



# Alleviating Abiotic and Abiotic Stress, Enhancing Soil Fertility, and Growth of Forest Tree Species PGPR: A Review

Parul Bhatt Kotiyal <sup>a++\*</sup> and Shivam Kumar Sharma <sup>a</sup>

<sup>a</sup> Forest Ecology and Climate Change, Forest Research Institute, Dehradun, 248006, India.

## Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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## 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-

<sup>++</sup>Scientist- E;

\*Corresponding author: E-mail: [parulbhatt29@gmail.com](mailto:parulbhatt29@gmail.com);

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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.*

## 1. INTRODUCTION

The fundamental reason for the worldwide decline in plant productivity is a variety of biotic and abiotic stresses in the environment [1,2,3,4]. 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 [5,6,7]. 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 [12,13,14,15]. 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 N<sub>2</sub> fixing bacteria isolated from *Pinus contorta* stems and needles improve inoculated seedlings' uptake of atmospheric N<sub>2</sub> in comparison to control seedlings [121]. Moreover, Kumar et al [25] showed that *Pseudomonas* sp. strain TR15a 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 [29,30]. 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 [31,32,33]. 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.

## 2. 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*, *Enterobacter*, *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].

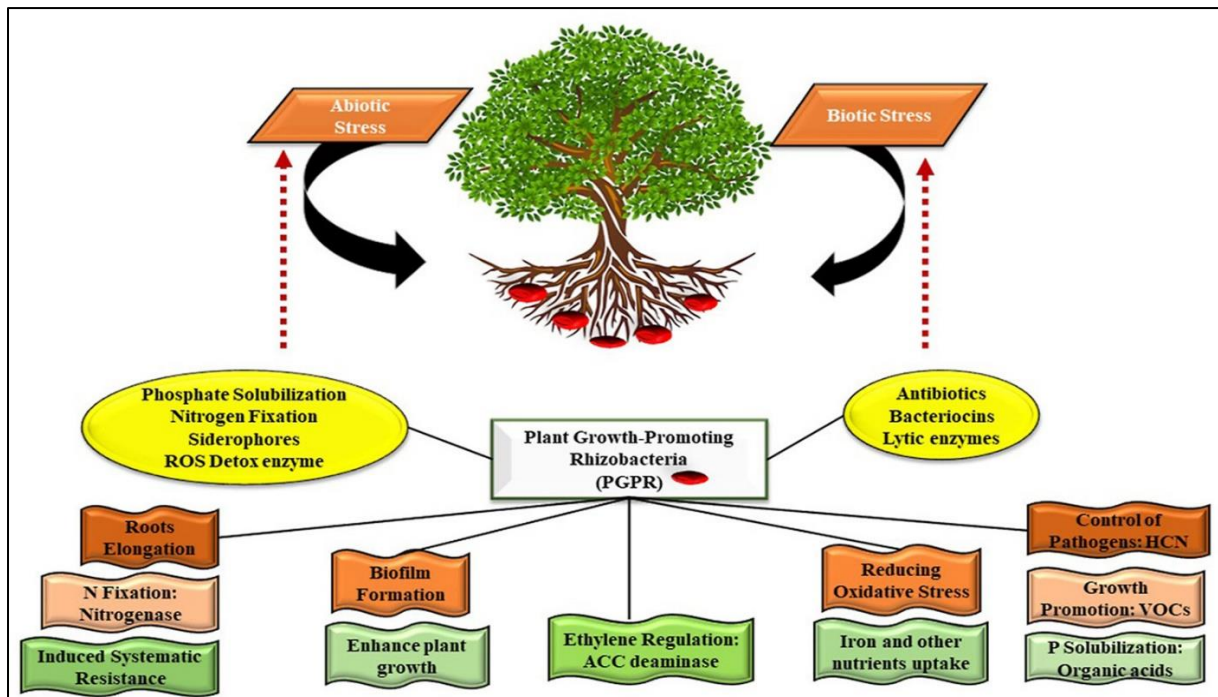


Fig. 1. Schematic diagram represents the effect of PGPR on various abiotic and biotic stress

## 3. 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 [41,42,43]. 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 [44,45,46]. 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.

### 3.1 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 [47,48]. 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 *Azospirillum* 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].

### 3.2 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 [58,59,60]. 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 [65,66,67]. 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  $\alpha$ -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].

### 3.3 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, 2,3,4].

IAA is produced by *Azotobacter* species at concentrations ranging from 2.09 to 33.28 mg/mL, according to the literature [70,71,72]. 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].

### 3.4 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 [75,76,77]. 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 [80,81,82,83].

## 4. 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.

### 4.1 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 [90,91,92,93].

### 4.2 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

**Table 1. PGPR showing their activities in various abiotic stresses**

<b>Abiotic stresses</b>	<b>PGPRs</b>	<b>PGPR- mediated mechanisms</b>
Drought as stress	<i>B. aquimaris</i> <i>Bacillus sp.</i> , <i>Enterobacter sp.</i> , <i>Pseudomonas fluorescens</i> , <i>A. chroococcum</i> <i>B. megaterium</i> <i>V. paradoxus</i> <i>E. cloacae</i> <i>B. licheniformis</i> , <i>P. fluorescens</i> , <i>A. brasilense</i> <i>A. piechaudii</i>	Indole acetic acid, Exopolysaccharides, ACC deaminase Indole acetic acid, Salicylic acid N <sub>2</sub> fixation, phosphorus solubilization, Antimicrobial compounds Polyamine secretion ACC deaminase ACC deaminase Abscisic acid ACC deaminase
Salinity as stress	<i>A. aneurinilyticus</i> , <i>Paenibacillus sp.</i> <i>B. amyloliquefaciens</i> <i>Glutamicibacter sp. YD01</i> <i>Bacillus sp.</i> , <i>Azospirillum</i> , <i>A. brasilense</i> , <i>P. stutzeri</i> <i>S. maltophilia</i> <i>A. vinelandii</i> , <i>A. lipoferum</i> , <i>B. circulans</i> <i>P. fluorescens</i> , <i>B. megaterium</i> and <i>B. subtilis</i> <i>P. oryzihabitans</i> <i>Burkholderia</i> <i>Bacillus safensis</i>	ACC deaminase, ACC deaminase, Salicylic acid ACC deaminase ACC deaminase, osmoregulators, ROS, acquisition of Na:K Phytohormones, osmoregulators, ROS Indole acetic acid, ACC deaminase  Auxin, gibberellins, kinetin, N <sub>2</sub> fixation Indole acetic acid, ACC deaminase Indole acetic acid, ACC deaminase, Salicylic acid Indole acetic acid, ACC deaminase
Water as stress	<i>P. putida</i> and <i>P. fluorescens</i> <i>P. putida</i> <i>Gluconacetobacter diazotrophicus</i> <i>Azospirillum spp. (Az19)</i>	Indole acetic acid, ACC deaminase ACC deaminase Abscisic acid, Phytohormones Proline production
Temperature as stress	<i>Bacillus spp.</i> <i>Azotoformans sp.</i> and <i>Pseudomonas sp.</i> <i>P. fragi</i> , <i>P. proteolytica</i> , <i>P. chloropaphis</i> <i>B. tequilensis</i>	Abscisic acid Phosphate availability, N <sub>2</sub> fixation Lowering chill injury, lipid peroxidation and ice-nucleating activity Apoplasmic antioxidant enzyme activities
Heavy Metal as stress	<i>S. acidiscabies</i>	Siderophores

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.

### 4.3 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.

### 4.4 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].

## 5. 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, nitrogen fixation, and P liquification [108,109,110]. 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 [101,42,98]. 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].

## 6. 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]. 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]. 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].

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 [125-127].

## 7. 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.

## 8. 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.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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