting rhizobacteria for rhizoremediation. *International Journal of Environmental Science and Technology* doi.org/10.1007/s13762-023-05078-2

Lindström, K., Mousavi, S.A. (2020). Effectiveness of nitrogen fixation in rhizobia. *Microbial Biotechnology* 13(5):1314-1335.

Liu, X., Zhang, K., Liu, Y., Xie, Z., Zhang, C. (2019). Oxalic acid from *Sesbania* rostrata seed exudates mediates the chemotactic response of *Azorhizobium caulinodans* ORS571 using multiple strategies. *Frontiers in Microbiology* 10:2727.

Liu, T., Wu, X., Li, H., Alharbi, H., Wang, J., Dang, P., Yan, W. (2020). Soil organic matter, nitrogen and pH driven change in bacterial community following forest conversion. *Forest Ecology and Management* 477:118473.

Liu, W.Y., Chung, K.M., Wong, C.F., Jiang, J.W., Hui, R.K., Leung, F.C. (2012). Complete genome sequence of the endophytic *Enterobacter cloacae* subsp. *cloacae* strain ENHKU01. *Journal of Bacteriology* 194(21):5965. https://doi.org/10.1128/JB.01394-12

Liu, X., Kokare, C. (2023). Microbial enzymes of use in industry. In “Biotechnology of Microbial Enzymes*”*, (G. Brahmachari, ed.). pp. 267-298. Academic Press.

Ma, Y., Oliveira, R.S., Freitas, H., Zhang, C. (2016). Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. *Frontiers in Plant Science* 7:918.

Mahala, D.M., Maheshwari, H.S., Yadav, R.K., Prabina, B.J., Bharti, A., Reddy, K.K. et al. (2020). Microbial transformation of nutrients in soil: An overview. *In* “Rhizosphere Microbes: Microorganisms for Sustainability”, (S.K. Sharma, U.B. Singh, P.K. Sahu, H.V. Singh, P.K. Sharma, eds.). vol. 23: Springer, Singapore. https://doi.org/10.1007/978-981-15-9154-9_7 .

Maldani, M., Aliyat, F.Z., Morabito, M., Giarratana, F., Nassiri, L., Ibijbijen, J. (2023). The effects of herbicide application on two soil phosphate solubilizing bacteria: *Pantoea agglomerans* and *Serratia rubidaea*. *Ecotoxicology* 32:720–735.

Martínez-Viveros, O., Jorquera, M.A., Crowley, D.E., Gajardo, G.M.L.M., Mora, M.L. (2010). Mechanisms and practical considerations involved in plant growth promotion by rhizobacteria. *Journal of Soil Science and Plant Nutrition* 10(3):293-319.

Mazoyon, C., Catterou, M., Alahmad, A., Mongelard, G., Guénin, S., Sarazin, V., Duclercq, J. (2023). *Sphingomonas sediminicola* Dae20 Is a highly promising beneficial bacteria for crop biostimulation due to its positive effects on plant growth and development. *Microorganisms* 11(8):2061.

Meena, M., Swapnil, P., Divyanshu, K., Kumar, S., Harish, Tripathi, Y.N., Upadhyay, R.S. (2020). PGPR-mediated induction of systemic resistance and physiochemical alterations in plants against the pathogens: Current perspectives. *Journal of Basic Microbiology* 60(10):828-861.

Mehmood, N., Saeed, M., Zafarullah, S., Hyder, S., Rizvi, Z.F., Gondal, A.S., Kupe, M. (2023). Multifaceted impacts of plant-beneficial *Pseudomonas* spp. in managing various plant diseases and crop yield improvement. *ACS Omega* 8(25):22296-22315.

Mei, C., Chretien, R.L., Amaradasa, B.S., He, Y., Turner, A., Lowman, S. (2021). Characterization of phosphate solubilizing bacterial endophytes and plant growth promotion *in vitro* and in greenhouse. *Microorganisms* 9(9):1935.

Mekonnen, H., Kibret, M. (2021). The roles of plant growth promoting rhizobacteria in sustainable vegetable production in Ethiopia. *Chemical and Biological Technologies in Agriculture* 8(1):1-11.

Misra, S., Chauhan, P.S. (2020). ACC deaminase-producing rhizosphere competent *Bacillus* spp. mitigate salt stress and promote *Zea mays* growth by modulating ethylene metabolism. *3 Biotech* 10(3):119.

Mondal, S., Mukherjee, S.K., Hossain, S.T. (2023). Exploration of plant growth promoting rhizobacteria (PGPRs) for heavy metal bioremediation and environmental sustainability: Recent advances and future prospects. *In* “Modern Approaches in Waste Bioremediation: Environmental Microbiology”, (M.P. Shah, ed.). pp. 29-55. Springer, Cham. https://doi.org/10.1007/978-3-031-24086-7_3

Mulani, R., Mehta, K., Saraf, M., Goswami, D. (2021). Decoding the mojo of plant-growth-promoting microbiomes. *Physiological and Molecular Plant Pathology* 115*:*101687.

Müller, H., Westendorf, C., Leitner, E., Chernin, L., Riedel, K., Schmidt, S., Eberl, L., Berg, G., (2009). Quorum-sensing effects in the antagonistic rhizosphere bacterium *Serratia plymuthica* HRO-C48. *FEMS Microbiology and Ecology* 67:468–478.

Mus, F., Crook, M.B., Garcia, K., Garcia Costas, A., Geddes, B.A., Kouri, E.D., Peters, J.W. (2016). Symbiotic nitrogen fixation and the challenges to its extension to nonlegumes. *Applied and Environmental Microbiology* 82(13):3698-3710.

Naing, A.H., Maung, T.T., Kim, C.K. (2021). The ACC deaminase-producing plant growth-promoting bacteria: influences of bacterial strains and ACC deaminase activities in plant tolerance to abiotic stress. *Physiologia Plantarum* 173(4):1992-2012.

Nair, K.P. (2023). What are microbial fertilizers and what is their role in bio farming? *In* “Extractive Farming or Bio-Farming? Making a Better Choice for the 21st Century”, pp. 11-40. SpringerBriefs in Environmental Science. Springer, Cham. https://doi.org/10.1007/978-3-031-34695-8_2

Nascimento, F.X., Rossi, M.J., Soares, C.R., McConkey, B.J., Glick, B.R. (2014). New insights into 1-aminocyclopropane-1-carboxylate (ACC) deaminase phylogeny, evolution and ecological significance. *PLOS One* 9(6):e99168.

Naureen, A., Nasim, F.U.H., Choudhary, M.S., Ashraf, M., Grundler, F.M., Schleker, A.S.S. (2022). A new endophytic fungus CJAN1179 isolated from the Cholistan desert promotes lateral root growth in *Arabidopsis* and produces IAA through tryptophan-dependent pathway. *Archives of Microbiology* 204(3):181.

Nega, A. (2014). Review on concepts in biological control of plant pathogens. *Journal of Biology, Agriculture and Healthcare* 4(27):33-54.

Nohwar, N., Khandare, R.V., Desai, N.S. (2019). Isolation and characterization of salinity tolerant nitrogen fxing bacteria from *Sesbania sesban* L. root nodules. *Biocatalysis and Agricultural Biotechnology* 21:101325

Ojuederie, O.B., Babalola, O.O. (2023). Growth enhancement and extenuation of drought stress in maize inoculated with multifaceted ACC deaminase producing rhizobacteria. *Frontiers in Sustainable Food Systems* 6:1076844.

Olanrewaju, O.S., Glick, B.R., Babalola, O.O. (2017). Mechanisms of action of plant growth promoting bacteria. *World Journal of Microbiology and Biotechnology* 33:1-16.

Orozco-Mosqueda, M.D.C., Santoyo, G., Glick, B.R. (2023). Recent advances in the bacterial phytohormone modulation of plant growth. *Plants* 12(3):606.

Ortiz, M., Leung, P.M., Shelley, G., Jirapanjawat, T., Nauer, P.A., Van Goethem, M.W., Greening, C. (2021). Multiple energy sources and metabolic strategies sustain microbial diversity in Antarctic desert soils. *Proceedings of the National Academy of Sciences* 118(45):e2025322118.

Ortiz-García, P., González Ortega-Villaizán, A., Onejeme, F.C., Müller, M., Pollmann, S. (2023). Do opposites attract? Auxin-abscisic acid crosstalk: New perspectives. *International Journal of Molecular Sciences* 24(4):3090.

Otaiku, A.A., Soretire, A.A., Mmom, P.C. (2022). Biofertilizer impacts on soybean [*Glycine max* (L.) Merrill] cultivation, humid tropics: biological nitrogen fixation, yield, soil health and smart agriculture framework. *International Journal of Agricultural Extension and Rural Development Studies* 9(1):38-139.

Pankievicz, V., Irving, T.B., Maia, L.G., Ané, J.M. (2019). Are we there yet? The long walk towards the development of efficient symbiotic associations between nitrogen-fixing bacteria and non-leguminous crops. *BMC Biology* 17(1):1-17.

Paul, E.A. (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry* 98:109-126.

Peng, Y., Chen, Q., Guan, C.Y., Yang, X., Jiang, X., Wei, M., Li, X. (2023). Metal oxide modified biochars for fertile soil management: Effects on soil phosphorus transformation, enzyme activity, microbe community, and plant growth. *Environmental Research* 231(3):116258.

Pieterse, C.M., Zamioudis, C., Berendsen, R.L., Weller, D.M., Van Wees, S.C., Bakker, P.A. (2014). Induced systemic resistance by beneficial microbes. *Annual Review of Phytopathology* 52:347-375.

Potysz, A., Bartz, W. (2023). Dissolution of red sandstones exposed to siderophore-producing bacterium *Pseudomonas fluorescens*: Experimental bioweathering coupled to a geochemical model. *Construction and Building Materials* 369*:*130584.

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

Prasad, K. (2023). Symbiotic endophytes of glomalin AM fungi, *Rhizobium*, and PGPR potential bio-stimulants to intensive global food production for sustainable agriculture system. *Journal of Microbes and Research* 2(2):2836-2187.

Pronk, L.J., Bakker, P.A., Keel, C., Maurhofer, M., Flury, P. (2022). The secret life of plant-beneficial rhizosphere bacteria: insects as alternative hosts. *Environmental Microbiology* 24(8):3273-3289.

Qi, S., Wang, J., Zhang, Y., Naz, M., Afzal, M.R., Du, D., Dai, Z. (2023). Omics approaches in invasion biology: Understanding mechanisms and impacts on ecological health. *Plants* 12(9):1860.

Raaijmakers, J.M., Mazzola, M. (2012). Diversity and natural functions of antibiotics produced by beneficial and plant pathogenic bacteria. *Annual Review of Phytopathology* 50:403-424.

Rabani, M.S., Hameed, I., Gupta, M.K., Wani, B.A., Fayaz, M., Hussain, H. et al. (2023). Introduction of biofertilizers in agriculture with emphasis on nitrogen fixers and phosphate solubilizers. *In* "Microbiomes for the Management of Agricultural Sustainability" (G.H. Dar, R.A. Bhat, M.A. Mehmood, eds.). pp. 71-93. Springer, Cham.

Rabara, S., Vishwakarma, N.P., Patel, S. (2023). Isolation and biochemical identification of N_2 fixing bacteria (*Azospirillium* sp.) from Saurashtra Region. *Current Agriculture Research Journal* 11(1):277-286.

Rahi, D.K., Soni, S.K. (2007). Applications and commercial uses of microorganisms. *In* "Microbes: A Source of Energy for 21st Century", (S.K. Soni, ed.). pp. 71-126. New India Publishing.

Ramesh, R., Phadke, G.S., (2012). Rhizosphere and endophytic bacteria for the suppression of eggplant wilt caused by *Ralstonia solanacearum*. *Crop Protection* 37:35–41.

Ramirez-Gil, J.G., Lopera, A.A., Garcia, C. (2023). Calcium phosphate nanoparticles improve growth parameters and mitigate stress associated with climatic variability in avocado fruit. *Heliyon* 9(8):e18658.

Rana, K.L., Kour, D., Kaur, T., Negi, R., Devi, R., Yadav, N., Yadav, A.N. (2023). Endophytic nitrogen-fixing bacteria: Untapped treasurer for agricultural sustainability. *Journal of Applied Biology and Biotechnology* 11(2):75-93.

Rani, A.A., Basha, S.M., Darsha, K.D., Christy, C.A., Nagaiah, H.P., Kasthuri, T., Pandian, S.K. (2023). Plant growth promoting rhizobacteria and their biofilms in promoting sustainable agriculture and soil health. *In* "Understanding Microbial Biofilms", (S.D., Neelam, A. Kungwani, eds.). pp. 629-647. Academic Press.

Rao, D.L.N., Gill, H.S. (1993). Nitrogen fixation, biomass production, and nutrient uptake by annual *Sesbania* species in an alkaline soil. *Biology and Fertility of Soils* 15:73-78.

Ratnaningsih, H.R., Noviana, Z., Dewi, T.K., Loekito, S., Wiyono, S., Gafur, A., Antonius, S. (2023). IAA and ACC deaminase producing-bacteria isolated from the rhizosphere of pineapple plants grown under different abiotic and biotic stresses. *Heliyon* 9(6):e16306

Rauf, M., Awais, M., Ud-Din, A., Ali, K., Gul, H., Rahman, M.M., Arif, M. (2021). Molecular mechanisms of the 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase producing *Trichoderma asperellum* MAP1 in enhancing wheat tolerance to waterlogging stress. *Frontiers in Plant Science* 11:614971.

Ravshanov, B., Namozov, F., Kurbonov, A., Abdalova, G., Karimov, A., Khaitov, B., Park, K. W. (2023). Integrative effect of nitrogen fertilization and biotreatments on rice growth and yield potential under open-field agriculture. *Journal of Plant Nutrition* 46(8):1701-1711.

Rawat, P., Das, S., Shankhdhar, D., Shankhdhar, S.C. (2021). Phosphate-solubilizing microorganisms: mechanism and their role in phosphate solubilization and uptake. *Journal of Soil Science and Plant Nutrition* 21:49-68.

Raza, A., Zahra, N., Hafeez, M.B., Ahmad, M., Iqbal, S., Shaukat, K., Ahmad, G. (2020). Nitrogen fixation of legumes: Biology and physiology. *In* "The Plant Family Fabaceae" (M. Hasanuzzaman, S. Araújo, S. Gill, eds.). pp. 43-74. Springer, Singapore. doi.org/10.1007/978-981-15-4752-2_3

Roy Choudhury, A., Trivedi, P., Choi, J., Madhaiyan, M., Park, J.H., Choi, W., Sa, T. (2023a). Inoculation of ACC deaminase-producing endophytic bacteria down-regulates ethylene-induced pathogenesis-related signaling in red pepper (*Capsicum annuum* L.) under salt stress. *Physiologia Plantarum* 175(2):e13909.

Roy, B., Maitra, D., Biswas, A., Chowdhury, N., Ganguly, S., Bera, M., Mitra, A.K. (2023b). Efficacy of high-altitude biofilm-forming novel *Bacillus subtilis* species as plant growth-promoting rhizobacteria on *Zea mays* L. *Applied Biochemistry and Biotechnology* doi.org/10.1007/s12010-023-04563-1.

Saadani, O., Jebara, S.H., Fatnassi, I.C., Chiboub, M., Mannai, K., Zarrad, I., Jebara, M. (2019). Effect of *Vicia faba* L. var. Minor and *Sulla coronaria* (L.) Medik associated with plant growth-promoting bacteria on lettuce cropping system and heavy metal phytoremediation under field conditions. *Environmental Science and Pollution Research* 26:8125-8135.

Sabbahi, R., Hock, V., Azzaoui, K., Saoiabi, S., Hammouti, B. (2022). A global perspective of entomopathogens as microbial biocontrol agents of insect pests. *Journal of Agriculture and Food Research* 10:100376.

Saharan, B.S., Nehra, V. (2011). Plant growth promoting rhizobacteria: a critical review. *Life Science Medical Research* 21(1):30.

Saikia, J., Sarma, R.K., Dhandia, R., Yadav, A., Bharali, R., Gupta, V.K., Saikia, R. (2018). Alleviation of drought stress in pulse crops with ACC deaminase producing rhizobacteria isolated from acidic soil of Northeast India. *Scientific Reports* 8(1):3560.

Sarkar, D., Rakshit, A., Al-Turki, A.I., Sayyed, R.Z., Datta, R. (2021). Connecting bio-priming approach with integrated nutrient management for improved nutrient use efficiency in crop species. *Agriculture* 11(4):372.

Sedri, M.H., Niedbała, G., Roohi, E., Niazian, M., Szulc, P., Rahmani, H.A., Feiziasl, V. (2022). Comparative analysis of plant growth-promoting rhizobacteria (PGPR) and chemical fertilizers on quantitative and qualitative characteristics of rainfed wheat. *Agronomy* 12(7):1524.

Seenivasagan, R., Babalola, O.O. (2021). Utilization of microbial consortia as biofertilizers and biopesticides for the production of feasible agricultural product. *Biology* 10(11):1111.

Senthilkumar, M., Madhaiyan, M., Sundaram, S.P., Kannaiyan, S. (2009) Intercellular colonization and growth promoting effects of *Methylobacterium* sp. with plant-growth regulators on rice (*Oryza sativa* L. Cv. CO-43). *Microbiology Research* 164(1):92–104.

Setiawati, T.C., Erwin, D., Mandala, M., Hidayatulah, A. (2022). Use of *Bacillus* as a plant growth-promoting rhizobacteria to improve phosphate and potassium availability in acidic and saline soils. *In* "First Asian PGPR Indonesian Chapter International e-Conference 2021 KnE Life Sciences", pp. 541–558. DOI 10.18502/kls.v7i3.11160 P.

Shah, G., Fiaz, S., Attia, K.A., Khan, N., Jamil, M., Abbas, A., Jumin, T. (2022). Indole pyruvate decarboxylase gene regulates the auxin synthesis pathway in rice by interacting with the indole-3-acetic acid–amido synthetase gene, promoting root hair development under cadmium stress. *Frontiers in Plant Science* 13:1023723.

Shahid, M., Khan, M.S., Singh, U.B. (2023). Pesticide-tolerant microbial consortia: Potential candidates for remediation/clean-up of pesticide-contaminated agricultural soil. *Environmental Research* 236(Pt 1):116724. doi: 10.1016/j.envres.2023.116724.

Sharma, B., Tiwari, S., Kumawat, K.C., Cardinale, M. (2023). Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. *Science of The Total Environment* 860:160476.

Sheoran, S., Kumar, S., Kumar, P., Meena, R.S., Rakshit, S. (2021). Nitrogen fixation in maize: breeding opportunities. *Theoretical and Applied Genetics* 134:1263-1280.

Shinde, R., Shahi, D.K., Mahapatra, P., Naik, S.K., Thombare, N., Singh, A.K. (2022). Potential of lignocellulose degrading microorganisms for agricultural residue decomposition in soil: a review. *Journal of Environmental Management* 320:115843.

Silva, L.I.D., Pereira, M.C., Carvalho, A.M.X.D., Buttrós, V.H., Pasqual, M., Dória, J. (2023). Phosphorus-solubilizing microorganisms: A key to sustainable agriculture. *Agriculture* 13(2):462.

Sindhu, S.S., Sehrawat, A., Glick, B.R. (2022). The involvement of organic acids in soil fertility, plant health and environment sustainability. *Archives of Microbiology* 204(12):720.

Singh, D., Verma, A.K., Choudhary, M., Mahawar, H., Thapa, S., Mehriya, M.L. (2023). Micronutrient mobilizer microorganisms: Significance in crop sustainability. *In* "Bioinoculants: Biological Option for Mitigating Global Climate Change", (S. Singh, R., Prasanna, K., Pranaw, eds.). pp. 115-145. Springer Nature, Singapore.

Singh, K., Gera, R., Sharma, R., Maithani, D., Chandra, D., Bhat, M.A., Bhatt, P. (2021). Mechanism and application of *Sesbania* root-nodulating bacteria: an alternative for chemical fertilizers and sustainable development. *Archives of Microbiology* 203:1259-1270.

Singh, R.P., Ma, Y., Shadan, A. (2022). Perspective of ACC-deaminase producing bacteria in stress agriculture. *Journal of Biotechnology* 352:36-46.

Singh, R.P., Pandey, D.M., Jha, P.N., Ma, Y. (2022). ACC deaminase producing rhizobacterium *Enterobacter cloacae* ZNP-4 enhance abiotic stress tolerance in wheat plant. *PLOS One* 17(5):e0267127.

Slattery, J.F., Coventry, D.R., Slattery, W. J. (2001). Rhizobial ecology as affected by the soil environment. *Australian Journal of Experimental Agriculture* 41(3):289-298.

Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., Kouisni, L. (2020). Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. *Plants* 9(8):1011.

Souza, R.D., Ambrosini, A., Passaglia, L.M. (2015). Plant growth-promoting bacteria as inoculants in agricultural soils. *Genetics and Molecular Biology* 38:401-419.

Spadaro, D., Droby, S. (2016). Development of biocontrol products for postharvest diseases of fruit: The importance of elucidating the mechanisms of action of yeast antagonists. *Trends in Food Science and Technology* 47:39-49.

Sridevi, M., Mallaiah, K.V. (2007). Bioproduction of indole acetic acid by *Rhizobium* strains isolated from root nodules of green manure crop, *Sesbania sesban* (L.) Merr. *Iranian Journal of Biotechnology* 5(3):178–182.

Subedi, P., Gattoni, K., Liu, W., Lawrence, K.S., Park, S.W. (2020). Current utility of plant growth-promoting rhizobacteria as biological control agents towards plant-parasitic nematodes. *Plants* 9:1167.

Sun, L., Zhang, X., Ouyang, W., Yang, E., Cao, Y., Sun, R. (2022). Lowered Cd toxicity, uptake and expression of metal transporter genes in maize plant by ACC deaminase-producing bacteria *Achromobacter* sp. *Journal of Hazardous Materials* 423:12703.

Taghavi, S., Garafola, C., Monchy, S., Newman, L., Hoffman, A., Weyens, N., Barac, T., Vangronsveld, J., vander Lelie, D. (2009). Genome survey and characterization of endophytic bacteria exhibiting a beneficial effect on growth and development of poplar trees. *Applied Environmental Microbiology* 75:748–757.

Tang, J., Li, Y., Zhang, L., Mu, J., Jiang, Y., Fu, H., Ye, Z. (2023). Biosynthetic pathways and functions of indole-3-acetic acid in microorganisms. *Microorganisms* 11(8):2077.

Tapia-Vázquez, I., Montoya-Martínez, A.C., De los Santos-Villalobos, S., Ek-Ramos, M.J., Montesinos-Matías, R., Martínez-Anaya, C. (2022). Root-knot nematodes (*Meloidogyne* spp.) a threat to agriculture in Mexico: Biology, current control strategies, and perspectives. *World Journal of Microbiology and Biotechnology* 38(2):26.

Thomas, L., Singh, I. (2019). Microbial biofertilizers: types and applications. *In* "Biofertilizers for Sustainable Agriculture and Environment", (B. Giri, R. Prasad, Q.S. Wu, A. Varma, eds.). pp. 1-19. Woodhead Publishing.

Timofeeva, A., Galyamova, M., Sedykh, S. (2022). Prospects for using phosphate-solubilizing microorganisms as natural fertilizers in agriculture. *Plants* 11(16):2119.

Ting, A.S., Meon, S., Kadir, J., Radu, S., Singh, G. (2008). Endophytic microorganisms as potential growth promoters of banana. *BioControl* 53:541-553.

Tjamos, S.E., Flemetakis, E., Paplomatas, E.J., Katinakis, P. 2005. Induction of resistance to *Verticillium dahliae* in *Arabidopsis thaliana* by the biocontrol agent K-165 and athogenesis-related proteins gene expression. *Molecular Plant-Microbe Interaction* 18:555–561

Tokas, D., Singh, S., Yadav, R., Singh, A.N. (2023). Plant-microbe interactions: Role in sustainable agriculture and food security in a changing climate. *In* "Plant-Microbe Interaction-Recent Advances in Molecular and Biochemical Approaches", (P. Swapnil, M. Meena, Harish, A. Marwal et al. eds.). pp. 363-391. Academic Press.

Tyśkiewicz, R., Nowak, A., Ozimek, E. Jaroszuk-Ściseł, J. (2022). *Trichoderma*: The current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. *International Journal of Molecular Sciences* 23(4):2329.

Van Lenteren, J.C., Bolckmans, K., Köhl, J., Ravensberg, W.J., Urbaneja, A. (2018). Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl* 63:39-59.

Vanková, R., Burketová, L., Brzobohatý, B., Černý, M., Hafidh, S., Hejátko, J., Žárský, V. (2023). Responses to abiotic and biotic stresses-from the cellular level to fruit development-contributions of the Czech Centre for Experimental Plant Biology. *Biologia Plantarum* 67:166-174.

Vurukonda, S.S.K.P., Giovanardi, D., Stefani, E. (2018). Plant growth promoting and biocontrol activity of *Streptomyces* spp. as endophytes. *International Journal of Molecular Sciences* 19(4):952.

Walpola, B.C., Arunakumara, K.K.I.U., Yoon, M.H. (2022). Phosphate solubilization by phosphate solubilizing microorganisms: Insight into the mechanisms. *Springerplus* 2:587.

Wan, W., Xing, Y., Qin, X., Li, X., Liu, S., Luo, X. et al. (2020). A manganese-oxidizing bacterial consortium and its biogenic Mn oxides for dye decolorization and heavy metal adsorption. *Chemosphere* 253:126627.

Wang, J., Diao, R., Wu, Z., Wan, S., Yang, S., Li, X. (2023). Transcriptomic and metabolomic analyses reveal the roles of flavonoids and auxin on peanut nodulation. *International Journal of Molecular Sciences* 24(12):10152.

Wang, X., Liang, G. (2014). Control efficacy of an endophytic *Bacillus amyloliquefaciens* strain BZ6-1 against peanut bacterial wilt *Ralstonia solanacearum*. *Biomedical Research International* 2014:465435. doi: 10.1155/2014/465435.

War, A.F., Bashir, I., Reshi, Z.A., Rashid, I. (2023). Seed-endophytes empower *Anthemis cotula* to expand in invaded range. *Current Plant Biology* 34:100281.

Weilharter, A., Mitter, B., Shin, M.V., Chain, P.S., Nowak, J., Sessitsch, A. (2011). Complete genome sequence of the plant growth-promoting endophyte *Burkholderia phytofirmans* strain PsJN. *Journal of Bacteriology* 193:3383–3384.

Wisniewski-Dyé, F., Borziak, K., Khalsa-Moyers, G., Alexandre, G., Sukharnikov, L.O., Wuichet, K. et al. (2011). *Azospirillum* genomes reveal transition of bacteria from aquatic to terrestrial environments. *PLOS Genetics* 7(12):e1002430.

Xiao, S., Wang, Z., Wang, B., Hou, B., Cheng, J., Bai, T., Zhang, J. (2023). Expanding the application of tryptophan: Industrial biomanufacturing of tryptophan derivatives. *Frontiers in Microbiology* 14:1099098.

Yadav, S., Singh, K., Chandra, R. (2019). Plant growth–promoting rhizobacteria (PGPR) and bioremediation of industrial waste. *In "*Microbes for Sustainable Development and Bioremediation*",* (R. Chandra, R.C. Sobti, eds.). pp. 207-241. CRC Press.

Yan, J., Li, Y., Yan, H., Chen, W.F., Zhang, X., Wang, E.T., Xie, Z.H. (2017). *Agrobacterium salinitolerans* sp. Nov., a saline–alkaline-tolerant bacterium isolated from root nodule of *Sesbania cannabina*. *International Journal of Systematic and Evolutionary Microbiology* 67(6):1906–1911

Yan, Y., Yang, J., Dou, Y., Chen, M., Ping, S., Peng, J. et al. (2008). Nitrogen fixation island and rhizosphere competence traits in the genome of root-associated *Pseudomonas stutzeri* A1501. *Proceedings of the National Academy of Sciences* 105:7564–7569.

Yang, M., Li, J., Wang, S., Zhao, F., Zhang, C., Zhang, C., Han, S. (2023). Status and trends of enzyme cocktails for efficient and ecological production in the pulp and paper industry. *Journal of Cleaner Production* 418:138196.

Yavuz, D., Baştaş, K.K., Seymen, M., Yavuz, N., Kurtar, E.S., Süheri, S., Türkmen, Ö., Gür, A. Kıymacı, G. (2023). Role of ACC deaminase-producing rhizobacteria in alleviation of water stress in watermelon. *Scientia Horticulturae* 321:112288.

Zainab, N., Din, B.U., Javed, M.T., Afridi, M.S., Mukhtar, T., Kamran, M.A., Chaudhary, H.J. (2020). Deciphering metal toxicity responses of flax (*Linum usitatissimum* L.) with exopolysaccharide and ACC-deaminase producing bacteria in industrially contaminated soils. *Plant Physiology and Biochemistry* 152:90-99.

Zamanzadeh-Nasrabadi, S.M., Mohammadiapanah, F., Hosseini-Mazinani, M., Sarikhan, S. (2023). Salinity stress endurance of the plants with the aid of bacterial genes. *Frontiers in Genetics* 14:1049608.

Zhao, S., Li, K., Zhou, W., Qiu, S., Huang, S., He, P. (2016). Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in north-central China. *Agriculture, Ecosystems and Environment* 216:82-88.

Zhou, W., Zeng, S., Yu, J., Xiang, J., Zhang, F., Takriff, M.S., Zhou, X. (2023). Complete genome sequence of *Bacillus licheniformis* NWMCC0046, a candidate for the laundry industry. *Journal of Basic Microbiology* 63(2):223-234.