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A Brief Review on Plant Growth Promoting Rhizobacteria (PGPR): A Key Role in Plant Growth

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Abstract

Plant Growth Promoting Rhizobacteria (PGPR) are beneficial microorganisms that colonize the rhizosphere and contribute to plant growth and health through various mechanisms. This review article provides an overview of PGPR and their essential role in promoting plant growth. It explores the diverse mechanisms employed by PGPR, such as nutrient solubilization, production of phytohormones, and biological control of pathogens. The paper also highlights the impact of PGPR on enhancing plant tolerance to abiotic stresses, such as drought and salinity. Furthermore, the review delves into the interactions between PGPR and plants' root systems, focusing on the modulation of root architecture and nutrient uptake. The importance of understanding PGPR-plant interactions for sustainable agriculture and future prospects of harnessing PGPR for agricultural practices are discussed.

Keywords:PGPR, plant growth promotion, rhizosphere, biological nitrogen fixation, phytohormones, nutrient uptake, biofertilizers, sustainable agriculture.

1. Introduction

Plant Growth-Promoting Rhizobacteria (PGPR) are a group of beneficial soil bacteria that colonize the rhizosphere, the region of soil surrounding plant roots. These rhizobacteria interact positively with plants, promoting growth and development through various direct and indirect mechanisms. PGPR form symbiotic or associative relationships with plants, providing them with essential nutrients, hormones, and protection against pathogens, thereby enhancing plant health and productivity [1].Plant Growth Promoting Rhizobacteria (PGPR) are beneficial soil bacteria that colonize the root surface or the rhizosphere of plants and provide numerous benefits to the host plants. PGPR have been extensively studied for their ability to enhance plant growth and overall plant health through various mechanisms.PGPR can solubilize phosphates and fix atmospheric nitrogen, making these essential nutrients more available to plants. They produce organic acids and enzymes that help break down complex organic matter, releasing nutrients that can be absorbed by plants. PGPR can enhance nutrient uptake and utilization, leading to improved plant growth and productivity [2].PGPR can activate the plant's immune response and induce systemic resistance against various pathogens. They trigger the production of defense-related compounds, such as phytohormones and antimicrobial substances, providing the plant with enhanced protection against diseases [3].PGPR can directly antagonize pathogenic microbes by producing antibiotics, siderophores, and lytic enzymes that inhibit their growth. They outcompete pathogens for resources, suppress their colonization, and protect the plant from diseases [4].PGPR is able to produce phytohormones that control plant growth and development, including auxins, cytokinins, and gibberellins. These hormones may encourage root and shoot development, which boosts plant vigor and increases biomass [5].Drought, salt, and heavy metal toxicity are just a few of the abiotic conditions that PGPR may help plants better withstand. They control the acquisition of nutrients, the balance of water, and the production of genes that respond to stress, which aids plants in surviving in challenging environments [6].

The objectives of this review articleto provide a concise overview of the significance and key roles of Plant Growth Promoting Rhizobacteria (PGPR) in promoting plant growth and overall plant health.

2. Mechanisms of PGPR-Mediated Plant Growth Promotion

The mechanisms of Plant Growth Promoting Rhizobacteria (PGPR)-mediated plant growth promotion involve a variety of beneficial interactions between PGPR and plants in the rhizosphere, leading to enhanced plant growth and overall plant health. Some of the key mechanisms include:

2.1.Nutrient solubilization and mineralization for enhanced nutrient availability

Plant Growth Promoting Rhizobacteria (PGPR) play a crucial role in nutrient solubilization and mineralization, enhancing nutrient availability to plants in the rhizosphere. The process involves the secretion of various organic acids and enzymes by PGPR, which help in the solubilization and mineralization of nutrients, making them more accessible to plants. Below are the key mechanisms and some references to support the role of PGPR in nutrient solubilization and mineralization:

2.1.1. Phosphorus Solubilization

Phosphorus solubilization is the process by which phosphorus (P), an essential nutrient for plant growth and development, is converted from an insoluble form into a soluble form that can be taken up and utilized by plants. In most soils, phosphorus is found in the form of various phosphate compounds, such as calcium phosphate and iron phosphate, which are not readily available for plant uptake due to their low solubility. Several groups of microorganisms, particularly certain bacteria and fungi, are capable of solubilizing phosphorus in the soil through different mechanisms. These microorganisms play a crucial role in enhancing phosphorus availability to plants and promoting overall plant health. [7].Phosphorus solubilization is particularly important in phosphorus-deficient soils, as it can significantly improve plant growth, crop yield, and overall agricultural productivity. Therefore, sustainable agricultural practices often focus on promoting the growth of beneficial microorganisms that can enhance phosphorus solubilization in the soil, reducing the need for synthetic phosphorus fertilizers and minimizing the risk of phosphorus runoff into water bodies, which can cause environmental issues like eutrophication.

2.1.2. Nitrogen Mineralization

Nitrogen mineralization is a biological process in which organic nitrogen present in organic matter, such as plant residues and organic debris, is converted into inorganic forms, predominantly ammonium (NH_4^+) and nitrate (NO_3^-). This conversion is carried out by various microorganisms, primarily bacteria and fungi, through the processes of ammonification and nitrification. During ammonification step, decomposers like bacteria and fungi break down complex organic nitrogen compounds, such as proteins and amino acids, into simpler forms like ammonia (NH_3) and ammonium (NH_4^+). In the nitrification process, different groups of bacteria convert the ammonium produced during ammonification into nitrite (NO_2^-) and then further into nitrate (NO_3^-). This step is essential because nitrate is the primary form of nitrogen taken up by plants [5].It's worth noting that not all PGPR possess all these capabilities, and their effectiveness in enhancing nitrogen availability can vary based on environmental conditions and the specific interactions between the bacteria and plants. Nonetheless, the presence and activities of nitrogen-fixing and nitrogen-mineralizing PGPR are essential components of sustainable agriculture and ecological balance. They can reduce the need for synthetic nitrogen fertilizers, which have adverse environmental impacts when overused and are also costly for farmers. By promoting the growth and activities of these beneficial bacteria, sustainable agriculture practices aim to optimize nitrogen utilization and minimize environmental consequences.

2.1.3. Iron and Other Micronutrient Solubilization

Plant Growth-Promoting Rhizobacteria (PGPR) are beneficial bacteria that reside in the rhizosphere, the soil region surrounding plant roots. These bacteria play a vital role in promoting plant growth and health by facilitating nutrient uptake and enhancing nutrient availability in the soil. One essential micronutrient for plants is iron, which is crucial for various biochemical processes, including chlorophyll formation and electron transport in photosynthesis. However, in alkaline soils, iron often becomes less available to plants due to its tendency to form insoluble compounds that are not easily taken up by roots. This can lead to iron deficiency and subsequent plant health issues. PGPR can address this problem by secreting siderophores, which are small organic molecules with high affinity for iron and other micronutrients, such as zinc, copper, and manganese. Siderophores act as chelators, binding to iron and other micronutrient cations, forming stable complexes that can be taken up more effectively by plant roots. By chelating iron, PGPR effectively increase its bioavailability to plants, overcoming the limitations imposed by alkaline soils and iron's tendency to precipitate into unavailable forms. Furthermore, PGPR can produce organic acids as part of their metabolic processes. These organic acids, such as citric acid, gluconic acid, and oxalic acid, have the capacity to promote the solubilization of various micronutrients in the soil, including zinc, copper, and manganese. Organic acids are capable of breaking down the chemical bonds between these micronutrients and soil particles, making them more soluble and, therefore, more accessible for plant uptake. By enhancing the solubilization of these micronutrients, PGPR contribute to improved plant nutrition and overall plant health. The ability of PGPR to secrete siderophores and organic acids is a remarkable adaptation that allows these bacteria to thrive in the rhizosphere and form mutually beneficial relationships with plants. The enhanced availability of iron and other micronutrients contributes to better nutrient uptake by plants, leading to improved growth, increased resistance to stress, and ultimately, more sustainable and productive agricultural systems. By reducing the need for synthetic micronutrient fertilizers, PGPR-based strategies also promote environmentally friendly and economically viable agricultural practices [8].

These mechanisms demonstrate the critical role of PGPR in enhancing nutrient availability for plant growth and development. By promoting nutrient solubilization and mineralization, PGPR contribute to improved nutrient uptake, higher crop yields, and sustainable agriculture practices.

2.2.Production of phytohormones: auxins, cytokinins, and gibberellins

Plant Growth Promoting Rhizobacteria (PGPR) are known to produce various phytohormones, including auxins, cytokinins, and gibberellins, which play essential roles in regulating plant growth and development. Here's a brief overview of how PGPR produce these phytohormones:

2.2.1. Auxins

Auxins are a group of plant hormones that promote cell elongation, root development, and tropic responses, such as phototropism and gravitropism. Some PGPR can produce auxins, particularly indole-3-acetic acid (IAA), which is the most common and biologically active auxin in plants.

PGPR can synthesize IAA through various pathways, including the indole-3-acetamide (IAM) pathway and the indole-3-pyruvic acid (IPyA) pathway. PGPR-produced auxins can influence plant growth by stimulating root elongation, enhancing lateral root formation, and promoting overall plant vigor [9].

2.2.2. Cytokinins:

Cytokinins are plant hormones that regulate cell division, shoot development, and leaf senescence. Some PGPR can produce cytokinins, such as isopentenyladenine (iP) and trans-zeatin (tZ), by synthesizing precursors like isopentenyldiphosphate (IPP) and dimethylallyldiphosphate (DMAPP). PGPR-produced cytokinins can positively impact plant growth by promoting shoot proliferation, delaying leaf senescence, and enhancing stress tolerance [5].

2.2.3. Gibberellins:

Gibberellins (GAs) are plant hormones that regulate various developmental processes, including stem elongation, seed germination, and flowering. While fewer PGPR are known to directly produce gibberellins, some can indirectly promote GA synthesis in plants by enhancing the expression and activity of key enzymes involved in GA biosynthesis, such as ent-kaurene synthase (KS) and ent-kaurene oxidase (KO).PGPR-mediated induction of gibberellin biosynthesis can lead to improved plant growth, particularly in terms of stem elongation and fruit development [10].

2.3.Suppression of plant pathogens through antibiosis and competition

Plant Growth Promoting Rhizobacteria (PGPR) can suppress plant pathogens through two primary mechanisms: antibiosis and competition. These mechanisms involve the production of antimicrobial compounds by PGPR and the competitive exclusion of pathogens, respectively. Let's explore each mechanism in detail:

2.3.1. Antibiosis:

Antibiosis refers to the process in which PGPR produce antimicrobial substances that inhibit the growth and development of plant pathogens. These antimicrobial compounds can directly kill or inhibit the growth of pathogens, providing a form of biological control against disease-causing microorganisms. PGPR employ various antimicrobial compounds, including antibiotics, enzymes, and secondary metabolites, to combat pathogens in the rhizosphere and on plant surfaces. Examples of antimicrobial substances produced by PGPR include; Antibiotics: PGPR can produce antibiotics that are effective against a wide range of pathogens. These antibiotics can interfere with the pathogen's cellular processes, leading to its suppression. Lysozymes and Chitinases; PGPR can secrete lysozymes and chitinases, which are enzymes that target the cell walls of certain pathogens. By breaking down the cell walls, these enzymes can disrupt the integrity of the pathogen's cells. Siderophores; PGPR can produce siderophores, which are small molecules that chelate iron and sequester it away from pathogens. This limits the availability of iron, an essential nutrient for many pathogens, thereby suppressing their growth [4].

2.3.2. Competition:

PGPR can competitively exclude plant pathogens from colonizing the rhizosphere or plant surfaces by outcompeting them for resources. PGPR establish a beneficial relationship with plants, occupying the root zone and preventing the establishment and proliferation of pathogenic microorganisms. Competition by PGPR can occur through the following mechanisms; Nutrient Competition: PGPR efficiently utilize nutrients present in the rhizosphere, leaving fewer resources available for pathogens, which struggle to survive under nutrient-limited conditions. Space Competition; by colonizing the root surfaces and establishing a dense biofilm, PGPR can physically prevent pathogens from attaching and colonizing the same sites. Root Exudates; PGPR can release root exudates that create an environment unfavorable for pathogenic microorganisms, inhibiting their growth and establishment. Induced Systemic Resistance (ISR); as mentioned in a previous response, PGPR can induce systemic resistance in plants, priming the plant's immune system to respond more effectively to pathogen attacks. The combination of antibiosis and competition by PGPR can lead to the suppression of plant pathogens, promoting healthier plants and reducing disease incidence in crops [9].

3. PGPR-Mediated Abiotic Stress Tolerance in Plants

Plant Growth Promoting Rhizobacteria (PGPR) play a significant role in enhancing abiotic stress tolerance in plants. Abiotic stresses, such as drought, salinity, temperature extremes, and heavy metal toxicity, can negatively impact plant growth and productivity. PGPR can mitigate the adverse effects of these stresses through various mechanisms, improving plant survival and performance under challenging environmental conditions.Here are some key ways PGPR mediate abiotic stress tolerance in plants:

3.1.Enhanced Nutrient and Water Uptake

Rhizobacteria that promote plant growth (PGPR) are essential for improving plant nutrient and water absorption. Rhizobacteria-plant connections that they forge with plant roots are advantageous because they improve the plant's capacity to absorb vital nutrients and water. The following are some significant ways that PGPR improve nutrient and water uptake:

As previously indicated, PGPR may create organic acids that encourage the solubilization of important nutrients from the soil, including phosphorus, zinc, copper, and manganese. By dissolving the chemical bonds that hold these nutrients to soil particles, the organic acids produced by PGPR make them easier for plant roots to absorb. By ensuring that plants have access to a wider variety of important components, this improved nutrient solubilization encourages healthier development and better harvests.In addition to solubilizing nutrients, PGPR also has the ability to mobilize nutrients in the rhizosphere. The PGPR may release and change complicated organic forms of nutrients into simpler, plant-available ones by generating enzymes like phosphatases. For example, they may convert organic phosphorus molecules into inorganic phosphates, which plants can absorb more readily. Some PGPR are able to convert ambient nitrogen gas into ammonium, a plant-absorbable form of nitrogen. These bacteria's ability to fix nitrogen gives plants an extra supply of nitrogen, lessening their reliance on artificial nitrogen fertilizers. This not only improves nutrient intake but also supports sustainable agriculture practices by reducing nitrogen pollution in the environment. PGPR is capable of synthesising plant growth hormones such auxins, cytokinins, and gibberellins. These hormones control the development of the roots and the intake of nutrients, among other elements of plant growth and development. PGPR may increase root surface area by promoting root development and architecture, which in turn enhances the plant's capacity to explore a wider soil volume for nutrients and water. By encouraging root elongation and branching, PGPR may improve water absorption. In order to create a root system with many branches, which increases the surface area for water absorption, PGPR produces plant growth hormones. In addition, certain PGPR create exopolysaccharides, which form biofilms around the root surface and aid in water retention and water stress defense. Plants that have PGPR can better withstand abiotic conditions like salt and drought. PGPR helps plants adapt to difficult environmental circumstances, guaranteeing greater growth and survival under stress. It does this by improving nutrient and water intake as well as creating stress-tolerant chemicals like osmoprotectants [11].

3.2.Osmolyte Accumulation

PGPR (Plant Growth-Promoting Rhizobacteria) can indeed play a crucial role in inducing the synthesis of compatible solutes or osmolytes in plants, especially under drought stress conditions. Compatible solutes, also known as osmoprotectants or osmolytes, are small organic molecules that accumulate in plant cells in response to environmental stresses, such as drought, salinity, or extreme temperatures. They help maintain cellular osmotic balance, protect cellular structures, and prevent water loss, ultimately improving plant tolerance to drought stress. Two important osmolytes induced by PGPR in plants under drought stress are: Proline;Proline is a common osmolyte that accumulates in plant cells under various stress conditions, including drought. PGPR can stimulate the synthesis of proline in plants by increasing the activity of enzymes involved in proline biosynthesis. Proline acts as an osmoprotectant by helping to stabilize cellular structures, protect proteins and enzymes from denaturation, and scavenge reactive oxygen species (ROS) that are produced under stress conditions. These functions contribute to maintaining cellular integrity and reducing cellular damage caused by dehydration. Glycine Betaine; Glycine betaine is another important osmolyte that helps plants cope with drought stress. PGPR can induce the synthesis of glycine betaine in plants, and this osmolyte plays a key role in protecting plant cells from dehydration and osmotic stress. Glycine betaine helps maintain cellular turgor pressure, stabilize cell membranes, and protect proteins and enzymes from denaturation. It also acts as a compatible solute by balancing cellular osmotic potential, which is critical for preventing water loss from the cells and maintaining proper cellular functioning under drought conditions.By promoting the synthesis of these osmolytes, PGPR enhance the drought tolerance of plants, enabling them to survive and continue essential physiological processes even under limited water availability. PGPR achieve this through a combination of mechanisms, including the activation of stress-responsive signaling pathways, enhanced nutrient uptake, and improved water use efficiency. Utilizing PGPR as bioinoculants or biofertilizers in agriculture can be a valuable approach to enhance plant resilience to drought stress, reduce the reliance on synthetic chemical inputs, and foster sustainable crop production in regions with water limitations [12].

3.3.Production of Antioxidants

By encouraging the development and activation of antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and peroxidases, PGPR play a critical role in reducing the damaging effects of ROS:

Superoxide dismutase (SOD) is a vital antioxidant enzyme that facilitates the conversion of superoxide radicals (O_2^-) into hydrogen peroxide (H_2O_2) and molecule oxygen (O_2). This procedure guards against the development of very harmful hydroxyl radicals (OH) and shields cells from superoxide radical-induced oxidative damage. Another essential antioxidant enzyme, catalase (CAT), converts hydrogen peroxide (H_2O_2) into water (H_2O) and oxygen (O_2). Catalase suppresses the production of hydroxyl radicals and shields plant cells from oxidative stress by lowering the amounts of hydrogen peroxide. A class of enzymes called peroxidases may also neutralize peroxides like hydrogen peroxide (H_2O_2) and other peroxides by utilising the reducing equivalents offered by certain substrates. Under stressful circumstances, these enzymes are essential for preserving cellular redox equilibrium and avoiding oxidative damage. By using a number of different pathways, PGPR may stimulate the synthesis and activity of several antioxidant enzymes, including. PGPR may activate stress-responsive signaling pathways in plants, which causes the overexpression of genes encoding antioxidant enzymes.PGPR may increase the availability of nutrients to plants, including necessary minerals like copper, zinc, and manganese, which are cofactors for antioxidant enzymes. Regulation of Plant Hormones: PGPR may affect the synthesis and communication of plant hormones including ABA and JA, which are involved in the activation of antioxidant defense systems. Plants are better able to withstand drought stress because to PGPR's ability to increase the activity of these antioxidant enzymes, maintain redox equilibrium, scavenge ROS, and shield cellular structures from oxidative damage. A potential approach for sustainable agriculture, especially in areas with water shortage or proneness to drought, is the interaction between PGPR and plants [13].

3.4.ABA Regulation

By controlling the synthesis and signaling of abscisic acid (ABA), a vital stress-responsive plant hormone, PGPR (Plant Growth-Promoting Rhizobacteria) may improve plant water usage efficiency and drought tolerance. The modulation of stomatal closure, which directly impacts a plant's capacity to store water during drought stress, is a key function of ABA. Plants increase the synthesis and accumulation of ABA in response to water deficiency circumstances. Increased ABA levels set off a series of physiological reactions intended to reduce transpirational water loss and save water within the plant. Stomata, tiny pores on the leaf surface in charge of gas exchange, including water vapor loss, close as one of the principal reactions. PGPR may affect the expression and activity of genes essential for ABA biosynthesis. In response to environmental signals like water availability, PGPR may adjust ABA production by encouraging or inhibiting the synthesis of ABA precursors and enzymes. Plants PGPRs have the ability to activate stress signaling pathways, which in turn activates genes involved in ABA production and signaling. In response to drought stress, this activation may boost ABA production, encouraging stomatal closure and water saving. Auxins, cytokinins, and gibberellins are a few examples of additional plant hormones that may interact with PGPR and affect ABA production and signaling. To maintain water homeostasis, PGPR can adjust ABA levels and reactions via these interactions. PGPR may increase the availability of nutrients to plants, including crucial components needed for ABA production, which may have an indirect impact on the amount of ABA in the plant. Under drought stress, PGPR helps plants quickly seal their stomata, reducing water loss via transpiration. With the help of this water-saving technique, plants may utilize water more effectively while still preserving water for vital physiological functions within the plant. Enhancing water usage efficiency not only makes it easier for plants to withstand drought stress, but it also results in more sustainably managed water use in agricultural contexts. PGPR-based techniques provide beneficial solutions for farming in water-scarce locations and contribute to more resilient and environmentally friendly agricultural practices by lowering the requirement for irrigation and preserving water resources [14].

PGPR-mediated improvement of drought resistance in plants is a promising strategy for sustainable agriculture, especially in regions facing water scarcity and climate change challenges. The multifaceted effects of PGPR in mitigating drought stress highlight their potential as eco-friendly and cost-effective tools for enhancing crop productivity and resilience.

4. Root System Modulation and Nutrient Uptake

Plant Growth Promoting Rhizobacteria (PGPR) play a significant role in root system modulation and nutrient uptake in plants. Through various mechanisms, PGPR enhance the root system architecture, increase root surface area, and improve nutrient uptake efficiency.

4.1.Impact of PGPR on root architecture and lateral root formation

PGPR (Plant Growth-Promoting Rhizobacteria) have a significant impact on root architecture and lateral root formation in plants. They can influence root growth and development, leading to changes in root morphology and branching patterns. The interactions between PGPR and plants result in enhanced root system development, which plays a crucial role in nutrient uptake, water acquisition, and overall plant growth and health.According to many research, PGPR has the ability to encourage root elongation and boost root length and density. Different studies revealed that inoculating wheat plants with certain PGPR strains dramatically boosted root length and density. This expanded root system enables plants to explore more soil, which results in better nutrient and water intake [15].PGPR can also stimulate lateral root formation, increasing the number of lateral roots in plants. These lateral roots play a crucial role in nutrient acquisition by exploring a larger soil volume and increasing the surface area available for nutrient uptake. In a study by Bano et al. (2019), it was observed that certain PGPR strains significantly enhanced lateral root formation in tomato plants [16].

4.2.Facilitation of nutrient uptake and assimilation by PGPR

Plant Growth Promoting Rhizobacteria (PGPR) facilitate nutrient uptake and assimilation in plants through various mechanisms that enhance nutrient availability, solubilization, and utilization. These beneficial interactions between PGPR and plants lead to improved nutrient acquisition and utilization efficiency, contributing to enhanced plant growth and overall health.

PGPR have the capacity to solubilize minerals found in soil, including phosphorus and micronutrients. They release chelating substances and organic acids that change nutrients from insoluble to soluble forms, making them more available to plants. By increasing the availability of nutrients in the rhizosphere, this improved nutrient solubilization encourages nutrient absorption by plant roots. Some PGPR have the ability to fix atmospheric nitrogen by using nitrogenase enzymes to transform atmospheric nitrogen (N_2) into ammonia (NH_3). Plants may use the ammonium ions produced as a source of nitrogen as a result of this process. By fixing nitrogen, PGPR increases the availability of nitrogen in nitrogen-deficient soils and supplements the plant's requirement for nitrogen. Auxins, cytokinins, and gibberellins are a few examples of the plant growth-promoting hormones that PGPR may produce and release. These hormones are essential for controlling several aspects of plant development, such as root development, the creation of lateral roots, and nutrient intake. By encouraging the synthesis of hormones, PGPR stimulates the growth of the root system, increasing nutrient absorption. Inducing systemic resistance in plants allows PGPR to prime their immune systems to react more quickly to pathogen invasions and nutritional deficiency. Producing defense-related substances, such as pathogenesis-related (PR) proteins and secondary metabolites, which improve nutrition absorption and assimilation under stress, is a part of this process. PGPR enhances the photosynthetic activity and metabolic processes in plants through enhancing nutrient availability and hormonal control. Greater energy output from photosynthesis allows for greater root development and nutrient absorption [13].

5. Interaction of PGPR with Plant Defense Mechanisms

Plant Growth Promoting Rhizobacteria (PGPR) interact with plant defense mechanisms in multiple ways, leading to enhanced plant resistance against pathogens and pests. These interactions involve the activation of plant defense responses, the priming of the plant's immune system, and the production of antimicrobial compounds.

5.1.Induced Systemic Resistance (ISR)

PGPR (Plant Growth-Promoting Rhizobacteria) can induce systemic resistance in plants, a phenomenon where the plant's immune system is primed to respond more effectively and promptly to potential pathogen attacks. This process is known as induced systemic resistance (ISR) or systemic acquired resistance (SAR). PGPR-triggered ISR is a crucial part of the plant's defense strategy, as it enhances the plant's ability to ward off pathogenic attacks. PGPR can activate specific defense signaling pathways in plants. This activation involves the recognition of certain molecules produced by the bacteria, which act as elicitors. These elicitors can be surface molecules of PGPR, such as lipopolysaccharides (LPS), or secreted metabolites. The recognition of these elicitors by the plant triggers defense signaling cascades, leading to the expression of defense-related genes. Once the defense signaling pathways are activated, plants start producing defense-related compounds, such as pathogenesis-related (PR) proteins, phytoalexins, and reactive oxygen species (ROS). PR proteins play a significant role in protecting the plant from pathogens by inhibiting their growth or directly attacking them. Phytoalexins are antimicrobial compounds synthesized in response to pathogen attack, providing protection against a wide range of pathogens. ROS, on the other hand, are highly reactive molecules that can directly damage pathogens and regulate defense responses. Interestingly, the defense signals triggered by PGPR in one part of the plant can move systemically to other parts of the plant, priming those areas for enhanced defense responses. This systemic movement of defense signals allows the entire plant to be prepared to respond more effectively to potential pathogen attacks, even in distant tissues. By inducing systemic resistance, PGPR contribute to the overall health and protection of the plant against various pathogens. The priming of the plant's immune system enables it to mount a rapid and robust defense response upon encountering pathogens, reducing the risk of disease development and minimizing the damage caused by infections. Utilizing PGPR to induce systemic resistance is an essential component of sustainable agriculture practices, as it can reduce the dependence on chemical pesticides and foster a more eco-friendly approach to pest management. The ability of PGPR to enhance the plant's defense mechanisms represents a promising strategy for promoting plant health and increasing crop productivity while minimizing the environmental impacts associated with traditional pest control methods [14].

5.2.Competition with Pathogens

Plant growth-promoting rhizobacteria, often known as PGPR, are able to successfully compete with pathogenic microbes in the rhizosphere, the area of soil close to plant roots. The rhizosphere is an active, fiercely competitive environment, and PGPR have developed a number of strategies to outcompete pathogens for nutrients and space. As a result, PGPR play a critical role in restricting pathogen establishment and proliferation in the root zone, thereby lowering the prevalence of plant diseases.PGPR can effectively scavenge and use resources in the rhizosphere, such as mineral nutrients and carbon sources. PGPR deprive pathogens of vital resources necessary for their development and multiplication by quickly devouring the available nutrients. Pathogens find it challenging to establish them in the root zone as a result of this nutritional competition. Some PGPR create substances that prevent the development of harmful microbes, such as antibiotics and antifungal drugs. These antimicrobial compounds are dispersed into the rhizosphere, where they make the environment unfriendly for pathogens and lower their population. PGPR may create biofilms on the surfaces of the roots, which act as physical barriers that protect the roots from infections. As barriers, the biofilms stop harmful germs from coming into direct touch with and infecting the root tissues. As noted in the preceding answer, PGPR may generate systemic resistance in plants, improving their capacity to fight off infections. By preparing the plant's immune system, PGPR helps the plant react to pathogen assaults more successfully, reducing the severity and spread of illnesses. PGPR effectively colonize the root surface and inhabit the microenvironments that are rich in root exudate. Because of this occupancy, harmful microbes have less room and resources to grow, which makes it difficult for them to take hold in these fiercely competitive niches. The PGPR's combination of these antagonistic processes reduces the number and activity of harmful bacteria in the rhizosphere. In turn, this suppresses plant diseases and enhances the plant's general health. A sustainable and ecologically friendly method of managing illness in agriculture is to use PGPR as biocontrol agents. Farmers may use less chemical fungicides and pesticides by encouraging the establishment of advantageous rhizobacteria, creating healthier and more durable agricultural systems. Furthermore, enhanced soil health and ecosystem balance are a result of the PGPR's pathogen control, further promoting sustainable farming methods [9].

5.3.Antibiosis and Antimicrobial Production

Some PGPR (Plant Growth-Promoting Rhizobacteria) are remarkably capable of producing a variety of antibacterial chemicals that aid in shielding plants against pathogens. These antimicrobial compounds act as organic weapons used by PGPR to prevent pathogen growth and development in the soil and rhizosphere. Antibiotics are chemicals that have the power to either kill or limit the development of certain microbes. PGPR has the ability to produce and release antibiotics. These antibiotics aim for the pathogens' cell walls, membranes, or cellular processes, interfering with their regular operations and leading to their mortality. A potent defensive mechanism that aids in controlling the spread of dangerous microbes in the root zone is the synthesis of antibiotics by PGPR. Some PGPR release lytic enzymes, sometimes referred to as hydrolytic enzymes, which disassemble the structural elements of pathogens. These enzymes may break down the target microorganisms' cell walls, proteins, and other macromolecules, resulting in their lysis and demise. The direct assault and destruction of harmful cells by lytic enzymes is successful. PGPR is capable of producing a wide range of secondary metabolites compounds that are not directly engaged in basic cellular functions but are crucial in ecological interactions. Some of these secondary metabolites have antimicrobial properties and can interfere with the growth and development of pathogens. For instance, certain secondary metabolites generated by PGPR may interfere with pathogen communication and virulence factors by causing disruptions in their quorum sensing mechanisms. These antimicrobial substances are delivered into the rhizosphere, where they deter harmful microbes from growing. By preventing pathogens from growing and developing, PGPR protect plants against illnesses, enhancing plant health and boosting overall agricultural production. It's crucial to remember that the antibacterial action of PGPR often only affects certain pathogens and has no negative effects on helpful microbes or the host plant. This particularity is critical for maintaining a stable and healthy microbial population in the rhizosphere, which is necessary for long-term plant development. In contemporary agriculture, using PGPR as biocontrol agents holds promise since it provides a safer, more environmentally friendly alternative to chemical pesticides and fungicides. Farmers may lessen their dependence on synthetic pesticides and advance a more sustainable and resilient agricultural system by using the natural antibacterial properties of PGPR [17].

5.4.Detoxification of Pathogen-Produced Toxins

The detoxification of pathogen-produced toxins by some PGPR (Plant Growth-Promoting Rhizobacteria) offers plants an additional line of defense against their harmful effects. Different toxins that pathogens can produce can harm plant cells directly and aid in the growth of plant diseases. By destroying or securing these toxins, PGPR shield plant cells from harm and help to lessen the damaging effects of pathogenic infections on plant health. Some PGPR have enzymatic machinery that can degrade particular pathogen-produced toxins. These detoxifying enzymes break down the hazardous substances into non-toxic forms, making them safe to plant cells. This procedure preserves the structural integrity and functional efficiency of plant tissues while counteracting the negative effects of the toxins. PGPR has the ability to sequester toxins, preventing them from harming plant cells. This sequestration can occur within the bacterial cells or in the rhizosphere, where PGPR can bind and immobilize toxins, keeping them away from the plant's sensitive tissues. Some PGPR can compete with pathogens for the precursors required for toxin production. By ingesting or using these precursors, PGPR reduce the resources available for pathogens to produce toxins. This rivalry prevents the pathogen from producing and releasing harmful substances. As discussed before, PGPR may produce systemic resistance in plants, including tolerance to toxins. By priming the plant's defense responses, PGPR can prepare the plant to better withstand the harmful effects of toxins and reduce the extent of damage caused by pathogenic infections. The multifaceted interactions between PGPR and plants include their detoxification abilities, which support plant health in general and disease defense. By countering the negative effects of toxins, PGPR help plants maintain their physiological functions and productivity, even under pathogen attack. One aspect of PGPR's advantageous function in fostering plant health and disease resistance is their capacity to detoxify toxins. The use of PGPR-based approaches in agricultural practices can provide long-term disease management solutions and lessen the reliance on toxic chemicals and fungicides that might have negative environmental effects [18].

5.5.Promotion of Systemic Signaling

Plants may engage certain signaling pathways that trigger systemic defenses against pathogens when PGPR (Plant Growth-Promoting Rhizobacteria) are present. The term "induced systemic resistance" (ISR) or "systemic acquired resistance" (SAR) refers to this process. When PGPR engage with plant roots, they set off a sequence of chemical signals that stimulate the plant's immune system, allowing it to react to pathogen attacks more quickly and effectively. A key component of the plant's defensive strategy, systemic signaling offers a strong and enduring fight against pathogens. The immunological receptors in the plant are able to detect the elicitors produced by PGPR, which are particular chemicals that are known as elicitors in microbes. These elicitors may be bacterial surface substances like lipopolysaccharides (LPS) or secreted metabolites. These elicitors' detection sets off communication cascades in plant cells, which activate genes involved in defense. The detection of microbial elicitors by plant receptors sets off a series of intracellular signaling processes, including the activation of mitogen-activated protein kinases (MAPKs) and other significant signaling molecules. These signaling processes cause the overexpression of genes involved in defense, including as those that code for proteins, enzymes, and antimicrobial substances associated to pathogenesis (PR). By activating these defense signaling pathways, the plant's immune system is prepared to respond in defense. The plant is "primed" to react to future pathogen assaults more quickly and effectively. In order to better prepare the plant to protect itself against future infections, priming entails the buildup of defense-related chemicals and the creation of a memory-like response. The systemic mobility of defense signals throughout the plant is one outstanding aspect of PGPR-induced systemic resistance. The defensive signals activated at the PGPR-plant interaction point may travel to distant regions of the plant, such as leaves and shoots. This systemic movement provides a broad-spectrum reaction to prospective pathogen assaults and enables the whole plant to be ready for defense.Even in locations where the plant is not in direct touch with the bacterium, PGPR improve the plant's capacity to react quickly and effectively to pathogen assaults. The plant can establish a strong and enduring defense, limiting the spread and severity of illnesses, thanks to the priming of its immune system and the systemic circulation of defensive signals. Sustainable agricultural techniques must include the induction of systemic resistance through PGPR. It supports a more environmentally friendly approach to pest control, lessens the dependency on chemical pesticides and fungicides, and increases the health and resilience of plants in diverse agricultural settings [19].

These interactions between PGPR and plant defense mechanisms contribute to improved disease resistance and overall plant health, making PGPR a valuable tool for sustainable agriculture and disease management.

6. Applications of PGPR in Sustainable Agriculture

Plant Growth Promoting Rhizobacteria (PGPR) have various applications in sustainable agriculture, offering environmentally friendly and economically viable solutions to enhance crop productivity, reduce chemical inputs, and improve soil health.

6.1.Use of PGPR as biofertilizers and biopesticides

6.1.1. Use of PGPR as Biofertilizers:

The PGPR (Plant development-Promoting Rhizobacteria) genus Azospirillum is widely recognized and has been the subject of substantial research. It offers major advantages for plant development and nutrient uptake. These microorganisms are well recognized for their capacity to stimulate plant development through a number of methods, including biological nitrogen fixation and phytohormone synthesis. The capacity of Azospirillum to fix atmospheric nitrogen gas (N_2) into a form that is accessible to biological systems is one of the organism's most significant contributions to plant development. Azospirillum bacteria collaborate with plants in the root zone to develop an associative symbiosis in which they invade the root surface or the intercellular spaces of the root cortex. Azospirillum has access to carbon sources generated from plants via this connection, while also giving the plant fixed nitrogen in the form of ammonia (NH3). The host plant may easily utilise the ammonia that Azospirillum produces as a source of nitrogen, minimizing the need for artificial nitrogen fertilizers. Azospirillum bacteria have the ability to synthesize and secrete a variety of phytohormones that encourage plant development, including auxins, cytokinins, and gibberellins. These phytohormones are crucial in controlling the proliferation of roots and shoots, the creation of lateral roots, and nutrient absorption in plants. Azospirillum may promote root development and boost nutrient uptake by plants by creating these phytohormones, which improves plant growth and productivity in general. Azospirillum bacteria also aid plants in absorbing other vital nutrients. These bacteria increase the root surface area and the activity of nutrient transporters via their growth-promoting actions on roots, which improves the absorption of minerals like phosphorus, potassium, and micronutrients. This improved nutrient absorption also aids in the general development and well-being of plants. Azospirillum contributes to biological nitrogen fixation and the production of phytohormones, which improve plant nutritional status, notably nitrogen availability. Plants may therefore grow more effectively, produce more, and be more resilient to environmental challenges. Additionally, the presence of Azospirillum encourages more ecologically friendly and sustainable farming methods by reducing the need for synthetic nitrogen fertilizers. The production of cereals, legumes, and other economically significant crops has seen the most widespread usage of azospirillum as a biofertilizer in a variety of agricultural settings. It is an important tool for environmentally friendly and sustainable agriculture since it may increase the availability of nitrogen and encourage plant development, which is advantageous for farmers and the environment [20].

Due to their extraordinary capacity to solubilize phosphates and fix atmospheric nitrogen, Bacillus species are often utilized as biofertilizers in agriculture. These helpful bacteria are important components of sustainable agricultural methods because of their major influence on plant development, nutrient availability, and soil health. Bacillus species are well recognized for their ability to produce organic acids and enzymes that can solubilize insoluble phosphates in soil. Bacillus bacteria break down the complicated forms of phosphorus by releasing these acids and enzymes, making it more palatable and accessible to plants. Because phosphorus is a crucial nutrient for many physiological processes in plants, increased phosphorus availability benefits root growth, blooming, and overall plant growth. Nitrogenase enzymes in certain Bacillus species may convert ambient nitrogen gas (N2) into ammonia (NH3). This mechanism is comparable to nitrogen fixation by rhizobia, the bacteria that grow on legume nodules. Bacillus bacteria offer an additional nitrogen supply to plants, decreasing their reliance on synthetic nitrogen fertilizers, by turning air nitrogen into a useable form. This helps agricultural systems control nitrogen in a sustainable way while also being beneficial to the plants. Bacillus species use a variety of ways to encourage plant development. These bacteria also solubilize phosphates and fix nitrogen, producing auxins, gibberellins, and cytokinins, which aid in plant development. These phytohormones have an impact on plant growth and development by boosting lateral root formation, improving nutrient absorption, and stimulating root and shoot growth. Increased plant vigor and higher crop yields are the results of the interaction of these factors. In addition to phosphate solubilization, Bacillus species may also mobilize other nutrients, such iron, potassium, and zinc, increasing their availability to plants. As a result of this enhanced nutrient absorption, plants are healthier overall and more resistant to environmental challenges. Soil-Borne Pathogen Suppression: Bacillus species have negative impacts on soil-borne pathogens. They create substances that prevent the growth and development of harmful germs, such as antibiotics and lytic enzymes. Bacillus bacteria work to protect plants from numerous illnesses by lowering the number of soil-borne pathogens, which results in healthier crops and higher yields. Bacillus species have gained widespread usage in agriculture as biofertilizers and biocontrol agents due to their many advantageous effects. By increasing the availability of nutrients, lowering the demand for artificial fertilizers, and offering organic defense against soil-borne diseases, they support sustainable agriculture methods. Using biofertilizers based on bacteria promotes ecologically and financially sound farming practices while enhancing soil health and long-term agricultural output [9].

Rhizobium's extraordinary capacity to establish symbiotic relationships with legume roots and fix atmospheric nitrogen makes it a popular choice for biofertilizer in legume crops. Rhizobium is a crucial nitrogen-fixing partner for leguminous plants because of its exceptional capacity to transform atmospheric nitrogen gas (N_2) into ammonia (NH_3), a form that is physiologically accessible. Rhizobium has a mutualistic relationship with the roots of leguminous plants. The roots develop specialized structures known as nodules as a consequence of this relationship. Rhizobium bacteria thrive and proliferate within these nodules, and the plant offers the bacteria a friendly habitat and carbon sources (sugars). Rhizobium bacteria in the nodules express a nitrogenase enzyme complex, allowing it to fix atmospheric nitrogen gas. The nitrogenase enzyme catalyzes the biological nitrogen fixation process, which transforms N2 into ammonia (NH3). The nodules subsequently convert ammonia into ammonium ions (NH4+), which the plant may easily absorb as a source of nitrogen. Rhizobium produces ammonia and ammonium ions in the nodules, which are transferred to the plant tissues and serve as a key source of nitrogen. The availability of nitrogen helps the plant grow, develop, and produce more.

Leguminous crops may rely on this nitrogen fixation process, which lessens their reliance on synthetic nitrogen fertilizers and the effect of agriculture on the environment. Rhizobium's capacity to fix nitrogen considerably increases the amount of nitrogen that is available in the soil, which benefits both succeeding crops in a rotation and the leguminous plant. Non-leguminous crops that come after legume crops in a succession benefit from the increased nitrogen availability. Legume crops associated with Rhizobium are able to obtain a significant amount of nitrogen from the atmosphere, which reduces the need for synthetic nitrogen fertilizers, which require a lot of energy to produce and can have negative environmental effects like nitrate leaching and greenhouse gas emissions. Rhizobium's symbiotic nitrogen fixation boosts soil fertility and nitrogen content. This encourages microbial activity, improves soil health, and aids in sustainable soil management. Rhizobium's capacity to fix nitrogen helps succeeding non-leguminous crops in a rotation because leftover nitrogen from the previous crop enriches the soil and improves the availability of nutrients for the new crops. Overall, using Rhizobium as a biofertilizer in legume crops provides an inexpensive and ecologically responsible way to increase crop output, save resources, and promote sustainable farming methods [21].

6.1.2. Use of PGPR as Biopesticides

By generating antimicrobial substances like pyrrolnitrin and pyoluteorin, which prevent the development of plant diseases, certain Pseudomonas species function as biopesticides. They may shield crops from illnesses brought on by bacterial and fungal pathogens. A well-known biopesticide for the management of insect pests is bt. It generates crystal proteins (Cry poisons) that are toxic to a particular class of insect pests but non-toxic to animals not intended as targets. Against different plant infections, Trichoderma species function as biopesticides and biocontrol agents. In addition to inducing plant defensive responses against illnesses, they also create enzymes that break down the cell walls of infections [21].

The use of PGPR as biofertilizers and biopesticides in agriculture provides sustainable and ecologically acceptable alternatives to traditional chemical inputs. Farmers may enhance soil health, encourage plant development, and successfully control pests and diseases while avoiding negative impacts on the environment and human health by using the positive features of these beneficial microbes.

6.2.Role of PGPR in sustainable crop production and reduced chemical inputs

PGPR (Plant Growth-Promoting Rhizobacteria) are renowned for their ability to solubilize nutrients, such as phosphorus and micronutrients, in the soil, increasing their availability to plants. Additionally, some PGPR can fix atmospheric nitrogen, converting it into a form usable by plants. These beneficial effects enhance nutrient availability and uptake, reducing reliance on chemical fertilizers in agriculture. Many PGPR can produce organic acids, enzymes, and other metabolites that can solubilize insoluble nutrients, such as phosphorus, iron, zinc, copper, and manganese, in the soil. These nutrients are often bound to soil particles and are not easily accessible to plants in their original form. PGPR solubilize these nutrients by breaking down the chemical complexes, converting them into soluble forms that plants can readily absorb through their roots. Increased Nutrient Availability: By solubilizing nutrients, PGPR effectively increases the pool of available nutrients in the soil. This expanded nutrient availability is particularly crucial for plants, improving their nutrient status and supporting their growth and development. The presence of PGPR in the rhizosphere enhances the nutrient-rich microenvironment around the plant roots, making it easier for the plants to uptake essential elements. Certain PGPR, such as Rhizobium species in legumes and Azospirillum species in non-leguminous plants, can fix atmospheric nitrogen. Nitrogen fixation is the process of converting nitrogen gas (N_2) from the air into ammonia (NH_3) and then into ammonium (NH_4^+), a form that plants can utilize as a nitrogen source. This biological nitrogen fixation provides a supplementary source of nitrogen to plants and is especially advantageous for plants growing in nitrogen-deficient soils. The enhanced nutrient availability and nitrogen fixation capabilities of PGPR reduce the need for chemical fertilizers in agriculture. PGPR offers a more sustainable and environmentally friendly alternative to synthetic fertilizers by providing additional nutrients and fixing nitrogen from the atmosphere. This practice contributes to reduced nutrient runoff and helps mitigate the negative impacts of excess fertilizer application on water bodies and ecosystems [14].

By harnessing PGPR's nutrient solubilization and nitrogen fixation abilities, farmers can promote plant health, increase crop yields, and foster more sustainable agricultural practices. Integrating PGPR-based biofertilizers into farming systems contributes to efficient nutrient management, reduced environmental pollution, and enhanced soil fertility, making it a valuable approach for modern agriculture [9].Auxins, cytokinins, and gibberellins are among the hormones that plants produce that promote growth, and PGPR stimulates the development of roots and shoots, enhancing plant growth and boosting agricultural yields. By generating antimicrobial substances and fostering systemic resistance in plants, PGPR helps prevent the spread of plant diseases. Their biocontrol efforts help to achieve sustainable pest management by lowering the requirement for chemical pesticides. By generating osmoprotectants, encouraging root development, and improving water and nutrient intake, PGPR aids plants in coping with drought and salt stress. This improves crop resilience in arid and water-scarce settings. The PGPR's actions, including as better nutrient cycling, the breakdown of organic matter, and the eradication of disease, all promote soil health. Using fewer chemicals also reduces agriculture's negative environmental effects [21].

6.3.Potential for PGPR application in organic and precision agriculture

PGPR (Plant Growth-Promoting Rhizobacteria) are renowned for their ability to solubilize nutrients, such as phosphorus and micronutrients, in the soil, increasing their availability to plants. Additionally, some PGPR can fix atmospheric nitrogen, converting it into a form usable by plants. These beneficial effects enhance nutrient availability and uptake, reducing reliance on chemical fertilizers in agriculture. Many PGPR can produce organic acids, enzymes, and other metabolites that can solubilize insoluble nutrients, such as phosphorus, iron, zinc, copper, and manganese, in the soil. These nutrients are often bound to soil particles and are not easily accessible to plants in their original form. PGPR solubilize these nutrients by breaking down the chemical complexes, converting them into soluble forms that plants can readily absorb through their roots. Increased Nutrient Availability: By solubilizing nutrients, PGPR effectively increases the pool of available nutrients in the soil. This expanded nutrient availability is particularly crucial for plants, improving their nutrient status and supporting their growth and development. The presence of PGPR in the rhizosphere enhances the nutrient-rich microenvironment around the plant roots, making it easier for the plants to uptake essential elements. Certain PGPR, such as Rhizobium species in legumes and Azospirillum species in non-leguminous plants, can fix atmospheric nitrogen. Nitrogen fixation is the process of converting nitrogen gas (N_2) from the air into ammonia (NH_3) and then into ammonium (NH_4^+), a form that plants can utilize as a nitrogen source. This biological nitrogen fixation provides a supplementary source of nitrogen to plants and is especially advantageous for plants growing in nitrogen-deficient soils. The enhanced nutrient availability and nitrogen fixation capabilities of PGPR reduce the need for chemical fertilizers in agriculture. PGPR offers a more sustainable and environmentally friendly alternative to synthetic fertilizers by providing additional nutrients and fixing nitrogen from the atmosphere. This practice contributes to reduced nutrient runoff and helps mitigate the negative impacts of excess fertilizer application on water bodies and ecosystems. Farmers can promote plant health, increase crop yields, and foster more sustainable agricultural practices by harnessing PGPR's nutrient solubilization and nitrogen fixation abilities. Integrating PGPR-based biofertilizers into farming systems contributes to efficient nutrient management, reduced environmental pollution, and enhanced soil fertility, making it a valuable approach for modern agriculture [22].

7. Future Prospects and Challenges

Sustainable agriculture will benefit from exploring untapped PGPR strains for innovative plant growth-promoting features. Researchers are discovering new and varied PGPR strains with growth-promoting properties as they learn more about microbial interactions with plants and the rhizosphere. Untapped PGPR strains may reveal unique plant growth-promoting characteristics. These qualities include the creation of growth-promoting metabolites and unique mechanisms of action that may dramatically increase plant growth and yield. Untapped PGPR strains may have plant or environment preferences. These strains may be identified and characterized to adjust microsystems to diverse crops, soils, and climates. Biotechnological applications like genetically engineering crops to promote growth and stress tolerance may increase agricultural output and sustainability using untapped PGPR strains with unique features. Novel PGPR strains may be biofertilizers and biopesticides, giving eco-friendly alternatives to synthetic fertilizers and insecticides. Bioinoculants made from these strains may provide tailored plant nourishment and insect control. Climate-resilient agriculture may benefit from untapped PGPR strains with drought, heat, or salt tolerance. In shifting climates, such strains may improve agricultural performance. Endophytic PGPR in plant tissues might provide unique growth-promoting features. Endophytic PGPR may show individual host plant interactions and reveal crop-improving features. Untapped PGPR strains may reveal synergistic growth-promoting microbial consortia. Consortia of suitable PGPR strains may improve effectiveness and enable more sustainable agricultural production. Characterizing untapped PGPR strains allows tailored and site-specific deployment of beneficial microorganisms for precision agriculture. This method optimizes PGPR and reduces environmental consequences. Untapped PGPR strains may aid soil restoration and bioremediation. They break down contaminants and restore deteriorated soils, promoting sustainable land use. Exploring new PGPR types and using them in farming can significantly affect food security worldwide by making crops more productive and resistant, especially in areas with natural problems and limited resources.

Conclusion

Rhizobacteria that promote plant growth use a variety of strategies to increase agricultural output. Some PGPR, including specific species of Rhizobium and Azospirillum, can fix atmospheric nitrogen into a form that plants can use. By increasing the nitrogen concentration of the soil, this method promotes better plant growth and development. In the soil, PGPR produces organic acids and enzymes that solubilize insoluble forms of minerals like phosphates and micronutrients. This improves nutrient absorption and makes these nutrients more readily available to plants. IAA, cytokinins, and gibberellins are among the phytohormones that PGPR produces and releases. These hormones promote cell proliferation, elongation, and root expansion, which benefits plant growth. PGPR enhances nutrient absorption by increasing root surface area via proliferation and hair growth. Promoting the expression of nutrient transporter genes in plant roots may also improve nutrient uptake. In reaction, the plant produces defense-related substances such as phytoalexins, reactive oxygen species (ROS), and pathogenesis-related (PR) proteins. PGPR stimulates the plant's immunological responses. As a result, the plant develops systemic resistance, which increases its resistance to several diseases. PGPR creates antimicrobial substances, siderophores, and lytic enzymes to stop plant pathogens from growing and acting. This biocontrol action guards against infections and helps control illnesses in plants. Proline and trehalose, two osmoprotectants produced by PGPR, aid plants in surviving drought and salt stress. These osmoprotectants keep the water balance in cells in check and shield plants from harm caused by water shortages. Some PGPR produces enzymes like phosphatases that liberate phosphorus from organic soil components and increase their availability for plant uptake. PGPR may affect the concentrations of many plant hormones, such as ethylene, abscisic acid (ABA), and jasmonate acid, which control plant development, growth, and stress responses. Exudates from plant roots, which are organic substances, might have a different composition depending on PGPR. The microbial ecology in the rhizosphere may shift, as a result, encouraging mutualistic interactions that promote plant development.

Competing Interest Statement:

None of the authors have any competing interests.

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