Acta Scientific MICROBIOLOGY (ISSN: 2581-3226)

Volume 5 Issue 4 April 2022

Review Article

Rhizobacteria that Promote Plant Growth and their Impact on Root System Architecture, Root Development, and Function

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DOI: 10.31080/ASMI.2022.05.1035

Received: February 17, 2022

Published: March 16, 2022

Abstract

The world's population has been rapidly increasing, as has the demand for basic essentials such as food. Today's agricultural need is increasing in yield while chemical fertilizers and pesticides, which are responsible for environmental deterioration, are being used less frequently. Due to many stresses that plants are subjected to today, a large portion of their yield has been lost. Due to their multifunctional plant protection and growth-related effects, agricultural manipulations of potentially beneficial rhizosphere microorganisms are quickly growing. Abiotic and biotic stresses are the two types of challenges that plants face. Plant Growth Promoting Rhizobacteria (PGPR) has exhibited both synergistic and antagonistic interactions with microorganisms in the surrounding environment to favorably improve plant growth. A highly specific communication system is used to regulate the direct and indirect effect. We attempted to cover all possible mechanisms of PGPR in this review article, as well as published studies for numerous ways that PGPR could be used to promote sustainable agriculture development through root system functioning and root architecture. PGPR impacts cell division, differentiation, root elongation, and development, resulting in increased root growth as well as improved shoot growth using number of ways, including the production of phytohormones such as cytokines, gibberellins, and auxins, as well as signaling that enhances overall plant development and health.

Keywords: PGPR; Rhizobacteria; Phytohormones; Root System Architecture; Root Functioning; Sustainable Agriculture

Introduction

Plant Growth Promoting Rhizobacteria are bacteria that invade plant roots and promote plant growth (PGPR). They play a crucial function in the photosynthetic terrestrial ecosystem. Rhizosphere is where these microorganisms live. The soil in touch with plant roots is known as the rhizosphere. The Rhizosphere is a limited zone of soil where the root system has an impact [28]. Because of the accumulation of a range of plant exudates, such as amino acids, carbohydrates, vitamins, nucleosides, organic acids, and signals that attract microorganisms while also providing energy and nutrition to bacteria, this zone is rich in nutrients when compared to bulk soil [38]. The primary carbon source for the microbial population is provided by root exudates. 10^{10} bacteria per gramme of soil, which is 10 to 100 times more bacteria than bulk soil. The Rhizosphere is populated by a variety of microorganisms, including Rhizobacteria, which colonies this habitat, and the Rhizo-microbiome, which is the microbial community linked with plant roots [20]. The rhizo-microbiome composition changes as the composition of root exudates changes along the root system, as do the stages of plant growth and plant genotypes [8]. Beneficial, harmful, and neutral

microorganisms associated with plants are categorized according to their impact on plant growth [28]. The following are some of PGPR's positive effects.

Microorganisms develop structures connected to interaction, such as nodules in the symbiosis between nodulating rhizobia and the *Fabaceae* family, and arbuscules in the Endomycorrhizal symbiosis, which encourage plant growth and give greater plant health [28].

Associative root symbiosis refers to a second sort of relationship that is less obligatory and particular. The bacteria colonise the root's surface and interior tissue. They compete for nutrition, making nutrients unavailable to dangerous microorganisms, and thereby preventing them from reproducing [24,41]. PGPR has a direct or indirect effect on the plant. Increase plant growth by (a) secreting growth regulators such as cytokines, auxin, and gibberellins, (b) lowering ethylene levels in plants, (c) solubilization of inorganic phosphate, (d) mineralization of organic phosphate, (e) nonsymbiotic nitrogen fixation, (f) forming organic matter, which includes amino acids, (g) synthesizing enzymes, and (h) activating disease-resistance On the other hand, one indirect approach involves lowering disease vulnerability and triggering a type of defence called as Induced Systematic Resistance. They also aid the plant's survival in the face of drought and other abiotic stresses [39]. PGPR are thought to interact with a wide range of host plant species and encompass a great taxonomic diversity within the Firmicutes and Proteobacteria phyla, as opposed to mutualistic symbionts [30,50]. By producing phytohormones or enzymatic activities, PGPR can increase root development and growth while also favouring the establishment of Rhizobial or Mycorrhizal symbiosis. They assist plants in coping with abiotic challenges such as heavy metal or other pollution contamination. Aside from that, they improve plants' ability to sequester heavy metals [25,30,31,41,43]. The success of phytoremediation of contaminated soil is an essential technique using PGPR [11,30,31,41]. As we all know, bacteria that lessen the severity of plant diseases are referred to as biocontrol agents, whereas antagonists are defined as bacteria that have antagonistic action toward a pathogen. The PGPR have an antagonistic effect because they produce hydrolytic enzymes that can lyse the pathogenic fungal cell, such as chitinases, glucanases, proteases, and lipases [49]. Aside from interactions with the host, PGPR can create siderophores, bacteriocins, and antibiotics that aid the host plant's survival and growth [29,39].

The main focus of this review study is on rhizobacteria's mechanism of action, roles, and rhizosphere ecology. The PGPR has a positive impact on the rhizosphere and benefits to plants. The root system, root development, and root functions are also discussed in this work, as well as how PGPR influences root functioning and architecture, as well as the effects of phytohormones on roots. PGPR also has an impact on whole-plant physiology, plant nutrition, and the transcriptome and metabolome of plants. The taxonomic/functional diversity of the rhizosphere, microbial communities, and plant molecular responses are also discussed in this work.

Figure 1: Schematic diagram of PGPR affecting root traits and plant benefits (image created by PP in MS Office 365 ProPlus, PowerPoint).

The effect of PGPR on root functioning, architecture, and structure of the root

Plant roots aid in nutrition absorption, root exploration, and soil distribution. Root tip, root meristem, differentiation and elongation zones, and developing lateral roots are all parts of the root [46]. They each play a different role. The root hairs are thin and tough. They're specialized epidermal cells that play a role in plant nutrition and microbial interactions. In the rhizobial colonization process, the roots emit chemicals, particularly the root tips, which cause root curling and the formation of root nodules [16]. Root System Architecture considers root system structure, principal lateral root arrangement, root length, and other factors (RSA). Also, Abiotic and biotic variables have an impact on RSA. PGPR also secretes phytohormones that modulate RAS, such as cytokines, gibberellic acid, jasmonic acid, and others.

PGPR phytohormone effects on root system architecture

The phytohormones produced by the PGPR will interfere with the primary hormonal pathways involved in plant root development, including auxin, cytokine, ethylene, gibberellins, abscisic acid, and RSA changes. Plant organ growth, root shape, and architecture are all aided by the balance of auxin and cytokinins [2]. Because they create auxins, cytokines, and secondary metabolites that interfere with plant pathways, PGPR affects the auxins and cytokines ratio. Cytokines are hormone-like signaling molecules that help plants regulate cytokines, growth, and development. The principal hormonal signals are governed by the location of vascular tissue, while cytokines cause vascular differentiation and regeneration in the presence of auxins [2]. In vascular tissues like Xylem fibres, cytokines encourage cell division. Various PGPR produce cytokine, such as *Arthrobacter giaomelloi, Azospirillum brasilense, Bacillus licheniformis*, and *Pseudomonas fluorescence* [17].

In root development, Cytokinins and Auxins play opposing functions. Auxins are involved in the development of lateral roots [31]. Cytokinin, on the other hand, suppresses root development and reverses the action of auxins [15]. Environmental and hormonal cues shape the root system's design [14]. Azospirillium baselines, for example, have nitrite reductase activity and, as a result, produce nitrous oxide during root colonization. Nitrous oxide then sends out signals and regulates the growth of lateral roots. 2,4-diacetylphloroglucinol (DAPG), which acts as a signal molecule at low concentrations and will rise. *Azospirillum brasilense* produces ethylene from the precursor methionine, which helps tomato plants grow root hairs. PGPR can also create Abscisic Acid (ABA) and Gibberellic Acid (GA), as well as regulate their levels in plants. Drought stress necessitates the use of ABA. The ABA level rises in response to water stress, allowing the stomata to close, reducing water loss [6]. Gibberellins promote primary root elongation and lateral root growth [19]. *Aspergillus spp., Azotobacter* spp., *Acinetobacter calcoacetius, Rhizobia* spp., and *Bacillus spp*. have all been found to produce gibberellin in PGPR. As a result, PGPR, which produces these hormones, may modify the hormonal balance involved in plant defence [24].

Figure 2: Effect of PGPR on Root System Architecture (RSA), nutrient acquisition and root functioning (image created by PP in MS Office 365 ProPlus, PowerPoint).

PGPR modifies the root cell wall

PGPR produces phytohormones and has favorable effects, but they can cause chemical alterations and root cell wall modifications [10]. For example, the *Bacillus pumilus INR-7* biocontrol agent increases lignin deposition in pearl millet epidermal tissues and improves plant defence mechanisms. Pathogens are inhibited, and illnesses are suppressed. When *Bacillus pumilus SE34* and *Bacillus subtilis UMA F6639* were infected, the resistance to fungal pathogens increased in both cases [35]. When *Pseudomonas fluorescence 63-28R* was injected, lignin accumulated in root cells and the oomycete *Phythum ultimum* was inhibited [7]. Inoculation of bean roots with *Pseudomonas putida* had the same result [3]. Plants are protected against phytopathogens by PGPR, which causes cell wall remodelling [38]. The crude cell wall of maize roots was examined, and it was discovered that roots infected with *Azospirillum lipoferum CRT 1* had decreased lignin concentration. This low lignin content aids in cell elongation, which leads to root elongation [32]. PGPR generates enzymes that are involved in cell wall lyses and pathogen neutralisation, such as ACC-deaminase, 1, 3-glucanase, and chitinase [37]. *Phytophthora capsic*i and *Rhizoctonia solani,* two of the world's most devastating crop diseases, are also inhibited by PGPR [40].

Rhizobacteria's effect on plant biology and functioning

PGPR is the most important bacteria in the rhizosphere because it colonizes the roots and promotes plant growth. They also play a role in chemical composition changes, maintaining the plant's hormonal balance, and so influencing plant biology, physiology, and functions. They boost plant development by improving nutrient uptake and metabolism, as well as inhibiting pathogens. They play a role in the signaling process. They influence plant gene expression and aid in the accumulation of plant metabolites. These findings demonstrate that PGPR has a wide range of effects on plant physiology and functioning, and they point to strategies to better understand PGPR's systemic influence.

PGPR'S effect on plant transcriptome

The influence of PGPR on gene expression in plants was studied using a variety of bacterial models. *Pseudomonas putida* inoculation of *Arabidopsis* leaves resulted in upregulation of 520 genes. Several metabolic activities, chemical production, ABA and Ca signaling, and ISR activation are all regulated by these genes [43]. Inoculation of *Azospirillum brasilense Sp 245* with ethylene receptors resulted in beneficial plant-bacterial interaction. It improves and creates circumstances that encourage rice growth and enable for harvesting twice a year [4]. In rice, *Herbaspirillum seropedicae* inoculation causes the expression of auxin and ethylene-sensitive genes, as well as the inhibition of the defence proteins PBZ1 and thionine [26]. Plants treated with biocontrol PGPR showed increased resistance to bacterial and fungal diseases. When transcriptome investigations using *Pseudomonas fluorescence WCS 417r* were conducted, it was discovered that bacteria boosted the expression of 97 genes in roots [8,12]. When roots were treated with PGPR, 8000 genes changed their expression in the leaves, indicating an increased defence system that included PR related proteins [18,34]. The PGPR increases defense-related transcripts, which leads to the production of proteins that are involved in plant defence mechanisms, as well as plant growth and development. As a result, plant immunology is influenced by helpful microorganisms.

PGPR'S effect on plant nutrient up taking

PGPR improves plant nutrition and consequently plant development, in addition to its plant health benefits. The majority of nutrients are absorbed by plants through their roots. The greater the surface area, the greater the absorption and thus the nutritional uptake. PGPR boosts nutrient absorption by increasing root surface area. To maintain a constant rate of nutrient intake, root growth and ion transportation are incompatible [17]. As a result, PGPR has an impact on both plant nutrient intake and plant growth rate. The nutrients supplied in the rhizosphere and the ion transport system are increased by PGPR. Rhizobacteria produce a variety of enzymes that aid in the breakdown of complex nutrients into simpler nutrients that are easier for plants to absorb. They also play a role in bacterial siderophore production, nitrogen fixation, and phosphate solubilization, among other things [29,33]. When fertilizers are employed, a large amount of phosphorus settles in the soil, yet plants only use a little amount. Plants absorb mono and diatomic phosphorus, while organic and inorganic forms must be solubilized by microorganisms [20]. *Pseudomonas* sp, *Rhizobium* spp, *Bacillus* spp, and many more PGPR spp, *Bacillus* spp, and many more PGPR spp, *Bacillus* spp, and many more PGPR spp, *Bacillus* spp, and many more PGPR spp, *Bacillus* spp, and many more PGPR spp, *Bacillus* spp, and The PGPR can also release low-molecular-weight organic acids such as gluconic acid, which chelates phosphate cations

[45]. Phosphatases are enzymes that hydrolyze organic phosphate molecules. Nitrogen fixation is another major function of PGPR. Although nitrogen is abundant in the atmosphere, it is not directly utilized by plants. These Rhizobacteria convert nitrogen to ammonia, which plants can use. Plant growth can be aided by some non-fixers as well. Most inoculation of Canola with *Achromobacter* spp. U80417 increased nitrates and potassium ions rates per root surface area unit, according to studies [10]. This boosts proton pump function and increases ion uptake rate [29]. Nitrate levels rose in seedlings infected with *Phyllobacterium brassicacearem STM 196* during 24 hours [48].

Nitrate and ammonium transporter transcripts were similarly impacted. The *Bacillus subtilis GB03* strain is best known for expressing HKT 1 in *Arabidopsis* seedling roots and shoots [44]. It extracts sodium ions (Na+) from the xylem in phloem tissue of the shoot and is involved in sodium ion (Na+) absorption [43]. The differential regulation of HKT1 produced decreased sodium ions uptake and increased potassium ions uptake in GB03 inoculation seedlings under salt-stress conditions [44]. PGPR influences root physiology and nutrition through nitrogen fixation, phosphorus solubilization, and siderophore production [29].

PGPR'S effect on plant metabolome

The metabolite composition of roots was studied to see how PGPR affected it. As a result, root enzyme activity is increased, metabolites are produced, and flavonoids cause alterations in root secretion [47]. The action of *Azospirillum* PGPR resulted in a one-third increase in carbon compound from roots. Chemicals produced by microbes, such as phenazines and DAPG, have the ability to boost plant species' total net amino acid outflow [42]. Flavonoids exudation on soybean roots is affected by *Chryseobacterium balustinum* [26]. *Azospirillum* may alter flavonoid exudation by Fabaceae roots [16].

Plants seeded with the PGPR strain produced more malate and other amino acids than plants that were not inoculated. In medicinal plants, PGPR aids in the accumulation of terpenoid and alkaloid components [51]. *Azospirillum* strains altered secondary metabolites in the roots and shoots, primarily benzorazinoids [11]. The secondary metabolites were replaced with phenolic molecules such as flavonoids and other substances under genobiotic conditions. PGPR infected roots have impacts on shoots as well. Secondary compound accumulations are also caused by a consortium of *Arbuscular Mycorrhiza* and PGPR. When consortia were inoculated, secondary metabolites such as total phenolic compounds, ortho dihydroxyl phenols, and phosphorus, potassium, zinc, and copper were at their highest levels. By forming various metabolites, PGPR aids in the tolerance of drought and salt stress. When infected with *Pseudomonas pseudoalcaligens,* a higher level of glycine was detected [42]. With reduced choline production, *Bacillus subtilis GB03* also produces glycine betaine, a choline precursor, and drought tolerance decreases [2007]. *Burkholderia phytofirmans PsJN* is an endophytic strain that helps grapevines survive cold stress and causes post-chilling recovery [1]. Stress-related metabolism, such as proline, aldehydes, and hydrogen peroxides, are created, as are cold-related defence genes [14]. The PGPR inoculation raises starch content and soluble sugars such as glucose, sucrose, and raffinose, all of which aid in maintaining a steady low temperature. PGPR thus plays a vital function in the maintenance of the plant metabolome [1].

Plant expression: PGPR'S beneficial functions in the rhizosphere

On diverse host plants, different and distinct expression patterns of PGPR plant beneficial qualities can be seen in space and time. One PGPR strain can induce multiple positive traits in plants, which may or may not be co-regulated. The plant and its related PGPR are affected by both biotic and abiotic influences. pH, oxygen, clay, mineralogy, heavy metals, and other abiotic variables and biotic variables, such as plant-produced chemicals or the rhizomicrobiome [16]. The following are some of the favorable biotic elements that influence the PGPR.

Root exudate regulation of PGPR functions

Because successful PGPR colonization in the rhizosphere is the first and most important step in protecting plants from soilborne diseases, it's important to assess the impact of root exudates in PGPR colonization. Amino acids, flavonoids, organic acids, and other substances are found in root exudates. Monocots and dicots have been reported to use them as signaling molecules. Root exudates are also known to be intimately linked to the rhizosphere microbiome, where they have a direct impact on various rhizobiome components and vice versa [16]. As a result, root exudate metabolites serve as mediators for plant-plant and plant-microbiome

interactions. PGPR are helpful soil bacteria that live freely in the rhizosphere. In the current agricultural system, plant growth in the presence of PGPR can reduce chemical fertilizer use by 25% [16]. Plants can influence bacterial gene expression, particularly genes encoding plant beneficial fruits, by releasing root exudates. The composition of root exudates is influenced by inter- and intraspecific genetic diversity [9]. The composition of root exudates is also affected by plant developmental stage and abiotic variables [1]. In *Pseudomonas protogens* CHAO, one of the key types of research aimed at studying the impact of root exudates variability on bacterial gene expression was carried out on phlA, which is involved in DAPG (2,4-diacetyl phloroglucinol) production [19]. In the rhizosphere of dicots like beans and cucumber, if the phlA gene is expressed, it will increase fourfold. This has an impact on plant genotype biocontrol activity [19]. Sugars in root exudates, in particular, influence fluorescent *Pseudomonas*' production of antimicrobial chemicals such as dapg, pyoluteorin, and pyrrolnitrin, with some strain-dependent effects [31]. Many compounds related to defence or development or involved in plant-microbe interactions are modulated in *Pseudomonas protegens CHO* due to expression of phlA and pltA in these bacteria [27], whereas a previous study reported repression of both DAPG and polyuteorin biosynthesis genes by salicylate [4,27]. The bioavailability of tryptophan is higher in graminaceous roots, such as *Avena barbata*, at the end of secondary root emergence [41]. In the absence of exogenous tryptophan, insignificant IAAn biosynthesis is observed. Exuded amino acids from the root, such as tyrosine and phenyl alanine, can also trigger ipdC/ppdc expression [23]. Apart from amino acids, plant roots also release vitamins such as pyridoxine and nicotinic acids, as well as organic acids such as phenyl acetic acid and prephenic acid [32]. All of these chemicals greatly boost IAA synthesis in *Aspergillus brasilense SP245* [51]. Plant helpful genes are selectively controlled, and compounds found in root exudates have an effect on genes engaged in plant beneficial functions. Plant physiological responses are influenced by the PGPR strain and cultivar combination [30].

Microbial signals regulate the actions of the PGPR

Several types of cell-to-cell communications signals exist between each PGPR strain and other rhizosphere-inhabiting bacteria, and their function allows bacteria to monitor their density and coordinate gene expressions only when quorum sensing is achieved, and other bacterial signals and gene expressions regulate cell density independently [34]. Quorum sensing is mediated by small diffusible molecules like N acyl homoserine lectones (AHLs). In fluorescent *Pseudomonas*, biosynthesis of antimicrobial compounds such as phenazine and colonisation properties is frequently subjected to AHLs-based Quorum sensing [13]. In *Serratia plymuthica G3*, an endophytic strain, quorum sensing favourably influences antifungal activity and exo enzyme synthesis while negatively regulating IAF production [49]. The first rain of *Azospirillum lipoferum*, a lipoferum species isolated from rice, has the ability to create AHL signals (Vial., *et al*. 2006). AHL inactivation reduces IAA generation, increases siderophore synthesis, and eliminates pectinase activity, but has no effect on cellulase activity or the psychostimulatory effects produced by the endophyte *Azospirillum lipoferum B518* [13]. The control functions connected to rhizosphere competence and adaptability to plant roots are generally believed to be dependent on quorum sensing regulations and their proteomic counterparts [12]. Some *Pseudomonas fluorescence* strains that lack the ability to produce AHL but possess the corresponding receptor may be able to identify a plant chemical and activate the expression of genes involved in biocontrol. Some pathogenic fungus strains produce toxic metabolites and have an impact on the positive qualities of PGPR plants, such as *Fusarium oxysporum*, which produces fusaric acid [19]. Furthermore, positive autoregulation in *Pseudomonas* protegens influences the mutual inhibition of DAPG and polyuteorin synthesis [14]. Four genes (ppdC, flgF, nirk, nifX, and nifB) were increased on roots in the presence of *Pseudomonas fluorescence F113* compared to its DAPG negative mutant [22]. Using DAPG as a signal, some beneficial *Pseudomonas* may boost *Azospirillum* PGPR's plant-friendly actions [22]. Field inoculation of maize with a consortium of two PGPR (*Azospirillum lipoferum CRT1* and *Pseudomonas fluorescence F113*) and one *mycorrhizal strain* (*Rhizophagus irregularis*/*Glomus intraradices JJ291*) resulted in an increase in root surface, root volume, and number of roots, though the differences were not significant when compared to a single *Rhizophagus* ino [25]. When carried out in any of the consortium members stated above, a considerable alteration of maize growth was discovered [24]. Consortia are utilised to explore the expression of plant functions in depth.

PGPR population ecology and impact on root system functioning

The mechanism of action of PGPR is examined using one individual strain and one host plant, but in actuality, PGPR strains do

not function individually in the rhizosphere, but rather as members of bacterial communities in which cell signals also coordinate all-individual strain activity. To study plant growth-promoting effects, it's crucial to take into account the complexities of the interaction between PGPR populations within the microbiome. As a result, functional ecology approaches are required, which take into consideration the relationship between the size, diversity, and activities of PGPR colonisation in the rhizosphere. PGPR ecology in the rhizosphere: from individual strains to functional groups. In soil, there are many taxonomic categories of PGPR strains [46]. As a result, taxonomically distinct PGPR strains coexist in soil and populate the same rhizosphere as non-PGPR bacterial community members. The taxonomic identity of bacterial isolates was researched and characterised their property of relevant effects, including their potential to suppress phytopathogens or impart a beneficial influence on plant growth [9]. If they execute tasks like ISR, nitrogen fixation, nutrient solubilization, plant growth improvement, and so on, the PGPR of some strains with the same functional group belong to the same population. When certain genes are identified, functional groupings are created. For example, nitrogen fixers can be examined using the nif H gene, which codes for the dinitrogenase subunit of the nitrogenise enzyme and is often used as a marker to track the growth of the diazotrophic community's diversity [19]. The ecology of the PGPR strain must be steady in order to achieve precise tuning between production levels of some key nutrients. However, the feasibility of a co-evolutionary pattern process to bridge the gap between potential plant benefit PGPR function and actual implementation by PGPR strains is unclear, and this should be considered. To make research easier and more detectable, some common regulatory effects for all functional group members should be maintained [28]. Other regulatory effects are sometimes taken into account for the relevant subset of functional groups. Zinc sulphate, for example, promotes DAPG synthesis in certain but not all *Pseudomonas* PGPR strains [31]. Second, interactions between different PGPR functional groups may occur, which may be competitive or inhibitory to each other [24]. This may result in signal jamming [12] and positive signalling [22], as well as modification of the root exudation process [24,26,45]. This interaction also influences PGPR performance by modulating PGPR colonisation patterns on roots [11,24]. Consortia may also form between various PGPR functional groups, with the potential for synergistic or antagonistic effects. This consortium is utilised to inoculate the important indigenous microorganisms.

Plant genotype impact on PGPR functional groups

Plants have a lot of genetic and phenotypic variety at different levels of species and subspecies [35,42]. Different plant genotypes have different effects on the number, diversity, and activity of the rhizomicrobiome in the rhizosphere [5] and these effects are clearly visible among different plant species [8,23,39] or varieties within species [8,23,36,39]. Root system structure, root exudation, and nutrient acquisition all show significant differences. This distinction can be seen in PGPR-producing microbial functional groups or in areas where PGPR predominates. The size or composition of nitrogen-fixing bacteria is controlled by host plants at the species and variety level, according to functional group analysis [44]. Because nitrogen-fixing bacteria are critical for the health of each plant. When nif H gene transcripts from the rhizosphere are analysed, the results show that only a small percentage of the community expresses nif H, and that the expression of nif H genes varies depending on the plant variety, implying that plant genotype has an impact on nitrogen fixing bacteria function [51]. Phosphate solubilizers are chosen differently depending on the host plant species [21,30,44] Sometimes ISR effects occur directly, while other times plant protection is provided by functional groups through competition or antagonism with parasites [38]. So microbial functional groups and plant genotypes are examined and used in the field selectively [2,8,28]. Plant genotype differences in rhizosphere ecology matter more in terms of plant protection efficacy [3,5,14].

Conclusion

In nature, every living creature exists in a delicate balance, and bacteria are one of the most important species involved in plant growth promotion and nutrient cycling. Plants engage in a variety of beneficial biotic interactions with the soil microbial population, including mutualism and commensalism. The microbial community in the rhizosphere supports plant growth and health by creating phytohormones and siderophores, assisting plants in absorbing nutrients, breaking down complicated substances into simpler forms, combating infections, and receiving shelter from plants. The PGPR plant interaction is essential for the growth and health of a variety of plants. These interactions are critical for increasing crop productivity, which is a critical component in agricultural countries such as India. Extensive research is being done to better understand the ecology and mode of action of PGPR-plant interactions. The molecular signaling and function of PGPR plant contacts must

also be investigated in greater depth, since this will help to improve the effect of this beneficial interaction. Plant growth-promoting rhizobacteria not only generate phytohormones and fight infections, but they also increase root system function, structure, root development, and overall root system architecture. That is a key component that aids in vegetative growth and improves the plant's general physiology. Production of the IAA The functioning of the root system and root architecture are also linked to the generation of several additional phytohormones. The phytohormone signal transduction pathway is aided by the alteration of plant roots by PGPR. The effects of PGPR on the root system also aid the plant's ability to withstand abiotic and biotic stress. The root system's design, functions, hormone levels, and plant metabolism could all be affected by PGPR. This adaptation aids resistance to external challenges such as salt, drought, heavy metals, pollution contamination, nutritional deficiencies, and so on. More experimental research is needed to better understand the interplay between microbial metabolites and host plants. As a result, the favorable effect of PGPR on root system function boosts plant growth and health.

Acknowledgement

The DST-FIST Sponsored Department of Microbiology and Biotechnology, University School of Sciences, Gujarat University, Gujarat, India, has given us with excellent facilities.

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