Alleviating Abiotic and abiotic stress, enhancing soil fertility, and growth of forest tree species PGPR: A review

ABSTRACT

The necessity for efficient mitigation techniques is highlighted by the worldwide loss in plant output caused by biotic and abiotic stressors. Promising bioinoculants known as Plant Growth-Promoting Rhizobacteria (PGPR) have been shown to provide improved nutritional availability, hormone regulation, and stress relief, among other advantages. Through several mechanisms such as phytohormone synthesis and ACC deaminase activity, they combat many environmental stressors such as pests, diseases, temperature variations, heavy metals, salt, and drought. Current research emphasizes the function of PGPR in a number of tree species, such as Quercus suber, Haloxylon ammodendron, and Acacia gerrardii. For example, inoculating Acacia gerrardii with Bacillus subtilis causes notable alterations in gene expression, indicating possible benefits in salinity and drought tolerance. Furthermore, in some nurseries, Quercus suber seedling quality is improved by a blend of bacterial inoculum and ECM fungus. Additionally, PGPR show effectiveness against heavy metal toxicity and heat stress. Sustainable plant growth depends on utilizing stress-resistant PGPR strains and maximizing microbial diversity. While breeding and genetic engineering provide long-term fixes, microbial inoculation offers a quick and affordable substitute. Moreover, PGPR promote environmental sustainability by improving soil fertility through processes including nitrogen fixation and phosphorus solubilization. In order to enhance plant development that is environmentally sustainable and optimize PGPR-mediated stress tolerance, it is essential to conduct multidisciplinary research and field investigations.

Keywords: Plant Growth-Promoting Rhizobacteria (PGPR), Abiotic stress, Heat stress, Sustainable plant growth, Microbial diversity, Environmental sustainability

INTRODUCTION

The fundamental reason for the worldwide decline in plant productivity is a variety of biotic and abiotic stresses in the environment [1, 2, 3, and 4]. Pests and phytopathogens, such as nematodes, viruses, fungi, and insects, can cause biological stresses. On the other hand, abiotic stressors are mostly brought on by abiotic variables, such as temperatures, flooding, increasing levels of heavy metals, varying salt levels in the field, and water scarcity [5, 6, and 7]. In addition to stressors, the availability of soil nutrients plays a role in tree growth and soil nutrient depletion as a result of excessive and frequent drainage as well as the widespread use of chemicals (pesticides, insecticides, and fertilizers). A damaging abiotic stressor, salinity affects approximately 6.73 million hectares in India [8]. According to recent projections, an increase in drainage regions and poor management of water resources might cause the amount of salt-affected soils to triple to 20 million hectares (m ha) by 2050 [9]. Soil salinity, caused by soluble salts, leads to nutrient deficiency in plants and affects soil properties [10, 11]. Plants can respond by modifying their signal transduction pathways when their metabolism is upset. Drought stress can reduce the biomass and turgor pressure of plants [12, 13, 14, and 15]. The plant has evolved a variety of coping mechanisms to withstand the pressures it has encountered. The creation of better plant varieties might help mitigate the major biotic and abiotic challenges to some degree. However, it is expensive and takes a long time to produce new genotypes that are resistant to abiotic stressors. Consequently, to counteract the impacts of biotic and abiotic pressures, other solutions must be used [14, 16]. Beneficial bacterial inoculation could be one of the most efficient biological management strategies for handling these abiotic stressors.

Plant growth-promoting rhizobacteria (PGPR) are a component of biofertilizers, which improve plant growth by increasing nutrient availability, producing phytohormones, and serving as biocontrol agents against insects and phytopathogens. [17, 18, 19]. Other similar processes are examples of direct mechanisms [20, 21]. An example of an indirect strategy is resistance to abiotic stress and control of plant pathogens [22]. Among the bacteria that comprise a dependable group of PGPR are the genera *Acinetobacter, Agrobacterium, Arthobacte, Azotobacter, Azospirillum, Burkholderia, Bradyrhizobium, Rhizobium, Frankia, Serratia, Thiobacillus, Pseudomonas,* and *Bacillus* [23]. Studies have shown that beneficial microbes alleviate abiotic stress through various strategies. Kushwaha et al. [24] reported that root-colonizing bacteria produce phytohormones that alleviated salinity-induced dormancy and elicited seedling growth. It has been discovered that N2 fixing bacteria isolated from *Pinus contorta* stems and needles improve inoculated seedlings' uptake of atmospheric N2 in comparison to control seedlings [121]. Moreover, Kumar et al [25] showed that *Pseudomonas* sp. strainTR15a and *Bacillus erophilus* strain TR15c promoted growth in stressed plants by producing indole acetic acid (IAA), siderophores, and solubilizing phosphates. Microorganisms carrying ACC-deaminase promote root development by blocking the synthesis of ethylene. [26, 27]. Reduced ethylene levels promoted root development and increased stressed plants' chances of surviving [28]. Microorganisms employ different strategies for stress tolerance [29]. Some secondary metabolites such as flavonoids, phytoalexins, phenylpropanoids, and carotenoids have been documented in stressed plants inoculated with microorganisms that helps the plants to tolerate the abiotic stress [31, 32, and 33]. Despite variations in plant colonization by microorganisms, positive effects are possible. It has been shown that when microbes are isolated from harsh environmental stress conditions, the alleviation of abiotic stress is possible [34]. Hence, this review article discusses the beneficial effects of microbes on abiotically stressed plants and highlights the microbial strains that are effective at alleviating abiotic stress effects to deploy them under extreme environmental conditions

ROLE OF PGPR IN PLANT GROWTH PROMOTION

PGPR protects plants from salt stress by improving antioxidant defenses, creating siderophores and exopolysaccharides (EPS), controlling phytohormones, promoting osmolyte production, increasing mineral uptake, and managing phytopathogens [35, 36] (Table 1). According to Araújo et al [37] in certain nurseries, *Quercus suber* L. seedling quality was enhanced up to twofold by utilizing a combination of ECM fungus and bacterial inoculum (*Suillus granulatus* (L.) Roussel + *Mesorhizobium* sp.). Several species of halotolerant soil bacteria such as *Arthrobacter*, *Azospirillum, Alcaligenes, Bacillus, Burkholderia, Enterobactor, Flavobacterium, Pseudomonas*, and *Rhizobium*, have been reported to ameliorate salt stress in plants [38, 39]. Their use as bio-inoculants is reported to increase soil organic matter and improve soil structure and water retention capacity. Apart from this, the use of PGPR in the form of bioinoculants is an eco-friendly and sustainable method [40].

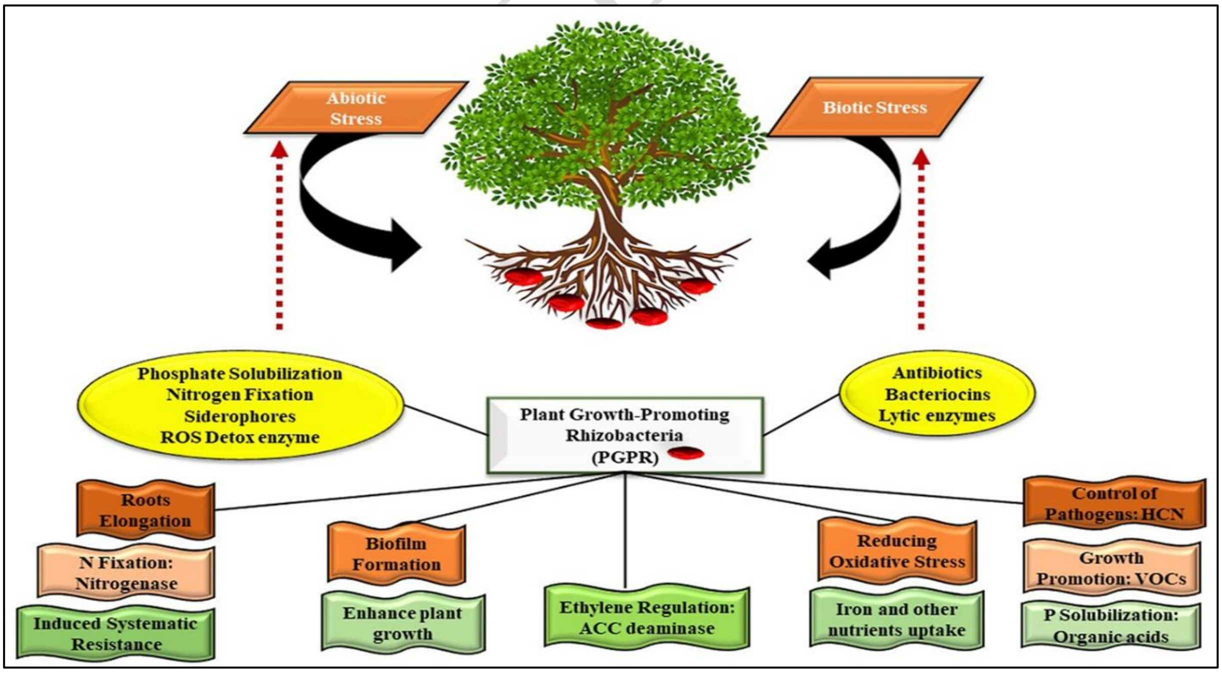

Fig. 1: Schematic diagram represents the effect of PGPR on various abiotic and biotic stress

METHODS FOR ALLEVIATING BIOTIC STRESSES USING PGPR AS A TOOL

Plant-beneficial microbe interactions can enhance plant growth, health, and capacity to absorb nutrients. They can also increase a plant's resistance to several disease-causing microorganisms [41, 42, and 43]. Direct interaction with the bioagents results in the manufacture of many plant growth hormones, such as kinetin, zeatin, 6-benzyl amino purine, diphenylurea, and thidi-azuron (TDZ)-type cytokinin, IAA- and IBA-type auxins, gibberellic acid, and enzyme ACC deaminase. Several researchers have found that the presence of ACC deaminase decreased the amount of ethylene in the roots of growing plants [44, 45, and 46]. Plants' tolerance to different stressors is aided by several other mechanisms, including symbiotic nitrogen fixation and the solubilization of minerals (phosphorus and potassium). Somal and Karnwal [42] conducted a comprehensive assessment of the literature regarding the beneficial effects of microorganisms in plant rhizospheres and their impact on plant growth through the optimization of stress resistance under unfavorable environmental circumstances.

Plant Hormone Biosynthesis

Hormone balance and host plant growth are significantly altered by PGPR colonization. Plants use phyto-hormones as messengers to manage different cellular processes and modulate cell functions [19]. These mechanisms involve the plant's reaction to pathogen interaction as well as abiotic and biotic stressors. Significant changes in plant development are brought about by PGPR colonization. Among these modifications included, but were not restricted to, promoting development, changing the form of the roots and shoots, and generating bioactive compounds [47, and 48]. Plant physiologic functions, such as growth, differentiation, development, and stomata movement, are also regulated by phytohormones. PGPR facilitates the formation of roots by producing indole-acetic acid (IAA). IAA can be produced by more than 80% of rhizosphere-associated bacteria including *Azosprillum* on rhizoplane*, Azotobacter, Enterobacter, Pseudomonas,* and *Staphylococcus* species [49]. In contrast, phytopathogenic bacteria mainly utilize the indole acetamide pathway to produce IAA, influencing the development of tumors in plants [50, 51]. In PGPR, the synthesis of IAA is one of the most crucial mechanisms for promoting plant development [52]. The biosynthesis of auxin is well conserved in plants and it is known that auxins also accelerate the production of xylem and roots [53]. Auxin promotes the creation of lateral roots by preventing root extension during development. After dividing into root primordia, which eventually develop into new lateral roots, activated endoderm pericycle cells [54, 55, 56]. Auxin biosynthesis, transport, and signaling control all of these lateral root development activities, including their initiation, growth, emergence, and elongation [57].

Biogenesis of ACC Deaminase Enzyme

The hydrolase enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase requires pyridoxal 5′ phosphate or PLP. ACC deaminase catalyzes the conversion of ACC, an ethylene precursor, into ammonia and alpha-ketobutyrate, hence decreasing the amount of ethylene produced in plant cells [58, 59, and 60]. A plant's synthesis of ethylene can be increased by a variety of environmental stresses, including metal toxicity, salt, drought, salinity, high-temperature, UV radiation, and damage from nematodes and fungal pathogens [61, 62]. Stress causes the generation of two peaks, the second of which is noticeably higher than the first. Stressors induce plants' ethylene concentration to rise, which in turn causes early aging, leaf abscission, lower production, and eventually the death of plants [63].

PGPR that can synthesize ACC deaminase and Indole-3-Acetic Acid (IAA) are important. These advantageous bacteria can either live inside plant tissues as endophytes or colonize plant roots [64]. Plant root exudates, which are especially high in sugars, organic acids, amino acids, and tryptophan, provide them with food. Bacteria create IAA when tryptophan is present, and this enhances the amount of IAA produced by the host plant [65, 66, and 67]. This process encourages cell growth and the formation of roots and shoots. Furthermore, IAA initiates the synthesis of ACC synthase, which is in charge of producing ACC. The plant ethylene precursor ACC is then partially broken down by bacterial ACC deaminase into ammonia and α-ketobutyrate, which significantly reduces ethylene levels and helps to prevent growth restriction, early senescence, and plant damage. ACC deaminase activity precedes ACC oxidase activation, which converts ACC to ethylene, thus regulating ethylene levels in plants [68].

Biogenesis of IAA

A plant growth regulator called indole acetic acid (IAA) is secreted by bacteria that live in the plant rhizosphere specially PGPR species, which are the principal producers [69]. It has been noted that the growth of bacteria that produce IAA is especially advantageous in salt- affected soils. Approximately 75% of the identified bacterial isolates are highly efficient in producing IAA [112]. There have been reports of IAA synthesizing efficiency and features in numerous rhizobacteria, pathogenic, symbiotic, and free-living bacterial species. [70]. Tryptophan and tryptophan-independent metabolic pathways are among the many metabolic pathways that the rhizobacterial species can use to create IAA. However, the primary mechanism by which phytopathogenic bacteria create IAA is the indole acetamide pathway, which influences the development of plant tumors [1, 2, 3, and 4].

IAA is produced by *Azotobacter* species at concentrations ranging from 2.09 to 33.28 mg/mL, according to the literature [70, 71, and 72]. Nevertheless, this value varies greatly depending on the species, the type of soil, and the nutrients available in the particular habitat. *Azospirillum* is one of the most efficient PGPRs in generating IAA although other bacteria from the genera *Aeromonas, Burkholderia, Azotobacter, Enterobacter, Pseudomonas, Bacillus,* and *Rhizobium* have also been shown to exhibit comparable activity ranging from 1.47 to 32.80 mg/ml in *Azotobacter* and 5.34 to 53.2 mg/ml in *Pseudomonas* [73, 74]. These species include the most common IAA-releasing strains, known to impact the strength of the plants, as PGPR strains. Increased root and shoot lengths are two benefits of IAA for plants; they allow the plant to absorb more micronutrients from the surrounding soil. IAA is essential for plant development because it encourages tissue growth, cell division, and morphological specialization in response to shifting environmental factors [73].

PGPR Application to Combat Insect Pest

To control pest infestations, a variety of chemical pesticides are used, but their effects on the environment and human health are worrisome. In addition to increasing plant productivity, certain bacteria protect against insect pests by producing virulence factors, metabolites, and pesticidal compounds through pathogenesis [75, 76, and 77]. It has been shown that certain strains of *Bacillus subtilis* have bioinsecticidal action and release bioactive compounds into the rhizosphere [78]. One important strategy used by many PGPR is the production of volatile chemicals. As the first PGPR with insecticidal action, *B. thuringiensis* has been used against lepidopteran larvae as well as other insects. Pesticide alternatives have been investigated, including environmentally benign biological pest management techniques [79]. According to studies, *Brevibacillus laterosporus* generates bioactive substances that are useful against a variety of insect species, such as enzymes and antibiotics [112]. In addition, studies have looked into the possibility of using rhizobacteria like *B. sphaericus* and *Bacillus pumilus* to control white grubs [80, 81, 82, and 83,].

METHODS FOR ALLEVIATING ABIOTIC STRESSES USING PGPR AS A TOOL

According to recent research, plants that are subjected to stressful conditions benefit from the presence of PGPRs as they synthesize proline. When *Arthrobacter, Burkholderia*, and *Bacillus* are inoculated under abiotic stress circumstances, researchers have shown that proline levels are raised [14, 15]. Furthermore, research conducted by [83, 84, 47] indicate that plant hormones produced by microbes associated with roots have the potential for use in metabolic engineering to improve host resistance to abiotic stressors.

Alleviating Heavy Metal Stress and Reduced Availability of Inorganic Nutrients

Important nutrients for plant growth, such as potassium, copper, iron, zinc, and phosphorus, tend to stay largely stationary in soil. The conversion of insoluble phosphorus into soluble form is mostly dependent on plant exudates; bacteria involved in this process use the carbohydrates in the exudate of the roots as a source of carbon. [42, 85]. Studies indicate that IAA treatment promotes the release of carbohydrates, which helps the soil mobilize phosphorus indirectly [86]. Inoculating maize with particular bacterial strains improves the plant's ability to absorb nutrients, especially potassium, phosphate, and nitrogen [87]. Apart from that, siderophores secreted by root-colonizing bacteria can help absorb different metals like copper, iron, and zinc [81]. Because heavy metal is non-biodegradable and disrupts natural processes and food chains, it poses a serious environmental risk on a worldwide scale. Through processes like organic acid release, pH adjustment, and chelating agent generation, bioremediation microorganisms especially rhizospheric bacteria—play a critical role in reducing heavy metal toxicity [88, 89]. Reports highlight the bio-reduction of highly toxic Cr (VI) as a promising remediation strategy. Various bacterial species isolated from metal-contaminated sites demonstrate potential for colonizing and adapting to metal-polluted environments, offering promising detoxification processes like bioaccumulation, biosorption, and oxidation-reduction [90, 91, 92, and 93,].

Abiotic stresses	PGPRs	PGPR- mediated mechanisms
Drought as stress	*B. aquimaris*	Indole acetic acid, Exopolysaccharides, ACC deaminase
	Bacillus sp.,Enterobacter sp., Pseudomons fluorescens,	Indole acetic acid, Salicylic acid
	A. chroococcum	N_2 fixation, phosphorus solubilization, Antimicrobial compounds
	B. megaterium	Polyamine secretion
	V. paradoxus	ACC deaminase
	E. cloacae	ACC deaminase
	B. licheniformis,	Abscisic acid
	P. fluorescens, A. brasilense *A. piechaudii*	ACC deaminase
Salinity as stress	*A. aneurinilyticus,*	ACC deaminase,
	Paenibacillus sp.	ACC deaminase, Salicylic acid
	B. amyloliquefaciens	ACC deaminase
	Glutamicibacter sp. YD01	ACC deaminase, osmoregulators, ROS, acquisition of Na:K
	Bacillus sp., Azospirillum, A. brasilense, P. stutzeri	Phytohormones, osmoregulators, ROS
	S. maltophilia	Indole acetic acid, ACC deaminase
	A. vinelandii, A. lipoferum, B. circulans P. fluorescens, , B. megaterium and B. subtilis	Auxin, gibberellins, kinetin, N2 fixation
	P. oryzihabitans	Indole acetic acid, ACC deaminase
	Burkholderia	Indole acetic acid, ACC deaminase, Salicylic acid
	Bacillus safensis	Indole acetic acid, ACC deaminase
Water as stress	*P. putida and P.fluorescens*	Indole acetic acid, ACC deaminase
	P. putida	ACC deaminase
	Gluconacetobacter diazotrophicus	Abscisic acid, Phytohormones
	Azospirillum spp. (Az19)	Proline production
Temperature as stress	*Bacillus spp.*	Abscisic acid
	Azotoformans sp. and Pseudomonas sp.	Phosphate availability, N2 fixation
	P. fragi, P. proteolytica, P. chloropaphis	Lowering chill injury, lipid peroxidation and ice-nucleating activity
	B. tequilensis	Apoplastic antioxidant enzyme activities
Heavy Metal as stress	*S. acidiscabies*	Siderophores

Table 1: PGPR showing their activities in various abiotic stresses

Alleviation of Drought Stress

PGPR increases plant resilience to abiotic stressors like drought by secreting osmolytes when there is a drought [94]. Osmolytes raise cellular osmotic potential and are produced by drought-tolerant plants in response to water shortage [95]. By modifying pathways linked to antioxidant defense, root shape, phytohormone activity, and osmolyte accumulation, these rhizobacteria—which are found in root exudates—help plants cope with environmental stressors. However, the length, intensity, stage of development, and kind of plant affected by the drought may have a substantial impact on the bacterial response. The increased production of biomass from roots and shoots in response to drought stress is likely mostly due to the synthesis of IAA by PGPR. In plant rhizospheres, ACC deaminase-producing bacteria modify ethylene signaling to prevent root dryness. Achromobacter piechaudii's ACC deaminase activity increases the biomass of the plant and is resistant to conditions when there is a shortage of water. [96]. Similar to *Achromobacter piechaudii* and *Azospirillum brasilense*, PGPR improves membrane stability and water consumption efficiency by reducing root dryness and increasing plant biomass [88, 97]. Additionally, under drought stress, these bacteria raise the proline level in plant tissues, which is essential for preserving cell hydration status [98]. Additionally, PGPR generates phenolic compounds and salicylic acid, which function as signaling molecules to activate genes and secondary metabolites responsive to stress [99]. *Pseudomonas putida* GAP-P45 and other PGPR strains increase proline buildup through inoculation, which is essential for plant drought resistance [100]. Furthermore, in water-stressed maize, *Bacillus thuringiensis* increases the concentration of shoot proline [42]. All things considered, PGPR is essential for shielding plants from dry stress and encouraging growth and development.

Alleviation of Salinity Stress

More than 5% of the Earth's surface is impacted by salinity, a crucial abiotic component, as a result of natural processes. When salts come into direct contact with roots, they have adverse effects on plants that greatly hinder development and metabolism, including cellular toxicity and soil desiccation. Plant Growth-Promoting Rhizobacteria (PGPR) might lessen the severity of the negative effects of salinity on plant output by influencing the size of panicles, tillers, spikelets, and grains [101, 102]. Plant physiology and biochemical features are positively impacted by the phytohormones produced by PGPR, such as gibberellic acid, IAA, IBA, ABA, and cytokinins. This leads to an enhanced capacity of plants to absorb nutrients, even in situations with elevated salinities. To mitigate the negative effects of salinity, PGPR invades plant roots and uses strategies such as chemotaxis, EPS, IAA, and ACC deaminase synthesis [101, 102]. Gibberellic acid and cytokinins, two phytohormones generated by PGPR, improve plant physiology and nutrient absorption even in salinized settings. While *Bacillus, Pseudomonas spp.* and *Streptomyces* strains promote plant development and reduce salt stress, studies show that specific species like *P. putida, P.aurantiaca,* and *P. chlororaphis* produce IAA under sodium chloride stress [103, 104]. Agrobacterium, *Bacillus, Klebsiella, Pseudomonas,* and *Ochrobactrum sp.* are among the rhizosphere's salt-tolerant bacteria that have been identified as showing potential in salt tolerance up to 10% NaCl levels [105, 106]. To properly manage salt stress, it is imperative to investigate microbial diversity.

Alleviation of Thermal Stress

Excessive temperatures have an impact on various aspects of plant life cycles, including growth, fertilization, production, and germination. However, the degree and vulnerability of these effects depend on factors such as ambient circumstances, plant ancestry, duration, and intensity. Sun damage, discoloration, leaf defoliation, root and shoot development, and seed output are all lowered by heat stress. Heat-tolerant bacteria, or HTB, appear to play a crucial part in how plants react to high temperatures, according to previous findings. A plant species' ability to reproduce and survive depends on the process of seed germination. Elevated temperatures during the imbibition of seeds may cause germination to be delayed or prevented, resulting in damaged or subpar seedlings as well as reduced growth and development of plants. HTB can counteract the adverse effects of elevated temperatures on seed germination. Some bacteria, like *Ochrobactrum pseudogrignonense* RJ12, Pseudomonas sp. RJ15, and Bacillus subtilis RJ46, can produce ACC deaminase, siderophores, IAA, phosphorous solubilization, and nitrogen fixation, which can increase the dry mass of treated plants, shoot and root development, and seed germination under osmotic stress conditions [107].

PGPR AND TREE DEVELOPMENT

PGPR may impact the plant in two ways: first, by generating phytohormones, and second, by activating the host plant's signaling pathways. A direct role has been described for the production of phytohormones such as gibberellins, auxins, cytokinin, abscisic acid, nitogen fixation, and P liquification [108, 109, and 110]. One example of an indirect mechanism in plants is the creation of HCN. Other examples include siderophores, volatile primary and secondary metabolites, antagonistic action, and induced systemic resistance to pathogens. Indirect mechanisms also include nutrient competition. A bacteria could influence a plant's growth and development through any one of these strategies. Over the past few decades, attempts have been made in many different parts of the world to decrease the use of chemical pesticides and fertilizers by increasing the percentage of land under sustainable agriculture that uses PGPR [101, 42, and 98]. In another study, Binucleate Rhizoctonia (BnR) inoculation significantly improved early growth of Scots pine seedlings in nitrogen-limited nursery soil after 86 days post-inoculation. The treated seedlings exhibited increased root length and reduced root width compared to non-inoculated seedlings [122]. The C4 perennial succulent xerohalophyte Haloxylon ammodendron is recognized for its remarkable resistance to salt and drought. He et al [123] discovered a novel strain of salt-tolerant bacteria in the rhizosphere of this plant, called Pseudomonas sp. M30-35. Abiotic stress tolerance and plant growth promotion (PGP) features are linked to 34 genes that Pseudomonas sp. M30-35 were found to possess. PGPR bacterian strain of Bacillus subtilis inoculation induced significant changes in gene expression in Acacia gerrardii, including activation of transcription factors regulating stress-related genes, suggesting its potential in alleviating salinity and drought effects [124].

PGPR AND SOIL AMELIORATION

PGPR, have been the subject of growing interest for several decades because of their potential to improve plant development and act as effective agents for managing plant stress. Microorganisms that are good for plants naturally live in. They take part in several soil activities that impact productivity, crop yields, and general plant health [113](Santoyo et al., 2017). Many attempts have been undertaken to investigate the diversity, distribution, and behavior of indigenous soil microorganisms in soil habitats to understand how microbial inoculants function and how they affect soil health [114] (Chenniappan et al., 2019). Growth-stimulating bacteria, like PGPR, can improve soil health through a variety of mechanisms, including the mineralization of soil organic matter, the breakdown of crop residues, the suppression of phytopathogens, nitrogen fixation, phosphate solubilization, heavy metal sequestering, and the production of phytohormones (i.e., indole acetic acid, gibberellins, or cytokinins) that allow plants to grow even in nutrient-deficient soils [115] Shameer and Prasad, 2018).

Eight bacterial taxa, including Acinetobacter, Pseudomonas, Massilia, Bacillus, Arthrobacter, Stenotrophomonas, Ochrobactrum, and Cupriavidus, were tested for their ability to solubilize phosphorus by Wan et al. [116]. Acinetobacter was found to have a remarkable capacity to solubilize phosphorus, which makes it a viable option for improving the fertility and quality of soil [117]. Small molecule organic acids secreted by phosphorus-solubilizing bacteria can dissolve inorganic phosphorus, as demonstrated by Liu et al. [118]. This process can modify soil characteristics and have an indirect effect on the rhizosphere's microbial community. Plant-unavailable P can be dissolved in either inorganic (calcium phosphate) or organic (phytin) forms by bacteria such as *Enterobacter cloacae, Pseudomonas pseudoalcaligenes*, and *Bacillus thuringiensis*, according to research by Pantigoso et al. [119]. Kour et al. [120] assessed how well soil samples taken from the Lesser Himalayan ecosystem could solubilize a sizable amount of phosphorus. The bacteria included in the evaluation were Bacillus, Enterobacter, Pseudomonas, Staphylococcus, Acinetobacter, Klebsiella, and Proteus. Based on the results, it was possible that these bacteria could improve soil fertility and plant growth because of their exceptional ability to solubilize phosphorus.

FUTURE PROSPECTUS

Bacterial isolates from stress-prone habitats are more effective than those from stress-free environments in developing plant tolerance to abiotic stresses such as drought, salt, and heavy metals. This is particularly relevant in the context of sustainable environmental practices. It is necessary for researchers to carefully evaluate the stress-adaptive characteristics of Plant Growth-Promoting Rhizobacteria (PGPR) before utilizing them in fields subjected to biotic or abiotic challenges. The kind of soil and the particular strains employed affect how effective PGPR-mediated stress tolerance is. To expand our knowledge in this sector, more investigation is required, especially fieldwork involving specialized biofertilizer organisms under stress. Although there are ways to improve stress tolerance through genetic engineering and plant breeding, these methods are very time- and money-consuming. Plant stress mitigation using microbial inoculation appears to be a viable, economical, and eco-friendly solution that takes little time to achieve. Stress-resistant naturally occurring PGPR strains are very helpful for nearby farmers, and using single or mixed effective PGPRs can help improve environmental sustainability.

CONCLUSION

In conclusion, the global decline in plant productivity due to biotic and abiotic stresses, exacerbated by factors like pests, diseases, temperature fluctuations, heavy metal accumulation, salt, and drought, underscores the urgent need for effective mitigation strategies. Plant Growth-Promoting Rhizobacteria (PGPR) emerge as promising bioinoculants, offering multiple benefits such as enhanced nutrient availability, hormone modulation, and stress alleviation. Through diverse mechanisms including phytohormone production, ACC deaminase activity, and osmolyte synthesis, PGPR mitigate abiotic stressors and counteract phytopathogens. Moreover, PGPR demonstrate potential in addressing thermal stress and heavy metal toxicity. Harnessing microbial diversity and leveraging stress-resistant PGPR strains are essential for sustainable plant growth. While genetic engineering and plant breeding offer long-term solutions, microbial inoculation presents a cost-effective and rapid alternative. Furthermore, PGPR play a crucial role in soil fertility enhancement through activities like phosphorus solubilization and nitrogen fixation, emphasizing their significance in promoting environmental sustainability. Moving forward, multidisciplinary research initiatives and field investigations using specialized biofertilizer organisms are imperative to maximize PGPR-mediated stress tolerance and advance environmental sustainability in plant growth.

REFERENCES

1. Ding LN, Liu R, Li T, Li M, Liu XY, Wang WJ, Yu YK, Cao J, Tan XL. Physiological and comparative transcriptome analyses reveal the mechanisms underlying waterlogging tolerance in a rapeseed anthocyanin-more mutant. Biotechnology for Biofuels and Bioproducts. 2022 May 20;15(1):55.
2. Singh RP, Jha PN. The PGPR *Stenotrophomonas maltophilia* SBP-9 augments resistance against biotic and abiotic stress in wheat plants. Frontiers in microbiology. 2017 Oct 9;8:275381.
3. Wang R, Wang M, Chen K, Wang S, Mur LA, Guo S. Exploring the roles of aquaporins in plant-microbe interactions. Cells. 2018 Dec 11;7(12):267.
4. Zubair M, Hanif A, Farzand A, Sheikh TM, Khan AR, Suleman M, Ayaz M, Gao X. Genetic screening and expression analysis of psychrophilic *Bacillus spp*. reveal their potential to alleviate cold stress and modulate phytohormones in wheat. Microorganisms. 2019 Sep 10;7(9):337.
5. Kapadia C, Patel N, Rana A, Vaidya H, Alfarraj S, Ansari MJ, Gafur A, Poczai P, Sayyed RZ. Evaluation of plant growth-promoting and salinity ameliorating potential of halophilic bacteria isolated from saline soil. Frontiers in plant science. 2022 Jul 15;13:946217.
6. Zhao B, Liu Q, Wang B, Yuan F. Roles of phytohormones and their signaling pathways in leaf development and stress responses. Journal of Agricultural and Food Chemistry. 2021 Mar 19;69(12):3566-84.
7. Zhao M, Haxim Y, Liang Y, Qiao S, Gao B, Zhang D, Li X. Genome-wide investigation of AP2/ERF gene family in the desert legume Eremosparton songoricum: Identification, classification, evolution, and expression profiling under drought stress. Frontiers in Plant Science. 2022 Aug 12;13:885694.
8. Mandal, A. K., GP Obi Reddy, and T. Ravisankar. "Digital database of salt affected soils in India using Geographic Information System." (2011).
9. Sharma PC, Singh A. ICAR-Central Soil Salinity Research Institute Annual Report 2016-17.
10. Gupta, A., Mishra, R., Rai, S., Bano, A., Pathak, N.*et al*. Mechanistic insights of plant growth promoting bacteria mediated drought and salt stress tolerance in plants for sustainable agriculture. *International Journal of Molecular Sciences* (2022) ;23(7), 3741.
11. Kumawat, K.C., Nagpal, S. and Sharma, P. Potential of plant growth-promoting rhizobacteria-plant interactions in mitigating salt stress for sustainable agriculture: A review.*Pedosphere* (2022) ;32(2), 223–245
12. Lalay G, Ullah S, Ahmed I. Physiological and biochemical responses of Brassica napus L. to drought-induced stress by the application of biochar and Plant Growth Promoting Rhizobacteria. Microscopy research and technique. 2022 Apr;85(4):1267-81.
13. Muthusamy M, Kim JY, Yoon EK, Kim JA, Lee SI. BrEXLB1, a *Brassica rapa* expansin-like B1 gene is associated with root development, drought stress response, and seed germination. Genes. 2020 Apr 8;11(4):404.
14. Rodriguez MV, Tano J, Ansaldi N, Carrau A, Srebot MS, Ferreira V, Martínez ML, Cortadi AA, Siri MI, Orellano EG. Anatomical and biochemical changes induced by *Gluconacetobacter diazotrophicus* stand up for *Arabidopsis thaliana* seedlings from *Ralstonia solanacearum* infection. Frontiers in plant science. 2019 Dec 23;10:484836.

15. Yin X, Gao Y, Song S, Hassani D, Lu J. Identification, characterization and functional analysis of grape (Vitis vinifera L.) mitochondrial transcription termination factor (mTERF) genes in responding to biotic stress and exogenous phytohormone. BMC genomics. 2021 Dec;22:1-6.
16. Wang X, Liu H, Zhang D, Zou D, Wang J, Zheng H, Jia Y, Qu Z, Sun B, Zhao H. Photosynthetic carbon fixation and sucrose metabolism supplemented by weighted gene co-expression network analysis in response to water stress in rice with overlapping growth stages. Frontiers in Plant Science. 2022 Apr 21;13:864605.
17. Khumairah FH, Setiawati MR, Fitriatin BN, Simarmata T, Alfaraj S, Ansari *et.al* .Halotolerant plant growth-promoting rhizo-bacteria isolated from saline soil improve nitrogen fixation and alleviate salt stress in rice plants (2022).
18. Manjunatha N, Manjunatha N, Li H, Sivasithamparam K, Jones MG, Edwards I, Wylie SJ, Agarrwal R. Fungal endophytes from salt-adapted plants confer salt tolerance and promote growth in wheat (Triticum aestivum L.) at early seedling stage. Microbiology. 2022 Sep 22;168(8):001225.

19. Zhang M, Liu L, Chen C, Zhao Y, Pang C, Chen M. Heterologous expression of a *Fraxinus velutina* SnRK2 gene in *Arabidopsis* increases salt tolerance by modifying root development and ion homeostasis. Plant Cell Reports. 2022 Sep;41(9):1895-906.
20. Kour D, Kaur T, Devi R, Chaubey KK, Yadav AN. Co-inoculation of nitrogen fixing and potassium solubilizing Acinetobacter sp. for growth promotion of onion (*Allium cepa*. Biologia. 2023 Sep;78(9):2635-41.

21. Upadhyay SK, Rajput VD, Kumari A, Espinosa-Saiz D, Menendez E, Minkina T, Dwivedi P, Mandzhieva S. Plant growth-promoting rhizobacteria: a potential bio-asset for restoration of degraded soil and crop productivity with sustainable emerging techniques. Environmental Geochemistry and Health. 2023 Dec;45(12):9321-44.

22. Gupta S, Pandey S. Plant growth promoting rhizobacteria to mitigate biotic and abiotic stress in plants. Sustainable Agriculture Reviews 60: Microbial Processes in Agriculture. 2023 Feb 22:47-68.

23. Khoso MA, Wagan S, Alam I, Hussain A, Ali Q, Saha S, Poudel TR, Manghwar H, Liu F. Impact of plant growth-promoting rhizobacteria (PGPR) on plant nutrition and root characteristics: Current perspective. Plant Stress. 2023 Dec 28:100341.

24. Kushwaha P, Kashyap PL, Bhardwaj AK, Kuppusamy P, Srivastava AK, Tiwari RK. Bacterial endophyte mediated plant tolerance to salinity: growth responses and mechanisms of action. World Journal of Microbiology and Biotechnology. 2020 Feb;36(2):26.

25. Kumar A, Maleva M, Bruno LB, Rajkumar M. 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. 2021 Aug 1;276:130038.

26. Ali S, Khan N. Delineation of mechanistic approaches employed by plant growth promoting microorganisms for improving drought stress tolerance in plants. Microbiological Research. 2021 Aug 1;249:126771.

27. Vaishnav A, Shukla AK, Sharma A, Kumar R, Choudhary DK. Endophytic bacteria in plant salt stress tolerance: current and future prospects. Journal of Plant Growth Regulation. 2019 Jun 15;38:650-68.

28. del Carmen Orozco-Mosqueda M, Glick BR, Santoyo G. ACC deaminase in plant growth-promoting bacteria (PGPB): An efficient mechanism to counter salt stress in crops. Microbiological Research. 2020 May 1;235:126439.

29. Trivedi P, Leach JE, Tringe SG, Sa T, Singh BK. Plant–microbiome interactions: from community assembly to plant health. Nature reviews microbiology. 2020 Nov;18(11):607-21.

30. Kaur S, Suseela V. Unraveling arbuscular mycorrhiza-induced changes in plant primary and secondary metabolome. Metabolites. 2020 Aug 18;10(8):335.

31. Mohammadi MA, Cheng Y, Aslam M, Jakada BH, Wai MH, Ye K, He X, Luo T, Ye L, Dong C, Hu B. ROS and oxidative response systems in plants under biotic and abiotic stresses: revisiting the crucial role of phosphite triggered plants defense response. Frontiers in Microbiology. 2021 Jul 1;12:631318.

32. Babalola, O. O. *Food Security and Safety*.Springer International Publishing. 2021

33. Chukwuneme, C. F., Ayangbenro, A. S., &Babalola, O.O. Impacts of land-use and management histories of maize fields on the structure, composition, and metabolic potentials of microbial communities.*Current Plant Biology*, 2021;*28*, 100228.
34. Morcillo, R. J., &Manzanera, M. The effects of plant-associated bacterial exopolysaccharides on plant abiotic stress tolerance. *Metabolites*, 2021;*11*(6), 337.

35. Shahzad, R., Khan, A. L., Bilal, S., Waqas, M., Kang, S. M., & Lee, I. J. Inoculation of abscisic acid-producing endophytic bacteria enhances salinity stress tolerance in *Oryza sativa*. *Environmental and Experimental Botany*, 2017;*136*, 68-77.

36. El-Esawi MA, Alaraidh IA, Alsahli AA, Alzahrani SM, Ali HM, Alayafi AA, Ahmad M. *Serratia liquefaciens* KM4 improves salt stress tolerance in maize by regulating redox potential, ion homeostasis, leaf gas exchange and stress-related gene expression. International journal of molecular sciences. 2018 Oct 24;19(11):3310.

37. Araújo GC, Sousa NR, Ramos MA, Vega AL, Castro PM. Performance of *Quercus suber* L. at nursery stage—application of two bio-inoculants under two distinct environments. Annals of forest science. 2018 Mar;75:1-2.

38. Egamberdiyeva, D. Plant-growth-promoting rhizobacteria isolated from a Calcisol in a semi-arid region of Uzbekistan: biochemical characterization and effectiveness. *Journal of Plant Nutrition and Soil Science*, 2005;*168*(1), 94-99.

39. Saghafi D, Ghorbanpour M, Shirafkan Ajirloo H, Asgari Lajayer B. Enhancement of growth and salt tolerance in Brassica napus L. seedlings by halotolerant Rhizobium strains containing ACC-deaminase activity. Plant Physiology Reports. 2019 Jun 1;24:225-35.

40. Arora NK, Fatima T, Mishra J, Mishra I, Verma S, Verma R, Verma M, Bhattacharya A, Verma P, Mishra P, Bharti C. Halo-tolerant plant growth promoting rhizobacteria for improving productivity and remediation of saline soils. Journal of Advanced Research. 2020 Nov 1;26:69-82.
41. Karnwal A, Dohroo A. Effect of maize root exudates on indole-3-acetic acid production by rice endophytic bacteria under influence of L-tryptophan. F1000Research. 2018;7.
42. Ashraf A, Bano A, Ali SA. Characterisation of plant growth-promoting rhizobacteria from rhizosphere soil of heat-stressed and unstressed wheat and their use as bio-inoculant. Plant Biology. 2019 Jul;21(4):762-9.
43. Zehra A, Raytekar NA, Meena M, Swapnil P. Efficiency of microbial bio-agents as elicitors in plant defense mechanism under biotic stress: A review. Current Research in Microbial Sciences. 2021 Dec 1;2:100054.
44. Xia Y, Farooq MA, Javed MT, Kamran MA, Mukhtar T, Ali J, Tabassum T, ur Rehman S, Munis MF, Sultan T, Chaudhary HJ. Multi-stress tolerant PGPR *Bacillus xiamenensis* PM14 activating sugarcane (*Saccharum officinarum L.*) red rot disease resistance. Plant physiology and biochemistry. 2020 Jun 1;151:640-9.
45. Jasrotia S, Salgotra RK, Sharma M. Efficacy of bioinoculants to control of bacterial and fungal diseases of rice (Oryza sativa L.) in northwestern Himalaya. Brazilian Journal of Microbiology. 2021 Jun;52:687-704.
46. Sharma R, Gal L, Garmyn D, Bru D, Sharma S, Piveteau P. Plant growth promoting bacterial consortium induces shifts in indigenous soil bacterial communities and controls Listeria monocytogenes in rhizospheres of *Cajanus cajan* and *Festuca arundinacea*. Microbial ecology. 2022 Jul 1:1-6.

47. Khan A, Singh AV. 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. 2021 Dec;37(12):198.
48. Ali B, Wang X, Saleem MH, Sumaira, Hafeez A, Afridi MS, Khan S, Ullah I, Amaral Júnior AT, Alatawi A, Ali S. PGPR-mediated salt tolerance in maize by modulating plant physiology, antioxidant defense, compatible solutes accumulation and bio-surfactant producing genes. Plants. 2022 Jan 27;11(3):345.
49. Bag S, Mondal A, Banik A. Exploring tea (Camellia sinensis) microbiome: Insights into the functional characteristics and their impact on tea growth promotion. Microbiological Research. 2022 Jan 1;254:126890
50. Ding LN, Liu R, Li T, Li M, Liu XY, Wang WJ, Yu YK, Cao J, Tan XL. Physiological and comparative transcriptome analyses reveal the mechanisms underlying waterlogging tolerance in a rapeseed anthocyanin-more mutant. Biotechnology for Biofuels and Bioproducts. 2022 May 20;15(1):55.
51. Zubair M, Hanif A, Farzand A, Sheikh TM, Khan AR, Suleman M, Ayaz M, Gao X. Genetic screening and expression analysis of psychrophilic *Bacillus spp.* reveal their potential to alleviate cold stress and modulate phytohormones in wheat. Microorganisms. 2019 Sep 10;7(9):337.

52. Park S, Kim AL, Hong YK, Shin JH, Joo SH. A highly efficient auxin-producing bacterial strain and its effect on plant growth. Journal of Genetic Engineering and Biotechnology. 2021 Dec;19:1-9.
53. Pasternak T, Palme K, Pérez-Pérez JM. Role of reactive oxygen species in the modulation of auxin flux and root development in *Arabidopsis thaliana*. The Plant Journal. 2023 Apr;114(1):83-95.

54. Garg T, Singh Z, Chennakesavulu K, Mushahary KK, Dwivedi AK, Varapparambathu V, Singh H, Singh RS, Sircar D, Chandran D, Prasad K. Species-specific function of conserved regulators in orchestrating rice root architecture. Development. 2022 May 1;149(9):dev200381.

55. Hassan SS, Kodakandla V, Redwan EM, Lundstrom K, Choudhury PP, Abd El-Aziz TM, Takayama K, Kandimalla R, Lal A, Serrano-Aroca Á, Azad GK. An issue of concern: unique truncated ORF8 protein variants of SARS-CoV-2. PeerJ. 2022 Mar 21;10:e13136.

56. Singh H, Singh Z, Kashyap R, Yadav SR. Lateral root branching: evolutionary innovations and mechanistic divergence in land plants. New Phytologist. 2023 May;238(4):1379-85.

57. Zhang, C., Yu, Z., Zhang, M., Li, X., Wang, M., Li, L., ... & Tian, H. Serratia marcescens PLR enhances lateral root formation through supplying PLR-derived auxin and enhancing auxin biosynthesis in *Arabidopsis*. *Journal of Experimental Botany*, 2022; *73*(11), 3711-3725.
58. Bziuk N, Maccario L, Straube B, Wehner G, Sørensen SJ, Schikora A, Smalla K. The treasure inside barley seeds: microbial diversity and plant beneficial bacteria. Environmental Microbiome. 2021 Oct 28;16(1):20.
59. El-Shamy MA, Alshaal T, Mohamed HH, Rady AM, Hafez EM, Alsohim AS, Abd El-Moneim D. Quinoa response to application of phosphogypsum and plant growth-promoting rhizobacteria under water stress associated with salt-affected soil. Plants. 2022 Mar 24;11(7):872.
60. Saeed Q, Xiukang W, Haider FU, Kučerik J, Mumtaz MZ, Holatko J, Naseem M, Kintl A, Ejaz M, Naveed M, Brtnicky M. Rhizosphere bacteria in plant growth promotion, biocontrol, and bioremediation of contaminated sites: a comprehensive review of effects and mechanisms. International Journal of Molecular Sciences. 2021 Sep 29;22(19):10529.
61. Kamran MA, Eqani SA, Bibi S, Xu RK, Monis MF, Katsoyiannis A, Bokhari H, Chaudhary HJ. Bioaccumulation of nickel by E. sativa and role of plant growth promoting rhizobacteria (PGPRs) under nickel stress. Ecotoxicology and environmental safety. 2016 Apr 1;126:256-63.
62. Niu X, Song L, Xiao Y, Ge W. Drought-tolerant plant growth-promoting rhizobacteria associated with foxtail millet in a semi-arid agroecosystem and their potential in alleviating drought stress. Frontiers in microbiology. 2018 Jan 11;8:2580.
63. Mariotti L, Scartazza A, Curadi M, Picciarelli P, Toffanin A. *Azospirillum baldaniorum* Sp245 induces physiological responses to alleviate the adverse effects of drought stress in purple basil. Plants. 2021 Jun 3;10(6):1141.

64. Sziderics AH, Rasche F, Trognitz F, Sessitsch A, Wilhelm E. Bacterial endophytes contribute to abiotic stress adaptation in pepper plants (*Capsicum annuum L*.). Canadian journal of microbiology. 2007 Nov;53(11):1195-202.
65. Gupta A, Bano A, Rai S, Kumar M, Ali J, Sharma S, Pathak N. ACC deaminase producing plant growth promoting rhizobacteria enhance salinity stress tolerance in *Pisum sativum*. 3 Biotech. 2021 Dec;11(12):514.
66. Gupta S, Kaushal R, Sood G, Bhardwaj S, Chauhan A. Indigenous plant growth promoting rhizobacteria and chemical fertilizers: impact on soil health and productivity of Capsicum (*Capsicum annuum L*.) in North Western Himalayan region. Communications in Soil Science and Plant Analysis. 2021 May 15;52(9):948-63.
67. Renoud S, Abrouk D, Prigent-Combaret C, Wisniewski-Dyé F, Legendre L, Moënne-Loccoz Y, Muller D. Effect of inoculation level on the impact of the PGPR *Azospirillum lipoferum* CRT1 on selected microbial functional groups in the rhizosphere of field maize. Microorganisms. 2022 Jan 31;10(2):325.
68. Glick BR. Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiological research. 2014 Jan 20;169(1):30-9.
69. Barazani OZ, Friedman J. Is IAA the major root growth factor secreted from plant-growth-mediating bacteria?. Journal of Chemical Ecology. 1999 Oct;25:2397-406.
70. Spaepen S, Bossuyt S, Engelen K, Marchal K, Vanderleyden J. Phenotypical and molecular responses of A *rabidopsis thaliana* roots as a result of inoculation with the auxin-producing bacterium *Azospirillum brasilense*. New Phytologist. 2014 Feb;201(3):850-61.
71. Chennappa G, Adkar-Purushothama CR, Naik MK, Suraj U, Sreenivasa MY. Impact of pesticides on PGPR activity of *Azotobacter sp*. isolated from pesticide-flooded paddy soils. Greener J Agric Sci. 2014;4(4):117-29.
72. Sumbul A, Ansari RA, Rizvi R, Mahmood I. *Azotobacter*: A potential bio-fertilizer for soil and plant health management. Saudi journal of biological sciences. 2020 Dec 1;27(12):3634-40.
73. Ahmad F, Ahmad I, KHAN MS. Indole acetic acid production by the indigenous isolates of *Azotobacte*r and fluorescent *Pseudomonas* in the presence and absence of tryptophan. Turkish Journal of Biology. 2005;29(1):29-34.
74. Ghosh PG, Sawant NA, Patil SN, Aglave BA. Microbial biodegradation of organophosphate pesticides. International Journal of Biotechnology & Biochemistry. 2010 Dec 1;6(6):871-7.
75. Zebelo S, Song Y, Kloepper JW, Fadamiro H. Rhizobacteria activates (+)-δ-cadinene synthase genes and induces systemic resistance in cotton against beet armyworm (*Spodoptera exigua*). Plant, Cell & Environment. 2016 Apr;39(4):935-43.
76. Zhang LN, Wang DC, Hu Q, Dai XQ, Xie YS, Li Q, Liu HM, Guo JH. Consortium of plant growth-promoting rhizobacteria strains suppresses sweet pepper disease by altering the rhizosphere microbiota. Frontiers in Microbiology. 2019 Jul 23;10:1668.
77. Zytynska SE, Eicher M, Rothballer M, Weisser WW. Microbial-mediated plant growth promotion and pest suppression varies under climate change. Frontiers in plant science. 2020 Sep 10;11:573578.
78. Siddiqui ZA, Futai K. Biocontrol of Meloidogyne incognita on tomato using antagonistic fungi, plant-growth-promoting rhizobacteria and cattle manure. Pest Management Science: formerly Pesticide Science. 2009 Sep;65(9):943-8.
79. Naeem K, Filippi R, Periche-Tomas E, Papageorgiou A, Bright P. The importance of socioeconomic status as a modulator of the bilingual advantage in cognitive ability. Frontiers in psychology. 2018 Sep 26;9:409975.
80. Agake SI, do Amaral FP, Yamada T, Sekimoto H, Stacey G, Yokoyama T, Ohkama-Ohtsu N. Plant growth-promoting effects of viable and dead spores of *Bacillus pumilus* TUAT1 on Setaria viridis. Microbes and environments. 2022;37(1):ME21060.
81. Li W, Lee SY, Cho YJ, Ghim SY, Jung HY. Mediation of induced systemic resistance by the plant growth-promoting rhizobacteria *Bacillus pumilus* S2-3-2. Molecular Biology Reports. 2020 Nov;47(11):8429-38.
82. Li Z, Song C, Yi Y, Kuipers OP. Characterization of plant growth-promoting rhizobacteria from perennial ryegrass and genome mining of novel antimicrobial gene clusters. BMC genomics. 2020 Dec;21:1-1.
83. Najafi Zilaie M, Mosleh Arani A, Etesami H, Dinarvand M. Improved salinity and dust stress tolerance in the desert halophyte Haloxylon aphyllum by halotolerant plant growth-promoting rhizobacteria. Frontiers in plant science. 2022 Aug 3;13:948260

84. Mahmood S, Daur I, Yasir M, Waqas M, Hirt H. Synergistic practicing of rhizobacteria and silicon improve salt tolerance: implications from boosted oxidative metabolism, nutrient uptake, growth and grain yield in mung bean. Plants. 2022 Jul 29;11(15):1980.
85. Somal MK, Karnwal A. Effect of stress tolerance endophytic bacteria on the growth of Rheum emodi under abiotic stress. Plant Biology (Stuttgart, Germany). 2022 Aug 24.
86. Shahid M, Shah AA, Basit F, Noman M, Zubair M, Ahmed T, Naqqash T, Manzoor I, Maqsood *A. Achromobacter sp.* FB-14 harboring ACC deaminase activity augmented rice growth by upregulating the expression of stress-responsive CIPK genes under salinity stress. Brazilian Journal of Microbiology. 2020 Jun;51:719-28.
87. Khalifa T, Elbagory M, Omara AE. Salt stress amelioration in maize plants through phosphogypsum application and bacterial inoculation. Plants. 2021 Sep 27;10(10):2024.
88. Curá JA, Franz DR, Filosofía JE, Balestrasse KB, Burgueño LE. Inoculation with *Azospirillum sp. and Herbaspirillum sp.* bacteria increases the tolerance of maize to drought stress. Microorganisms. 2017 Jul 26;5(3):41.
89. El-Esawi MA, Alaraidh IA, Alsahli AA, Alzahrani SM, Ali HM, Alayafi AA, Ahmad M. *Serratia liquefaciens* KM4 improves salt stress tolerance in maize by regulating redox potential, ion homeostasis, leaf gas exchange and stress-related gene expression. International journal of molecular sciences. 2018 Oct 24;19(11):3310.
90. Li X, Li D, Yan Z, Ao Y. Biosorption and bioaccumulation characteristics of cadmium by plant growth-promoting rhizobacteria. RSC advances. 2018;8(54):30902-11.
91. Anarakdim K, Gutiérrez G, Cambiella Á, Senhadji-Kebiche O, Matos M. The effect of emulsifiers on the emulsion stability and extraction efficiency of Cr (VI) using emulsion liquid membranes (ELMs) formulated with a green solvent. Membranes. 2020 Apr 21;10(4):76.
92. Cheng X, Yang B, Zheng J, Wei H, Feng X, Yin Y. Cadmium stress triggers significant metabolic reprogramming in *Enterococcus faecium* CX 2–6. Computational and Structural Biotechnology Journal. 2021 Jan 1;19:5678-87.
93. Zhou Z, Zhu L, Dong Y, You L, Zheng S, Wang G, Xia X. Identification of a novel chromate and selenite reductase FesR in *Alishewanella sp.* WH16-1. Frontiers in Microbiology. 2022 Mar 8;13:834293.
94. Rashid U, Yasmin H, Hassan MN, Naz R, Nosheen A, Sajjad M, Ilyas N, Keyani R, Jabeen Z, Mumtaz S, Alyemeni MN. Drought-tolerant *Bacillus megaterium* isolated from semi-arid conditions induces systemic tolerance of wheat under drought conditions. Plant Cell Reports. 2022 Mar 1:1-21.
95. Saradadevi GP, Das D, Mangrauthia SK, Mohapatra S, Chikkaputtaiah C, Roorkiwal M, Solanki M, Sundaram RM, Chirravuri NN, Sakhare AS, Kota S. Genetic, epigenetic, genomic and microbial approaches to enhance salt tolerance of plants: A comprehensive review. Biology. 2021 Dec 1;10(12):1255.
96. Saravanakumar D, Samiyappan R. ACC deaminase from Pseudomonas fluorescens mediated saline resistance in groundnut (*Arachis hypogea*) plants. Journal of applied microbiology. 2007 May 1;102(5):1283-92.
97. Lade SB, Román C, Cueto-Ginzo AI, Serrano L, Sin E, Achón MA, Medina V. Host-specific proteomic and growth analysis of maize and tomato seedlings inoculated with *Azospirillum brasilense* Sp7. Plant physiology and biochemistry. 2018 Aug 1;129:381-93.
98. Singh RP, Pandey DM, Jha PN, Ma Y. ACC deaminase producing rhizobacterium Enterobacter cloacae ZNP-4 enhance abiotic stress tolerance in wheat plant. PloS one. 2022 May 6;17(5):e0267127.
99. Jangra M, Devi S, Satpal, Kumar N, Goyal V, Mehrotra S. Amelioration effect of salicylic acid under salt stress in Sorghum bicolor L. Applied biochemistry and biotechnology. 2022 Oct;194(10):4400-23.
100. Ghosh D, Gupta A, Mohapatra S. Dynamics of endogenous hormone regulation in plants by phytohormone secreting rhizobacteria under water-stress. Symbiosis. 2019 Mar 15;77:265-78.
101. Khan A, Singh AV. 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. 2021 Dec;37(12):198.
102. Ali B, Wang X, Saleem MH, Sumaira, Hafeez A, Afridi MS, Khan S, Ullah I, Amaral Júnior AT, Alatawi A, Ali S. PGPR-mediated salt tolerance in maize by modulating plant physiology, antioxidant defense, compatible solutes accumulation and bio-surfactant producing genes. Plants. 2022 Jan 27;11(3):345.

103. Abbaszadeh-Dahaji P, Atajan FA, Omidvari M, Tahan V, Kariman K. Mitigation of copper stress in maize (*Zea mays*) and sunflower (*Helianthus annuus*) plants by copper-resistant *Pseudomonas* strains. Current microbiology. 2021 Apr;78:1335-43.
104. Abdelkrim S, Jebara SH, Saadani O, Abid G, Taamalli W, Zemni H, Mannai K, Louati F, Jebara M. In situ effects of Lathyrus sativus-PGPR to remediate and restore quality and fertility of Pb and Cd polluted soils. Ecotoxicology and environmental safety. 2020 Apr 1;192:110260.
105. Albdaiwi RN, Khyami-Horani H, Ayad JY, Alananbeh KM, Al-Sayaydeh R. Isolation and characterization of halotolerant plant growth promoting rhizobacteria from durum wheat (*Triticum turgidum subsp. durum*) cultivated in saline areas of the dead sea region. Frontiers in Microbiology. 2019 Jul 23;10:421038.
106. Alexander A, Singh VK, Mishra A. Halotolerant PGPR *Stenotrophomonas maltophilia* BJ01 induces salt tolerance by modulating physiology and biochemical activities of Arachis hypogaea. Frontiers in Microbiology. 2020 Oct 14;11:568289.
107. Abulfaraj AA, Jalal RS. Use of plant growth-promoting bacteria to enhance salinity stress in soybean (Glycine max L.) plants. Saudi Journal of Biological Sciences. 2021 Jul 1;28(7):3823-34.
108. Checcucci A, Azzarello E, Bazzicalupo M, De Carlo A, Emiliani G, Mancuso S, Spini G, Viti C, Mengoni A. Role and regulation of ACC deaminase gene in *Sinorhizobium meliloti*: is it a symbiotic, rhizospheric or endophytic gene?. Frontiers in genetics. 2017 Jan 30;8:6.
109. Checcucci A, Bazzicalupo M, Mengoni A. Exploiting nitrogen-fixing rhizobial symbionts genetic resources for improving phytoremediation of contaminated soils. Enhancing Cleanup of Environmental Pollutants: Volume 1: Biological Approaches. 2017:275-88.
110. Liu J, Kharat M, Tan Y, Zhou H, Mundo JL, McClements DJ. Impact of fat crystallization on the resistance of W/O/W emulsions to osmotic stress: Potential for temperature-triggered release. Food research international. 2020 Aug 1;134:109273.
111. Karnwal A, Shrivastava S, Al-Tawaha AR, Kumar G, Kumar A, Kumar A. PGPR-mediated breakthroughs in plant stress tolerance for sustainable farming. Journal of Plant Growth Regulation. 2023 May 1:1-7.

112. Li Z, de Vries RH, Chakraborty P, Song C, Zhao X, Scheffers DJ, Roelfes G, Kuipers OP. Novel modifications of nonribosomal peptides from *Brevibacillus laterosporus* MG64 and investigation of their mode of action. Applied and environmental microbiology. 2020 Nov 24;86(24):e01981-20.
113. Santoyo G, Pacheco CH, Salmerón JH, León RH. The role of abiotic factors modulating the plant-microbe-soil interactions: toward sustainable agriculture. A review. Spanish journal of agricultural research. 2017;15(1):13.

114. Chenniappan C, Narayanasamy M, Daniel GM, Ramaraj GB, Ponnusamy P, Sekar J, Ramalingam PV. Biocontrol efficiency of native plant growth promoting rhizobacteria against rhizome rot disease of turmeric. Biological control. 2019 Feb 1;129:55-64.

115. Shameer S, Prasad TN. Plant growth promoting rhizobacteria for sustainable agricultural practices with special reference to biotic and abiotic stresses. Plant Growth Regulation. 2018 Apr;84:603-15.

116. Wang L, Lin H, Dong Y, Li B, He Y. Effects of endophytes inoculation on rhizosphere and endosphere microecology of Indian mustard (Brassica juncea) grown in vanadium-contaminated soil and its enhancement on phytoremediation. Chemosphere. 2020 Feb 1;240:124891.

117. Wan W, Qin Y, Wu H, Zuo W, He H, Tan J, Wang Y, He D. Isolation and characterization of phosphorus solubilizing bacteria with multiple phosphorus sources utilizing capability and their potential for lead immobilization in soil. Frontiers in microbiology. 2020 Apr 23;11:752.

118. Liu J, Qi W, Li Q, Wang SG, Song C, Yuan XZ. Exogenous phosphorus-solubilizing bacteria changed the rhizosphere microbial community indirectly. 3 Biotech. 2020 Apr;10:1-1.

119. Pantigoso HA, Manter DK, Fonte SJ, Vivanco JM. Root exudate-derived compounds stimulate the phosphorus solubilizing ability of bacteria. Scientific Reports. 2023 Mar 10;13(1):4050.

120. Kour D, Rana KL, Yadav N, Yadav AN. Bioprospecting of phosphorus solubilizing bacteria from Renuka Lake ecosystems, lesser Himalayas. Journal of Applied Biology and Biotechnology. 2019 Sep 10;7(5):1-6.
121. Anand R, Chanway C. N 2-fixation and growth promotion in cedar colonized by an endophytic strain of Paenibacillus polymyxa. Biology and Fertility of Soils. 2013 Feb;49:235-9.
122. Gronberg H, Kaparakis G, Sen R. Binucleate Rhizoctonia (Ceratorhiza spp.) as non-mycorrhizal endophytes alter Pinus sylvestris L. seedling root architecture and affect growth of rooted cuttings. Scandinavian journal of forest research. 2006 Dec 1;21(6):450-7.
123. He AL, Niu SQ, Zhao Q, Li YS, Gou JY, Gao HJ, Suo SZ, Zhang JL. Induced salt tolerance of perennial ryegrass by a novel bacterium strain from the rhizosphere of a desert shrub Haloxylon ammodendron. International Journal of Molecular Sciences. 2018 Feb 5;19(2):469.
124. Lara-Chavez A, Lowman S, Kim S, Tang Y, Zhang J, Udvardi M, Nowak J, Flinn B, Mei C. Global gene expression profiling of two switchgrass cultivars following inoculation with Burkholderia phytofirmans strain PsJN. Journal of experimental botany. 2015 Jul 1;66(14):4337-50.
125. Kishore SM, Priyadharshini TB, & Sowmya , K. (2024). Soil Arthropods: An Unsung Heroes of Soil Fertility. *Journal of Advances in Biology & Biotechnology*, *27*(6), 118–126. https://doi.org/10.9734/jabb/2024/v27i6872
126. Bathrobas , D. J. (2023). Soil Fertility Reclamation of Abandoned Mining Sites through Organic Intervention. *Asian Journal of Soil Science and Plant Nutrition*, *9*(3), 33–47. https://doi.org/10.9734/ajsspn/2023/v9i3184
127. Zhen L, Zoebisch MA, Chen G, Feng Z. Sustainability of farmers' soil fertility management practices: A case study in the North China Plain. Journal of environmental Management. 2006 Jun 1;79(4):409-19.
128.
129.