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RESEARCH ARTICLE

The Contribution of Stress-Tolerant Plant Growth-Promoting Rhizobacteria (PGPR) from Abiotic-Stressed Ecosystems to Sustainable Plant Management: A Comprehensive Review

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ABSTRACT

Plant Growth-Promoting Rhizobacteria (PGPR) represent a promising avenue for sustainable agriculture, offering multifaceted benefits to plants, including enhanced growth, nutrient uptake, and stress tolerance. Abiotic stressors, such as drought, salinity, temperature extremes, and soil contamination, pose significant challenges to agricultural productivity and sustainability. In response, researchers have turned their attention to isolating PGPR from abiotic stressed regions, where microbial communities have evolved mechanisms to thrive under harsh environmental conditions. This review provides a comprehensive overview of the role of PGPR in mitigating abiotic stress in agriculture, with a focus on their isolation and characterization from stress-prone environments.

The introduction sets the stage by highlighting the importance of PGPR in sustainable agriculture and the adverse effects of abiotic stress on plant growth and productivity. We discuss the mechanisms by which abiotic stressors disrupt plant physiology and metabolism, underscoring the need for innovative strategies to enhance crop resilience in the face of climate change. The rationale for isolating PGPR from abiotic stressed regions is elucidated, emphasizing its practical implications for addressing global challenges in agriculture and food security.

This review examines methodologies for isolating stress-tolerant PGPR strains, factors influencing their abundance and diversity in abiotic stressed environments, and case studies demonstrating successful isolation and characterization efforts. We explore the applications of stress-tolerant PGPR in sustainable agriculture, including biofertilization, bioremediation, and crop protection, with a focus on real-world examples and field trials. Challenges and future directions in harnessing PGPR from abiotic stressed regions are discussed, highlighting the need for scalable solutions and interdisciplinary collaborations.

In conclusion, harnessing stress-tolerant PGPR from abiotic stressed regions holds great promise for sustainable agriculture, offering innovative solutions to mitigate the adverse effects of climate change on crop productivity and environmental sustainability. Through a comprehensive analysis of current research findings and future perspectives, this review aims to underscore the significance of PGPR-based strategies for sustainable development and food security in a changing climate.

INTRODUCTION

Plant Growth-Promoting Rhizobacteria (PGPR) play a crucial role in sustainable agriculture by enhancing plant growth, improving nutrient uptake, and conferring resistance against various biotic and abiotic stresses.[1] These beneficial microbes, commonly found in the rhizosphere, interact symbiotically with plants, promoting their growth and development.[2,3] In recent years, there has been growing recognition of the importance of PGPR in mitigating the adverse effects of abiotic stressors, such as drought, salinity, extreme temperatures, and soil contamination, on crop productivity.[4,5] As climate change exacerbates the frequency and intensity of these stressors, the need to identify and harness stress-tolerant PGPR strains becomes increasingly urgent for ensuring food security and environmental sustainability.[6,7]

Abiotic stressors pose significant challenges to agricultural productivity, affecting plant physiology, metabolism, and overall growth. Drought, for example, disrupts water availability, leading to reduced photosynthetic activity and yield losses, while salinity inhibits nutrient uptake and imposes osmotic stress on plants.[8,9] Temperature extremes can disrupt enzymatic processes and alter membrane fluidity, compromising plant resilience to stress.[10] These challenges underscore the importance of understanding the intricate interactions between plants and their associated microbiota, particularly PGPR, in adapting to and mitigating the effects of abiotic stress in agricultural ecosystems.[11]

Considering these challenges, the isolation of PGPR from abiotic stressed regions emerges as a promising strategy for sustainable agriculture. Abiotic stressed environments, such as arid and saline soils, harbor microbial communities adapted to survive and thrive under harsh conditions.[12] By isolating PGPR from these environments, researchers can identify strains with enhanced stress tolerance and explore their potential applications in agricultural systems.[13] Furthermore, studying PGPR from abiotic stressed regions provides insights into the mechanisms underlying microbial adaptation to environmental stress, which can inform strategies for enhancing plant resilience in the face of climate change.[14]

The rationale for isolating PGPR from abiotic stressed regions extends beyond mere academic curiosity; it holds practical implications for addressing global challenges in agriculture and food security.[15] By elucidating the role of stress-tolerant PGPR in enhancing crop resilience and productivity, this research contributes to the development of sustainable farming practices that minimize reliance on chemical inputs and mitigate environmental degradation.[16,17] Moreover, harnessing the potential of PGPR from abiotic stressed regions aligns with the principles of precision agriculture, wherein microbial inoculants are tailored to specific environmental conditions and crop requirements, thereby optimizing resource use efficiency, and minimizing ecological footprint.[18,19]

In this review, we will explore the role of PGPR in mitigating abiotic stress in agriculture, with a focus on their isolation from abiotic-stressed regions. [20,21] We will examine the mechanisms underlying PGPR-mediated stress tolerance in plants, discuss methodologies for isolating stress-tolerant PGPR strains, and evaluate their potential applications in sustainable agriculture. [22,23] Through a comprehensive analysis of current research findings and future perspectives, we aim to highlight the significance of harnessing PGPR from abiotic stressed regions for sustainable development and food security in a changing climate. [24,25]

ABIOTIC STRESSES IN AGRICULTURE

In the realm of agricultural sustainability, Plant Growth-Promoting Rhizobacteria (PGPR) play a pivotal role in alleviating the detrimental impacts of abiotic stresses on plant growth and productivity.[26] PGPR is a diverse group of soil bacteria that establish symbiotic relationships with plants, particularly in the rhizosphere, where they exert beneficial effects on plant growth through various mechanisms.[27] One primary avenue through which PGPR contributes to stress mitigation is by enhancing nutrient uptake and utilization in plants.[28] Through processes such as nitrogen fixation, solubilization of phosphates, and production of growth-promoting hormones like auxins and cytokinins, PGPR assists plants in acquiring essential nutrients, even under conditions of nutrient scarcity induced by abiotic stressors like drought and salinity.[29]

Moreover, PGPR employs a range of direct and indirect mechanisms to bolster plant stress tolerance and resilience.[30] Direct mechanisms involve the synthesis and secretion of stress-responsive compounds such as osmoprotectants, antioxidants, and enzymes that detoxify reactive oxygen species (ROS), thus alleviating oxidative stress induced by abiotic stressors.[31] Additionally, PGPR can modulate plant hormone levels, regulate stomatal conductance, and activate stress-responsive gene expression pathways in host plants, enhancing their capacity to withstand environmental stressors. Indirectly, PGPR contributes to plant stress resilience by antagonizing phytopathogens, inducing systemic resistance, and promoting plant defense mechanisms, thereby reducing the susceptibility of plants to stress-induced diseases, and improving overall crop health and yield potential.[32] The multifaceted mechanisms employed by PGPR highlight their potential as sustainable bioresources for bolstering agricultural resilience and productivity in the face of global environmental challenges.[33]

Furthermore, the efficacy of PGPR-mediated stress mitigation is not only confined to laboratory experiments but has also been demonstrated in field trials and real-world agricultural settings. Numerous studies have reported the beneficial effects of PGPR inoculation on crop performance under various abiotic stress conditions, including drought, salinity, and heavy metal contamination.[34] By harnessing stress-tolerant PGPR strains and integrating them into agricultural practices, farmers can reduce their reliance on chemical inputs, enhance soil fertility and health, and sustainably improve crop yields. Additionally, the use of PGPR-based biofertilizers and biostimulants offers a cost-effective and environmentally friendly approach to enhancing agricultural productivity while minimizing the ecological footprint of farming operations.[35] Overall, the widespread adoption of PGPR-based strategies holds immense promise for promoting agricultural sustainability and food security in the face of escalating environmental challenges.[36]

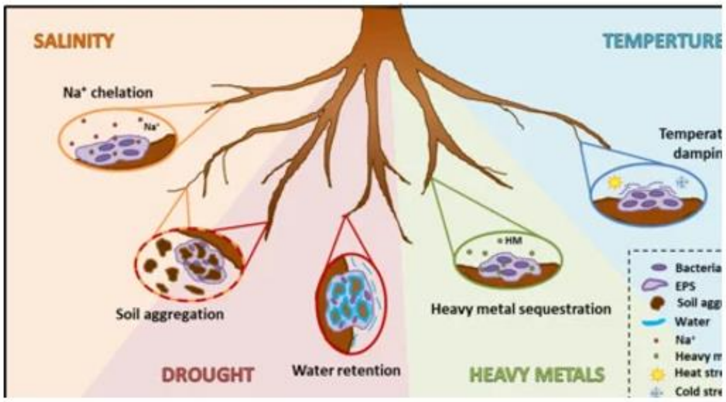

Figure 1. Abiotic Stress [37]

Table 1. Plant growth-promoting rhizobacteria (PGPR) are employed to alleviate stress in agricultural settings. [38-43]

Abiotic Stress	**Plant Species**	**Rhizobacteria**	**Plant Growth-Promoting Process**
Drought	Maize (Zea mays)	Pseudomonas putida, Bacillus amyloliquefaciens, Enterobacter cloacae, Rhizobium leguminosarum	Production of osmolytes and exopolysaccharides to improve water use efficiency and root protection
Salinity	Soybean (Glycine max)	Bacillus subtilis, Halomonas sp., Marinobacter sp., Azospirillum brasilense, Pseudomonas stutzeri	Production of siderophores to chelate iron and improve nutrient uptake
Heat Stress	Tomato (Solanum lycopersicum)	Azospirillum brasilense, Arthrobacter sp., Pseudomonas fluorescens, Rhizobium etli, Bacillus megaterium	Production of phytohormones to stimulate root growth and enhance stress tolerance
Heavy Metal Toxicity	Wheat (Triticum aestivum)	Arthrobacter sp., Pseudomonas aeruginosa, Ochrobactrum anthropi, Sinorhizobium meliloti, Klebsiella pneumoniae	Biodegradation of heavy metals and mobilization of nutrients
Drought	Maize (Zea mays)	Pseudomonas putida, Bacillus amyloliquefaciens, Enterobacter cloacae, Rhizobium leguminosarum	Production of osmolytes and exopolysaccharides to improve water use efficiency and root protection
Salinity	Soybean (Glycine max)	Bacillus subtilis, Halomonas sp., Marinobacter sp., Azospirillum brasilense, Pseudomonas stutzeri	Production of siderophores to chelate iron and improve nutrient uptake
Heat Stress	Tomato (Solanum lycopersicum)	Azospirillum brasilense, Arthrobacter sp., Pseudomonas fluorescens, Rhizobium etli, Bacillus megaterium	Production of phytohormones to stimulate root growth and enhance stress tolerance

Heavy Metal Toxicity	Wheat (Triticum aestivum)	Arthrobacter sp., Pseudomonas aeruginosa, Ochrobactrum anthropi, Sinorhizobium meliloti, Klebsiella pneumoniae	Biodegradation of heavy metals and mobilization of nutrients
Drought	Maize (Zea mays)	Pseudomonas putida, Bacillus amyloliquefaciens, Enterobacter cloacae, Rhizobium leguminosarum	Production of osmolytes and exopolysaccharides to improve water use efficiency and root protection

Plants encounter a variety of environmental challenges known as abiotic stresses, which can significantly hinder their growth and productivity. [44,45] These stresses include drought, salinity, heat stress, and heavy metal toxicity. Fortunately, a group of beneficial bacteria called plant growth-promoting rhizobacteria (PGPR) offers a potential solution. These bacteria colonize the root zone (rhizosphere) of plants and engage in various mechanisms to promote plant growth and enhance tolerance to abiotic stresses. [46,47]

Combating Drought: Maize (Zea mays) cultivation can be significantly impacted by drought conditions.[48] Several PGPR species can mitigate these effects. **Pseudomonas putida** is well-known for producing osmolytes and exopolysaccharides, which help plants retain water and improve water use efficiency.[49] **Bacillus amyloliquefaciens** can also contribute by colonizing roots and promoting the production of stress-protective enzymes. **Enterobacter cloacae** and **Rhizobium leguminosarum** further enhance drought tolerance through nitrogen fixation and phosphate solubilization, respectively, ensuring essential nutrients are available for stressed plants. [50,51]

Alleviating Salinity Stress: Soybean (Glycine max) is a valuable crop but can be sensitive to the high salt content in the soil. [52,53] PGPR helps in these conditions. **Bacillus subtilis** is a key player, producing siderophores that chelate iron, making it more accessible to plants even in saline environments. **Halomonas sp.** and **Marinobacter sp.**, naturally adapted to salty environments, further contribute by solubilizing mineral nutrients trapped in saline soils. **Azospirillum brasilense** and **Pseudomonas stutzeri** join the effort by fixing atmospheric nitrogen and promoting root growth, respectively, strengthening the plant's overall resilience.[54]

Mitigating Heat Stress: Tomato (Solanum lycopersicum) production can suffer under high temperatures. PGPR offers support through various mechanisms. **Azospirillum brasilense** is known for producing phytohormones like auxins and cytokinins, which stimulate root growth and enhance stress tolerance.[55] **Arthrobacter sp.** contributes by producing compatible solutes that protect plant cells from heat damage. **Pseudomonas fluorescens** joins the fight by synthesizing siderophores, ensuring iron availability for essential plant processes even during heat stress. **Rhizobium etli** and **Bacillus megaterium** further bolster plant health through nitrogen fixation and phosphate solubilization, respectively, ensuring stressed plants have access to vital nutrients. [56,57]

Countering Heavy Metal Toxicity: Wheat (Triticum aestivum) growth can be hampered by heavy metal contamination in soil. PGPR offers some relief through various processes. **Arthrobacter sp.** can degrade certain heavy metals, rendering them less harmful to plants.[58] **Pseudomonas aeruginosa** contributes by chelating heavy metals, reducing their free ion concentration and potential toxicity. **Ochrobactrum anthropi** and **Sinorhizobium meliloti** further assist by solubilizing phosphates and fixing atmospheric nitrogen, respectively, ensuring stressed plants have access to essential nutrients for growth despite the presence of heavy metals.[59] **Klebsiella pneumoniae** joins the effort by producing siderophores, facilitating iron uptake even in heavy metal-contaminated soils.

This highlights the diverse range of PGPR and its mechanisms for promoting plant growth and enhancing tolerance to various abiotic stresses. By harnessing the power of these beneficial bacteria, we can potentially improve agricultural productivity and ensure the sustainability of crop production even in challenging environmental conditions.[60]

ROLE OF PGPR IN MITIGATING ABIOTIC STRESS

The isolation of Plant Growth-Promoting Rhizobacteria (PGPR) from abiotic stressed regions represents a critical step in harnessing their potential for sustainable agriculture.[61] Methodologies for isolating PGPR from soil and plant rhizosphere vary, encompassing classical microbiological techniques as well as modern molecular biology approaches.[62] Classical methods involve serial dilution plating on selective media followed by biochemical and physiological characterization of isolated colonies, while molecular techniques such as PCR-based screening and metagenomic analysis enable the identification and characterization of specific PGPR strains based on their genetic makeup and functional traits.[63] Additionally, advancements in high-throughput sequencing technologies have revolutionized the study of microbial communities in abiotic stressed environments, facilitating the identification of novel PGPR species and their functional attributes.[64]

Several factors influence the abundance and diversity of PGPR in abiotic stressed environments, including soil physicochemical properties, climatic conditions, and plant-microbe interactions. Abiotic stressors such as drought, salinity, and heavy metal contamination exert selective pressures on microbial communities, shaping their composition and functional diversity.[65] PGPR strains adapted to abiotic stressed environments often exhibit specialized metabolic pathways and stress-responsive mechanisms that enable them to thrive under harsh conditions. Case studies of successful isolation and characterization of stress-tolerant PGPR strains provide valuable insights into the ecological significance and biotechnological potential of these microbes.[66] By elucidating the genetic and physiological mechanisms underlying PGPR-mediated stress tolerance, researchers can develop targeted strategies for enhancing crop resilience and productivity in abiotic stressed environments, thereby advancing the goals of sustainable agriculture and environmental conservation.[67]

ISOLATION OF PGPR FROM ABIOTIC STRESSED REGIONS

The isolation of Plant Growth-Promoting Rhizobacteria (PGPR) from abiotic stressed regions involves a range of methodologies tailored to capture the diverse microbial communities thriving in these environments.[68] Classical techniques for isolating PGPR from soil and plant rhizosphere typically involve serial dilution plating on selective media supplemented with carbon and nitrogen sources, followed by biochemical and physiological characterization of isolated colonies.[69] These methods allow researchers to culture and identify PGPR strains based on their morphological characteristics, metabolic activities, and plant growth-promoting traits.[70] In addition to traditional approaches, molecular biology techniques such as polymerase chain reaction (PCR) amplification of specific gene markers and next-generation sequencing enable the targeted isolation and characterization of PGPR strains based on their genetic composition and functional attributes.[70] Metagenomic analysis of soil and rhizosphere microbial communities further enhances our understanding of the abundance, diversity, and ecological roles of PGPR in abiotic stressed environments, providing valuable insights into their biotechnological potential for sustainable agriculture.[71]

Several factors influence the abundance and diversity of PGPR in abiotic stressed environments, shaping the composition and functional traits of microbial communities. Soil physicochemical properties, including pH, texture, moisture content, and nutrient availability, play a critical role in determining the distribution and activity of PGPR strains.[72] Abiotic stressors such as drought, salinity, temperature extremes, and heavy metal contamination exert selective pressures on microbial populations, favoring the proliferation of stress-tolerant PGPR species adapted to survive and thrive under adverse conditions.[73] Plant-microbe interactions also influence the abundance and diversity of PGPR in the rhizosphere, as plants release root exudates containing carbon compounds that attract and stimulate the growth of beneficial rhizobacteria. Understanding the complex interplay between environmental factors, plant physiology, and microbial ecology is essential for elucidating the mechanisms driving the dynamics of PGPR communities in abiotic stressed environments.[74]

In addition to the classical microbiological techniques and modern molecular biology approaches mentioned earlier, another effective method for isolating Plant Growth-Promoting Rhizobacteria (PGPR) from abiotic stressed regions involves the use of selective growth media tailored to mimic the specific environmental conditions of the target habitat.[75] These specialized media formulations incorporate substrates and nutrients that favor the growth of stress-tolerant PGPR strains adapted to harsh environmental conditions such as aridity, salinity, or heavy metal contamination. By selectively enriching PGPR populations that thrive in these challenging environments, researchers can isolate strains with unique stress tolerance mechanisms and explore their potential applications in sustainable agriculture.[76]

Moreover, culture-independent methods, such as metagenomic analysis and high-throughput sequencing, offer valuable insights into the diversity and functional potential of microbial communities in abiotic stressed environments.[77] These techniques involve extracting genetic material directly from soil or rhizosphere samples and sequencing the microbial DNA to identify and characterize PGPR strains based on their genetic composition and functional traits. Metagenomic analysis allows researchers to survey the entire microbial community present in each habitat, providing a comprehensive understanding of the ecological roles and biotechnological potential of PGPR in abiotic stressed environments.[78] By combining culture-dependent and culture-independent approaches, researchers can gain a holistic understanding of the microbial diversity and functional dynamics in abiotic stressed regions, paving the way for the discovery of novel PGPR strains and their applications in sustainable agriculture.[79]

Nitrogen Fixation

Nitrogen is an indispensable macronutrient crucial for plant growth and development, playing vital roles in protein synthesis, photosynthesis, and the formation of nucleic acids.[80] However, the continuous depletion of nitrogen in agricultural soils poses a significant challenge.[81] Despite its abundance in the atmosphere, plants cannot directly utilize atmospheric nitrogen.[82] Herein lies the importance of Plant Growth-Promoting Rhizobacteria (PGPR), which play a pivotal role in nitrogen fixation and supplementing plant nutrition under such circumstances.[83] These nitrogen-fixing bacteria can be categorized into two types: symbiotic and free-living nitrogen-fixing bacteria. They form symbiotic relationships with plants or exist freely in the soil, converting atmospheric nitrogen into a form that plants can readily absorb and utilize for their growth and development. [84-87]

Among the PGPR genera known for their nitrogen-fixing abilities are Bradyrhizobium, Rhizobium, Frankia, Mesorhizobium, and Sinorhizobium. These bacteria facilitate nitrogen fixation and supply plants with essential nitrogen, thus promoting overall plant health and vigor.[88] Notably, nitrogen-fixing PGPR strains not only enhance plant nutrition but also exhibit nematicidal activity, offering a dual benefit to host plants. For instance, banana plants treated with nitrogen-fixing bacteria showed suppressed populations of harmful nematodes, leading to improved banana growth. [89,90] Similarly, bacteria like Paenibacillus polymyxa, known for their nitrogen-fixing capabilities, contribute to plant development while also demonstrating effectiveness against plant-parasitic nematodes, thus contributing to sustainable agriculture practices.[91]

Phytohormone formation

The diversity among Plant Growth-Promoting Rhizobacteria (PGPR) strains can lead to the production of various plant growth-promoting chemicals, including phytohormones and plant growth regulators such as auxins (such as indole butyric acid, indole acetic acid, and phenylacetic acid), cytokinins (like trans-zeatin ribose, isopentenyl adenine riboside, isopentenyl adenosine, and zeatin), abscisic acid, gibberellic acid, ethylene, brassinosteroids, polyamines, jasmonates, strigolactones, salicylic acid, and other plant growth regulator compounds.[92-94] Among these, indole acetic acid stands out as the most prevalent phytohormone.[95] These microbial-produced phytohormones are recognized for their role in promoting plant development and enhancing plant-bacterial interactions. They primarily function by stimulating elongation, cell division, tissue expansion, and other favorable effects on plant growth and metabolism.[96] Furthermore, the inclusion of bacteria capable of producing indole acetic acid has been linked to improved plant development and increased resistance to diseases. Phytohormones synthesized by PGPR have also been demonstrated to shield plants from the detrimental impacts of various environmental stressors.[97]

The application of phytohormone-producing PGPR strains in the field, typically through seed application, holds promise for improving both plant growth and nematode biocontrol.[98] For example, studies have shown that the production of indole acetic acid by strains like Streptomyces fradiae NKZ-259 enhances plant growth while simultaneously reducing pest populations. Similarly, strains like Pseudomonas simiae MB751, which produce indole acetic acid, have been found to play a role in controlling nematode populations and promoting plant growth. [99,100] Hence, the ability of bacteria to directly influence phytohormone synthesis can significantly impact their effectiveness in stimulating plant growth.[101]

Phosphate Solubilization

Phosphorus, another vital element essential for plant development, plays diverse roles in facilitating nucleic acid formation, protein synthesis, tissue growth, cell division, and energy conversion within plants.[102,103] However, in agricultural settings, phosphate compounds often exist in insoluble forms, limiting their availability to plants.[104] In such scenarios, Plant Growth-Promoting Rhizobacteria (PGPR) play a crucial role by employing various mechanisms such as chelation, organic acid generation, and acidification to solubilize inaccessible phosphorus, making it available for plant uptake. Several genera of PGPR, including Arthrobacter, Bacillus, Enterobacter, Flavobacterium, Microbacterium, Pseudomonas, Rhizobium, Rhodococcus, and Serratia, are known to act as phosphate solubilizers. [105-107] These bacteria possess the capability to enhance phosphate bioavailability by solubilizing and mineralizing phosphate compounds present in the soil, thus benefiting plant growth and nutrient uptake.

Studies have demonstrated the effectiveness of phosphate-solubilizing bacteria in suppressing populations of plant-parasitic nematodes. For instance, bacterial species like Pseudomonas fluorescens, Pseudomonas lilacinus, and Trichoderma viride have been found to reduce the populations of nematode cysts in potato plants.[108] Similarly, inoculating tomato plants with Bacillus megaterium not only improved growth parameters and nutrient contents but also led to a reduction in nematode populations. Additionally, certain phosphate-solubilizing bacteria like Brevibacillus laterosporus and Photorhabdus luminescens exhibit protease activity, which contributes to their ability to control nematode populations. [109,110] Overall, the application of phosphate-solubilizing PGPR strains holds promise for enhancing soil fertility, promoting plant growth, and mitigating the detrimental effects of plant-parasitic nematodes in agricultural systems.[111]

Siderophores and ammonia production

Living organisms rely on iron for essential biological functions such as electron transport, respiration, photosynthesis, and enzyme activation.[112] However, iron often exists in an insoluble form in soil under aerobic conditions, posing a challenge for organisms to access it.[113] To overcome this limitation, Plant Growth-Promoting Rhizobacteria (PGPR) have evolved unique strategies to bind and transport insoluble iron by producing low molecular weight siderophores in environments with limited iron availability.[114] Various genera of PGPR, including Aeromonas, Azadirachta, Azotobacter, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Rhizobium, Serratia, and Streptomyces, contribute to iron mobilization through siderophore synthesis, facilitating iron uptake by plant cells and promoting plant growth and development.[115-117]

Moreover, certain PGPR strains like Enterobacter, Pseudomonas, and Bacillus possess multifaceted properties beneficial for plant development and exhibit nematicidal activity. These bacteria not only stimulate cell division, physiological processes, and tissue development in plants but also provide additional support to host plants in dealing with nematode infections.[118] PGPR strains exert a direct influence on plant development by modulating various physiological and biochemical pathways, thereby enhancing plant vigor and resilience.[119] In addition to their direct effects on plant growth, PGPR play a crucial role in assisting host plants in combatting nematode infections, highlighting their multifunctional roles in promoting plant health and productivity.[120]

Potassium solublization

Potassium is a crucial macronutrient required for various biochemical and physiological processes essential for plant development.[121] However, most of the potassium in soil exists in forms that are not readily accessible to plants. Rhizospheric microorganisms, including some phosphate-solubilizing bacteria, play a vital role in making potassium more available to plants by solubilizing the insoluble forms and releasing them in a usable form. [122,123] To achieve potassium solubilization, Plant Growth-Promoting Rhizobacteria (PGPR) employ various mechanisms, including chelation, organic acid secretion, reduction, acidolysis, and ion exchange.[124]

A diverse range of microbial species, such as Bacillus edaphicus, Acidithiobacillus ferrooxidans, Burkholderia spp., B. mucilaginosus spp., Pseudomonas spp., and Paenibacillus spp., are known to be involved in potassium solubilization processes.[125-127] These bacteria possess the ability to transform insoluble potassium compounds into soluble forms that plants can readily absorb and utilize for their growth and development.[128-131] Furthermore, inoculating soil with potassium-solubilizing bacteria has been shown to have positive effects on tomato plant development and exhibit nematicidal activity, contributing to improved plant health and productivity.[132,133] Overall, the role of PGPR in potassium solubilization highlights their importance in enhancing soil fertility and promoting plant growth in agricultural ecosystems.[133]

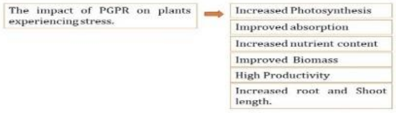

Figure 2. Effect of PGPR on Plant Growth

APPLICATIONS OF STRESS-TOLERANT PGPR IN SUSTAINABLE AGRICULTURE

Stress-tolerant Plant Growth-Promoting Rhizobacteria (PGPR) offer multifaceted applications in sustainable agriculture, addressing key challenges related to nutrient availability, soil contamination, and crop protection. In the realm of biofertilization, stress-tolerant PGPR plays a crucial role in enhancing nutrient uptake and utilization in stressed plants.[134] By colonizing the rhizosphere and promoting the solubilization of nutrients such as nitrogen, phosphorus, and potassium, PGPR improves soil fertility and enhances plant growth even under conditions of nutrient scarcity induced by abiotic stressors like drought and salinity.[135,136] Additionally, PGPR produces plant growth-promoting substances such as auxins, cytokinins, and gibberellins, which stimulate root growth and nutrient assimilation, further augmenting plant resilience to environmental stress.[137,138]

In the context of bioremediation, stress-tolerant PGPR offer a promising strategy for mitigating the deleterious effects of soil contamination on plant growth and productivity. Through processes such as rhizodegradation, bioaccumulation, and metal sequestration, PGPR facilitate the remediation of contaminated soils by detoxifying pollutants and enhancing soil health.[139,140] Furthermore, stress-tolerant PGPR can alleviate the phytotoxic effects of heavy metals and organic pollutants on plants, enabling them to thrive in environments previously considered unsuitable for cultivation.[141,142] In crop protection, stress-tolerant PGPR demonstrates the ability to induce systemic resistance against both abiotic stressors and pathogens.[143] By activating plant defense mechanisms and priming the immune system, PGPR confer enhanced resistance to drought, salinity, temperature extremes, and microbial pathogens, thereby reducing crop losses and improving yield stability.[144] Case studies and field trials have provided compelling evidence of the effectiveness of stress-tolerant PGPR in real-world agricultural settings, validating their potential as sustainable bioresources for enhancing crop resilience and productivity in the face of environmental challenges.[145]

CHALLENGES AND FUTURE DIRECTIONS

Challenges and future directions in the utilization of Plant Growth-Promoting Rhizobacteria (PGPR) in agriculture encompass a range of key considerations essential for maximizing their potential impact on sustainable farming practices. Scaling up PGPR-based interventions for large-scale agricultural systems presents a significant challenge due to the complexity of microbial interactions in diverse agroecosystems.[146] While laboratory and small-scale field trials have demonstrated the efficacy of PGPR in enhancing crop productivity and resilience to abiotic stresses, translating these findings into practical applications on a commercial scale requires careful optimization of formulation, delivery methods, and application protocols.[147] Moreover, ensuring the consistency and reliability of PGPR inoculants across different environmental conditions and crop species is essential for maximizing their efficacy and cost-effectiveness in diverse agricultural settings.[148] Addressing logistical and technological challenges associated with large-scale production and distribution of PGPR inoculants, as well as integrating them into existing agricultural practices, will be crucial for realizing the full potential of PGPR-based strategies in sustainable agriculture.[149,150]

Furthermore, advancing our understanding of the complex interactions between PGPR, plants, and abiotic stressors is essential for optimizing their use in mitigating environmental stresses and enhancing crop resilience.[151-154] Elucidating the molecular mechanisms underlying PGPR-mediated stress tolerance in plants, as well as the signaling pathways involved in plant-microbe interactions, will provide valuable insights into the factors driving the effectiveness of PGPR-based interventions[155-158] Integrating multi-omics approaches, including genomics, transcriptomics, proteomics, and metabolomics, offers a powerful tool for unraveling the intricacies of microbial-plant interactions and identifying key genetic determinants of stress tolerance in PGPR strains. Harnessing advances in omics technologies for targeted isolation and characterization of stress-tolerant PGPR will enable the development of tailored inoculants with enhanced efficacy and specificity for different environmental conditions and crop species.[159-162] Moreover, addressing policy implications and socio-economic considerations for promoting the adoption of PGPR-based strategies in agriculture, such as incentivizing sustainable farming practices, supporting research and development initiatives, and fostering collaboration between stakeholders, will be essential for realizing the potential of PGPR as a viable and environmentally friendly solution for enhancing agricultural productivity and resilience in a changing climate.[163].some PGPR species of Azospirillum also have nitrogen fixing abilities and stress tolerance effect .[164]. Plants with systemic induced resistance (SIR) are better able to fend off diseases caused by a wide range of pathogens. The efficacy of oxalic acid to induce SIR in tomato (Lycopersicon esculentum Mill.) against Fusarium oxysporum f.sp. lycopersici (Fol)-caused wilt was investigated using a susceptible cultivar in a climate chamber. [165].

CONCLUSION

In conclusion, the utilization of stress-tolerant Plant Growth-Promoting Rhizobacteria (PGPR) from abiotic stressed regions holds immense potential for revolutionizing sustainable agriculture. This review has emphasized the multifaceted benefits of PGPR in mitigating abiotic stressors such as drought, salinity, temperature extremes, and soil contamination, while simultaneously enhancing plant growth, nutrient uptake, and stress tolerance. By isolating and harnessing stress-tolerant PGPR strains from harsh environmental conditions, researchers can unlock innovative solutions to improve crop resilience, productivity, and environmental sustainability in the face of climate change.

Moving forward, addressing challenges, and exploring future directions in PGPR-based interventions will be critical for realizing their full potential in sustainable agriculture. Scaling up PGPR-based strategies for large-scale agricultural systems demands optimization of formulation, delivery methods, and application protocols, alongside ensuring consistency and reliability across diverse environmental conditions and crop species. Overcoming logistical and technological barriers associated with the production and distribution of PGPR inoculants, and integrating them into existing agricultural practices, will be pivotal for maximizing their efficacy and cost-effectiveness. Through interdisciplinary collaborations and concerted efforts, we can harness the power of stress-tolerant PGPR to transform agricultural systems, mitigate the adverse effects of climate change on crop productivity, and foster a more resilient and sustainable future for generations to come.

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