Review Article
Alleviating abiotic stress, enhancing soil fertility, and growth of forest tree species by sustainable application of PGPR-A review

ABSTRACT

The worldwide decline in plant productivity results from a plethora of biotic and abiotic stressors, including pests, diseases, temperature fluctuations, heavy metal accumulation, salt, and drought. Excessive drainage and chemical use exacerbate soil nutrient depletion. Salinity, affecting millions of hectares of land, underscores the urgency for effective mitigation strategies. Plant Growth-Promoting Rhizobacteria (PGPR) offer promising solutions by improving nutrient availability, hormone regulation, and stress alleviation. Studies demonstrate PGPR's diverse mechanisms for combating abiotic stresses, including phytohormone production, ACC deaminase activity, and osmolyte synthesis. PGPR also mitigates heavy metal toxicity and thermal stress, highlighting their potential for sustainable plant growth. Leveraging microbial diversity and stress-resistant PGPR strains, coupled with cost-effective microbial inoculation, presents a compelling strategy for enhancing environmental sustainability in plant cultivation. Multidisciplinary research efforts are crucial for optimizing PGPR-mediated stress tolerance and promoting sustainable environmental practices. This review looks at how PGPR improves soil fertility, reduces abiotic stress, and encourages the growth of forest trees. It highlights the many mechanisms at work, offers selection guidance for strains, and emphasizes the significance of sustainable application techniques. In the end, the review confirms that PGPR is a viable and long-term strategy to improve the productivity and health of forest ecosystems.

Keywords: Plant Growth-Promoting Rhizobacteria (PGPR), Abiotic stress mitigation, Soil fertility improvement, Sustainable plant growth, Environmental sustainability, Forest ecosystem health

INTRODUCTION

The fundamental reason for the worldwide decline in Plant productivity is a variety of biotic and abiotic pressures in the environment [1, 2, 3, and 4]. Biologic stressors include those brought on by pests and phytopathogens such as nematodes, viruses, fungi, and insects. 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 careless 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 circumstances or abiotic 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 crop plant breeds might help mitigate the major biotic and abiotic challenges to some degree. However, it is expensive and takes a long time to produce fresh breeds that are resistant to abiotic stressors. Consequently, to counteract the impacts of biotic and abiotic pressures in agriculture, 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 species *Acinetobacter, Agrobacterium, Arthobacter, 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. Moreover, Kumar, et al. [25] showed that *Pseudomonas* sp.

and *Bacillus* promoted growth in stressed plants by producing indole acetic acid (IAA), siderophores, and solubilizing phosphates. ACC-deaminase-containing microorganisms inhibit ethylene synthesis, enhancing root growth [26, 27]. Lowered ethylene levels resulted in root growth and improved the survival of stressed plants [28]. Microorganisms employ different strategies for stress tolerance [29]. Evidence suggests secondary metabolites are involved, despite reports claiming microbes alleviate abiotic stress by triggering basic metabolisms (plant growth, food uptake, photosynthesis, and antioxidant enzymes [30]. Some secondary metabolites such as flavonoids, phytoalexins, phenylpropanoids, and carotenoids have been documented in stressed plants inoculated with microorganisms [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 EPS, controlling phytohormones, promoting osmolyte production, increasing mineral uptake, and managing phytopathogens [35, 36]. According to Araújo et al [37] in certain nurseries, Quercus suber L. seedling quality was enhanced up to two fold by utilizing a combination of ECM fungus and bacteria inocula. Plant biomass differed significantly among nurseries. 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].

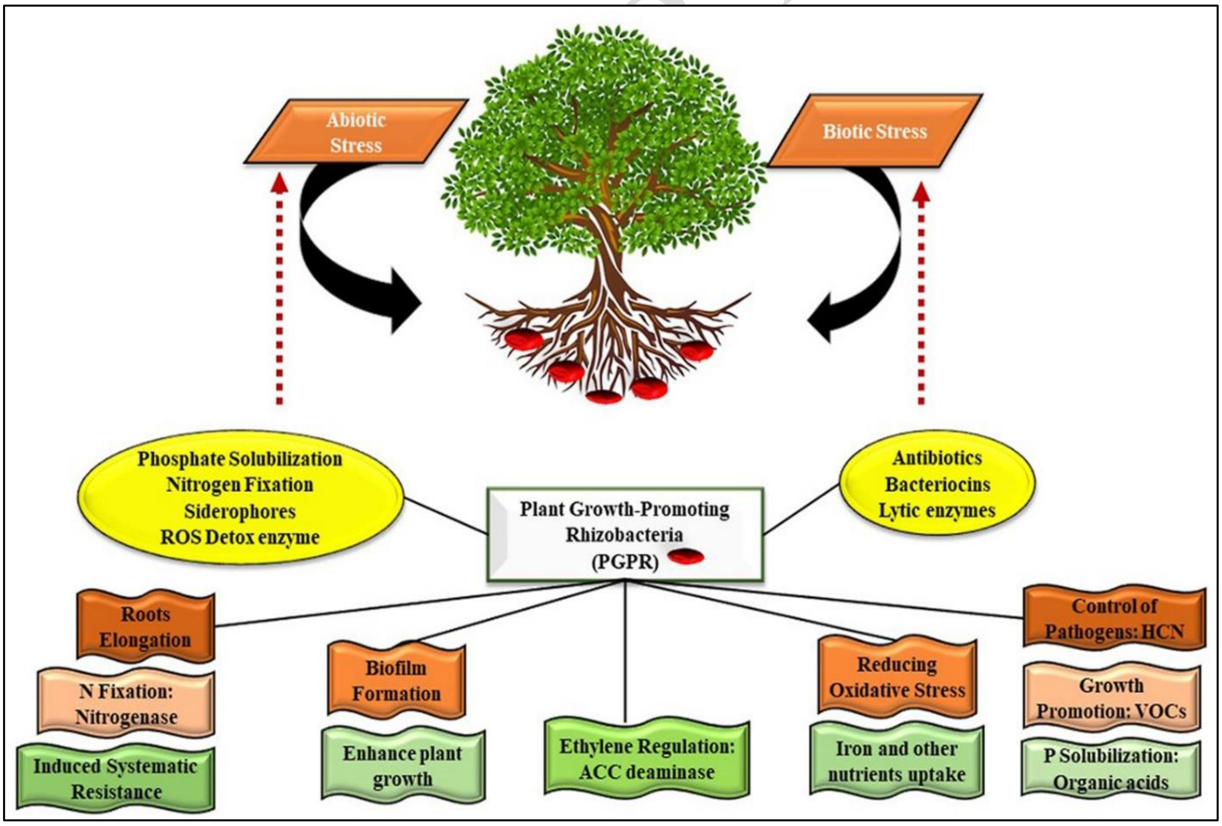

Fig. 1: Schematic diagram represents the effect of PGPR (plant growth-promoting rhizobacteria) on various abiotic and biotic stress

TECHNIQUES FOR REDUCING BIOTIC STRESSES USING PGPR AS A TOOL

Plant-beneficial microbe interactions can enhance a plant's 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 ACC deaminase, kinetin, zeatin, 6-benzyl amino purine, diphenylurea, and thidiazuron (TDZ)-type cytokinin, IAA- and IBA-type auxins, gibberellic acid, and ACC. 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 pressures 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] (Zhang et al., 2022). 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 *Azospirillum, 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 methods 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 beta-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, severe temperature conditions, UV radiation, and damage from nematodes and plant diseases [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].

Plant Growth-Promoting Rhizobacteria (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. Tryptophan causes bacteria to produce IAA, which in turn increases host plant production of IAA [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 (Indole Acetic Acid) Plant hormone

A plant growth regulator called indole acetic acid (IAA) is secreted by bacteria that live in the soil, especially PGPR species, which are the principal producers [69]. It has been noted that the growth of bacteria that produce IAA is especially advantageous in salinity-rich or salty soils. Roughly 75% of the bacterial isolates that have been found to generate IAA do so very efficiently. Numerous rhizobacteria, pathogenic, symbiotic, and free-living bacterial species have been reported to possess IAA synthesizing efficiency and characteristics [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 [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 treat bug 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, and 78]. It has been shown that certain strains of *Bacillus subtilis* have bioinsecticidal action and release bioactive compounds into the rhizosphere [79]. One important strategy used by many Plant Growth-Promoting Rhizobacteria (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 [80]. According to studies, *Brevibacillus laterosporus* generates bioactive substances that are useful against a variety of insect species, such as enzymes and antibiotics (Li et al., 2022). In addition, studies have looked into the possibility of using rhizobacteria like *B. sphaericus* and *Bacillus pumilus* to cure white grubs [81, 82, 83, and 84].

TECHNIQUES FOR REDUCING ABIOTIC STRESSES USING PGPR AS A TOOL

According to recent research, plants that are subjected to stressful conditions benefit from the presence of Plant Growth-Promoting Rhizobacteria (PGPRs) as they synthesize proline. When *Arthrobacter, Burkholderia*, and *Bacillus* are injected under abiotic stress circumstances, researchers have shown that proline levels are raised [14, 15]. Furthermore, research conducted by Najafi Zilaie et al., Mahmood et al., and Khan and Singh [84, 85, 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. Plant exudates play a key role in the transformation of insoluble phosphorus into soluble form; bacteria participating in this process use carbohydrates from the exudate of roots as a source of carbon [42, 86]. Studies indicate that IAA treatment promotes the release of carbohydrates, which helps the soil mobilize phosphorus indirectly [87]. Inoculating maize with particular bacterial strains improves the plant's ability to absorb nutrients, especially potassium, phosphate, and nitrogen [88]. Apart from that, siderophores secreted by root-colonizing bacteria can help absorb different metals like copper, iron, and zinc [81]. Because heavy metal pollution 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 [89, 90]. 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 [91, 92, 93, and 94].

Alleviating Drought Stress

Plant growth-promoting rhizobacteria (PGPR) increase plant resilience to abiotic stressors like drought by secreting osmolytes when there is a drought [95]. Osmolytes raise cellular osmotic potential and are produced by drought-tolerant plants in response to water shortage [96]. 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 [97]. Similar to *Achromobacter piechaudii* and *Azospirillum brasilense*, PGPR improves membrane stability and water consumption efficiency by reducing root dryness and increasing plant biomass [88, 98]. Additionally, under drought stress, these bacteria raise the proline level in plant tissues, which is essential for preserving cell hydration status [99]. Additionally, PGPR generates phenolic compounds and salicylic acid, which function as signaling molecules to activate genes and secondary metabolites responsive to stress [100]. *Pseudomonas putida* GAP-P45 and other PGPR strains increase proline buildup through inoculation, which is essential for plant drought resistance [101]. 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.

Alleviating 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 [102, 103]. Both gram-negative and gram-positive In order to mitigate the negative effects of salinity, PGPR invades plant roots and use strategies such as chemotaxis, EPS, IAA, and ACC deaminase synthesis [102, 103]. 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 [104, 105]. 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 [106, 107]. To properly manage salt stress, it is imperative to investigate microbial diversity.

Alleviating 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 [108].

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, N2 fixation, and P liquefaction [109, 110, and 111]. 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 [102, 42, and 99].

FUTURE PROSPECTUS

When it comes to promoting plant tolerance to abiotic stresses like salinity, heavy metals, and drought, bacterial isolates from stress-prone habitats are more effective than those from stress-free environments when it comes to 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, a wide range of biotic and abiotic factors, such as pests, diseases, temperature changes, the buildup of heavy metals, salt, and drought, are to blame for the worldwide reduction in plant yield. These problems are made worse by excessive drainage and chemical use, which depletes the nutrients in the soil. The adverse effects of salt on tree development and soil qualities, which are present across millions of hectares of land, highlight the pressing need for effective mitigation techniques. In this quest, Plant Growth-Promoting Rhizobacteria (PGPR) show great promise as partners, providing a variety of benefits such as improved nutrient availability, hormone modulation, and stress reduction. The review elucidates the various ways by which PGPR counteracts abiotic stressors, such as the production of phytohormones, ACC deaminase, and osmolytes, in addition to their capacity to enhance mineral absorption and counteract phytopathogens.

Furthermore, the utilization of Plant Growth Promoting Rhizobacteria (PGPR) presents considerable promise for tackling issues related to thermal stress and heavy metal toxicity. To achieve sustainable tree or plant growth, it is essential to investigate microbial diversity and leverage the resilience of naturally occurring stress-resistant PGPR strains. Microbial inoculation presents a compelling option due to its cost-effectiveness and speedy implementation, even though genetic engineering and plant breeding offer longer-term alternatives. To maximize PGPR-mediated stress tolerance and advance environmental sustainability in tree or plant culture, multidisciplinary research initiatives and field investigations using specialist biofertilizer organisms are needed.

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