Leveraging plant growth promoting rhizobacteria for sustainable agriculture and environment: An Overview

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ABSTRACT

The term "soil health" refers to specific qualities of soil that allow it to support crop growth and productivity over time without harming the environment. Healthy soil contains abundant microorganisms, including plant growth promoting rhizobacteria (PGPR), which perform various beneficial functions in the rhizosphere. PGPR aid in nutrient cycling and uptake prevents the growth of harmful plant pathogens, stimulates plant immunity, and directly enhances plant growth by producing phytohormones and other compounds. They also can clean up soil pollution through bioremediation. This article overviews examines literature on how PGPR contributes to maintaining soil health and reducing the need for toxic agrochemicals. Ultimately, the goal is to promote more sustainable agriculture practices using PGPR as biocontrol agents, plant growth stimulators, and rhizoremediators.

Keywords: PGPR, biofertilizer, bioinoculant, rhizosphere, sustainable agriculture, sustainable environment, soil fertility

1. INTRODUCTION

The demand for high-quality, nutritious food from a balanced diet is one of the major obstacles we confront in feeding the rising global population. However, as pointed out by, the reckless use of chemical fertilizers to boost agricultural yields has damaged agroecosystems [1]. Soil biota, terrestrial and marine flora and fauna, and natural insect predators like bee populations have all been negatively impacted by chemical pesticides used to manage plant diseases and insect pests [2]. In addition, agrochemicals have various toxic effects on human health, as [3] noted. As a result, beneficial and native microbiota have been depleted, altered, or even lost as a result of agricultural practices that rely primarily on chemical pesticides.

Environmental sustainability is a critical issue worldwide, as human activities have caused significant environmental harm, including soil health and the destruction of plant habitats, growth, and development, as [4] noted. There is a pressing need to develop, adopt, and promote sustainable alternatives to the problem of rising demand and misuse of synthetic chemicals and the damage they do to the world's agroecosystems over time. Today, more than ever, conventional and harmful agrarian practices that have a negative impact on the environment must be avoided if we want to meet future agricultural needs [5] highlighted. The heavy use of chemical fertilizers has acidified fertile soils [6]. This highlights the importance of educating farmers and encouraging novel and appropriate farming practices to meet the challenge of boosting productivity without compromising environmental stability. The accumulation of heavy metals such as cadmium (Cd) and zinc (Zn) in soil significantly decreases rice yield and is hazardous to the human body via rice accumulation [7]

Plant growth-promoting rhizobacteria (PGPR) have come under focus due to their potential to aid plant development and act as stress buffers. According to, beneficial microbes for plant crops play an important part in a number of soil activities that have far-reaching effects on plant health, crop yields, and agricultural output [8,9,159]. To assure the effective functioning of microbial inoculants and their effects on soil health, extensive study is needed to investigate indigenous soil microbial diversity, distribution, and behaviour in soil environments [10]. Metal-contaminated soil can be cleansed using *Bacillus* spp. as part of bioremediation processes. When used in the right quantity, it can boost carbon sequestration and act as a powerful denitrifying agent in agricultural ecosystems. [11]. Plant growth promoting bacteria (PGPR) are beneficial for plant growth in nutrient-deficient soils because they can improve soil health in a number of ways. These ways include nitrogen fixation, phosphate solubilization, heavy metal sequestration, phytohormone production (e.g., indole acetic acid, gibberellins, or cytokinins), mineralization of soil organic matter, decomposition of crop residues, suppression of phytopathogens, and more [12,13]

The potential for PGPR to produce useful compounds is of great significance to the biotechnology sector, and it is vital for enhancing plant growth and stress management. And so, PGPR has emerged as a major force in the agricultural sector [14,15,16]. In order to take full use of PGPR, however, it is essential to comprehend their mechanisms of action in improving soil health and fostering sustainable agriculture. Therefore, this research aims to explain and illustrate the various methods used by PGPR to improve soil health and agricultural output in a sustainable manner. Figure 1 depicts the many applications and functioning of PGPR.

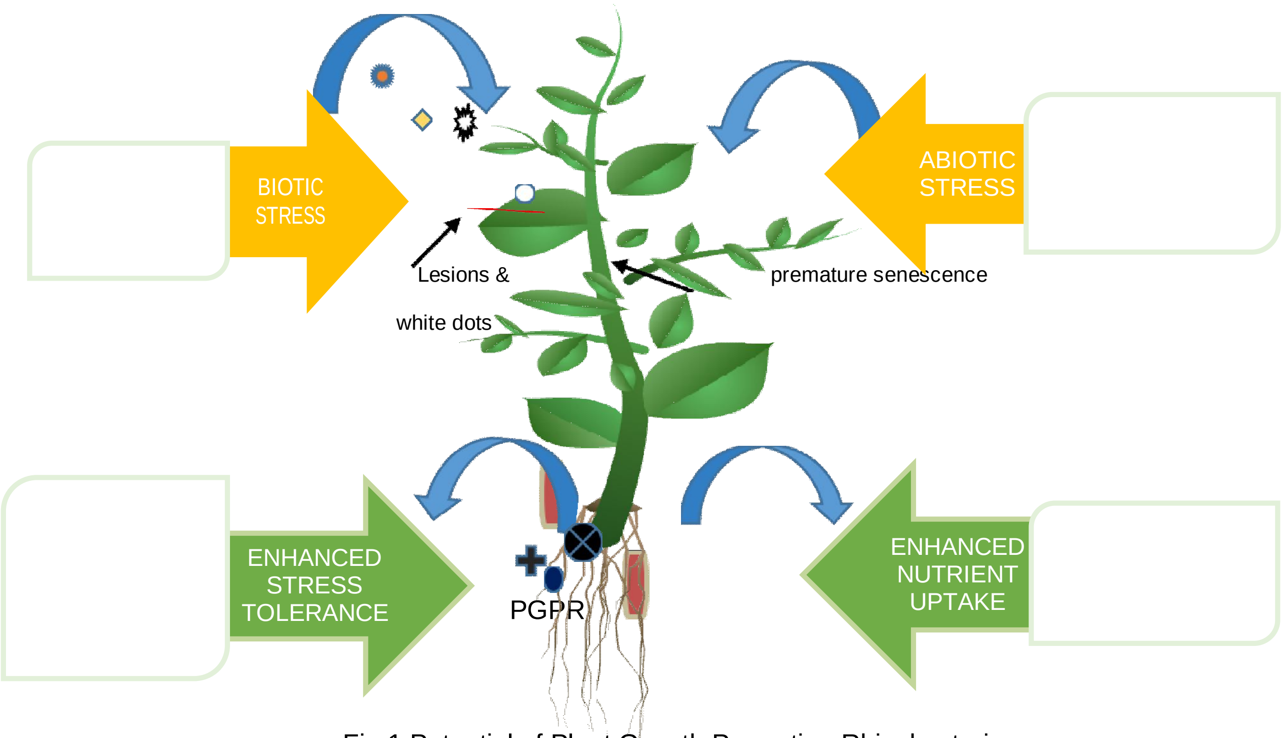

Fig.1 Potential of Plant Growth Promoting Rhizobacteria

2. RHIZOSPHERE AS AN ECOLOGICAL SYSTEM

Plant root secretions have a direct effect on the region around roots, known as the rhizosphere [17]. Due to their assistance in nutrient uptake and defence against pathogen attack, the activities of microbes in this zone are essential for plant functioning [18]. For many activities that affect fertility of the plant, the interaction among plant, soil and microbes is crucial [19]. Plants flourish when rhizobacteria associate with and communicate with their roots in the rhizosphere. When roots colonize the soil, PGPR increases the nutrient accessibility in the rhizosphere and foster plant's progression [20]. Root exudates, which contain diverse chemicals secreted by plants, contribute to the distinctive chemistry of the rhizosphere. Sugars, amino acids, organic acids, flavonoids, proteins, and fatty acids are all components of these secretions [21]. Depending on the plant's physiological state, plant species, and the microorganisms present, these root exudates work as signals, playing as repellents for various pathogens or as attractants for benefcient microbes [19]. Many rhizobacterial species use root exudates and send signal molecules in the rhizosphere [22]. Therefore, by acting as crucial growth substrates for soil microbes, root exudates are pivotal in promoting plant augmentation and inducing defences against phytopathogens. Most soil organic carbon stores as rhizodeposition, which comprises root cell fragments and the detritus they are associated with, as well as exudates, lysates mucilage and mucigel [23]. Energy from rhizodeposits is used by soil microorganisms to break down organic materials in the soil and release readily available nutrients for plants. The abundance of nutrients in the rhizosphere allows the inhabitants to search and reside in ecofriendly root zones. All of the rhizosphere's residents are on the hunt for the best root zones and ecological niches to call home due to the abundance of nutrients in the rhizosphere. Rhizobacteria have adapted numerous biological strategies to survive in this hostile habitat.

3. RHIZOBACTERIA: STRENGTHENING PLANT AND SOIL

The symbiotic interaction of PGPR with plant roots, escalates plant growth, yield, and disease resistance [24]. These bacteria plays an important role in soil fertilization through the process of solubilization and biofixation of pivotal nutrients. These bacteria play a crucial role in soil fertilization through bio solubilization and biofixation of essential nutrient elements [25] and intensifies the nutritional value of crops by increasing their antioxidant activities, phenolic contents, and photosynthetic pigments [26]. Lettuce and soybeans, for example, have had their nutrient content boosted by the presence of *Azotobacter, Pseudomonas, and Bacillus* species [27]. They are perfect for fostering plant development and thwarting disease because of their ideal traits [28], a broad spectrum of activity, strong rhizosphere competence, and simplicity of mass reproduction. They also protect the environment. [29]. *Pseudomonas azotoformans* FAP5 produces a biofilm that benefits wheat (*Triticum aestivum L.*), improving morphological and physiological traits [30]

By metabolizing natural and synthetic chemicals, PGPRs can thrive in various soil conditions due to their metabolic versatility. Given the efficacy and mechanism of action of PGPRs, it has become evident that combinations of PGPR treatments suppress pathogens more effectively than single treatments. [31]. Consequently, PGPRs are the most valuable biofertilizer components. Moreover, PGPRs can be categorized based on the good they do. Utilizing a wide variety of PGPRs allows for acquiring agriculturally valuable characteristics. The soil is the natural habitat of rhizobacteria, which promotes plant growth. They decompose crop residues, synthesize and decompose organic soil materials, and fix and solubilize nutrients in the presence of other soil rhizobacteria. These measures ultimately improve soil quality and plant yields [32]. Important parameters in PGPR rhizosphere colonization include soil moisture and other environmental conditions [33].

PGPR can interact with plant roots by generating biomolecules that improve soil fertility [34]. They can break down and mineralize complex organic compounds to decompose plant remains. As mineralized organic compounds are formed and incorporated into the ground, soil quality is improved [35]. The root system is profoundly affected by the phytohormones that PGPR can produce. Table 1 outlines PGPR species' roles as bioremediation, plant growth promoters, and crop protectors.

Table 1 : List of Bacterial species with their Function

Bacterial species	Function	Mechanism	Effect on plant	Reference

P. fluorescens	Biostimulation	Phosphate Solubilization, IAA production	Tomato (Lycopersicon esculentum Mill)	[36]
***Bacillus* sp.**	Bioremediation	Phytoextraction and immobilization of the metal	Rice (*Oryza sativa* L.),	[7]
Azospirillum lipoferum, Bacillus subtilis, Arthrobacter protophormiae, Dietzia natronolimnaea, Bacillus sp.	Biostimulation	Phytohormone(s) production	Rice (*Oryza sativa* L.), Tomato (*Solanum lycopersicum* L.), Wheat (*Triticum aestivum* L.)	[37]
Acetobacter diazotrophicus	Biofertilization	Nitrogen fixation	-	[38]
Azotobacter chroococcum	Biostimulation Bioprotection	Gibberellin production Siderophore production	Cereals	[39,40]
Advenella kashmirensis	Biostimulation	Cytokinin production	-	[41]
Agrobacterium radiobacter	Bioprotection	Antibiotics	-	[42]
Achromobacter xylosoxidans	Biofertilization	Ammonia production	Agricultural fields	[43]
Azospirillum diazotrophicus	Biofertilization	Nitrogen fixation	Sugarcane (Saccharum officinarum)	[44]
Azospirillum brasilense	Biofertilization Biostimulation Bioremediation	Nitrogen fixation IAA production Phosphate solubilization Reclamation of degraded land Heavy metals uptake	Rice (Oryza sativa) Cereals	[45,46,47,48]
Azospirillum lipoferum	Biostimulation	Gibberellin production	Rice (Oryza sativa)	[49]

Bacillus aerius	Bioprotection	HCN production	-	[50]
Bacillus amyloliquefaciens	Biostimulation Bioprotection Bioprotection	Gibberellin production Lipopeptides Antibiotics Bacteriocins	Rice (Oryza sativa) - Tomato (Solanum lycopersicum)	[51,52,53,54]
Bacillus atrophaeus	Biostimulation	IAA production	Soybean (Glycine Max L.)	[55]
Bacillus anthracis	Bioprotection	Protease production	Wheat (Triticum aestivum L.)	[56]
Bacillus aryabhattai	Biofertilization	Zinc solubilization	Soybean (Glycine Max L.) and Wheat (Triticum aestivum L.)	[57]
Bacillus circulans	Biofertilization Bioprotection	Potassium solubilization Protease production Lipopeptides Acquired and induced systemic resistance Amylase production	Tomato (Solanum lycopersicum) - Bean (Phaseolus vulgaris) Tomato (Solanum lycopersicum) Soybean (Glycine Max L.)	[58,59,60,61, 62, 63]

4. MECHANISMS EXERTED BY PGPR

PGPR promotes plant growth directly and indirectly by releasing vitalizing compounds, escalating nutrient absorption from the soil, and defending plants from phytopathogen causing infection [70]. By creating an array of compounds that promote plant growth and have antimicrobial properties, PGPR maintains the health of the soil and plants. Others may be volatile, while some may be excreted or diffused in a solid medium. Many works have provided in-depth reviews of examples of such compounds/mechanisms [15]. The importance of identifying these mechanisms or the application of indirect plant growth promotion mechanisms have amply proven the beneficial function of PGPR, which significantly impacts sustainable agriculture [71]. As a result, numerous bioprotectant PGPR is now produced commercially by numerous companies worldwide [72].

4.1 BIOLOGICAL NITROGEN FIXATION

Nitrogen-fixing bacteria employ an enzyme system called nitrogenase to convert atmospheric nitrogen into forms that plants may utilize, a process known as biological nitrogen fixation (BNF) [73]. BNF can occur in two main types: symbiotic nitrogen fixation, which involves members of the *Rhizobiaceae* family with leguminous plants [74], and nonsymbiotic nitrogen fixation, which involves various genera such as *Arthrobacter,* and *Acetobacter, Clostridium, Azotobacter, Bacillus, Pseudomonas,* and *Diazotrophicus* [75]. Beneficial soil bacteria, such as PGPR, fix air nitrogen and release it into the soil, where it can be used by plants [76]. Thus, plant-microbe interactions through biological nitrogen fixation play a significant role in organic fertilizer production [77].

Recent research has indicated that the *Azospirillum* species can provide adequate nitrogen to sunflowers and boost their yield and productivity [78]. In addition to producing indoleacetic acid (IAA), these bacteria are capable of fixing up to 15 kg/ha/year of nitrogen. This plant hormone helps plants absorb nutrients and develop to their full potential [79]. The use of nitrogen-fixing bacteria can minimize production costs by reducing the amount of chemical fertilizers required. Increased nutrient availability and less reliance on synthetic nitrogen fertilizers are both benefits of PGPR's nitrogen-fixing capability.

Additionally, unlike using a single species, combining different rhizobacterial species improves soil health and promotes sustainable agriculture. Some common nitrogen-fixing bacteria, such as rhizobia, have been found to coexist with various PGPR in the roots of nonleguminous plants, according to recent studies. The synergistic formation of nodules and enhanced nitrogen fixation capacity may arise from the interaction of PGPR, such as Pseudomonas species, with *Rhizobium* [80]. And it's possible that other bacteria, such as Gammaproteobacteria (*Pseudomonas*) and Betaproteobacteria (*Burkholderia*), can form nodules in *Robinia pseudoacacia* roots because they've acquired crucial rhizobia-encoded genes for nodulation and nitrogen fixation via horizontal gene transfer [81]. These results shed light on the complex web of relationships that exists between plant-growth-promoting saprophytic bacteria like rhizobia and nitrogen-fixing bacteria like nitrobacter [29]

4.2 PHOSPHATE SOLUBILIZATION

Phosphorus (P) is a vital nutrient for plants since it aids in root growth, seed development, and crop maturity [82] and is involved in many metabolic activities such photosynthesis, respiration, production of macromolecules, and signal transduction. [83]. However, plants can only absorb low amounts of phosphatic fertilizers due to their fixation in the soil as insoluble complexes [84]. Phosphate fertilizers are extremely wasteful and unhealthy for the ecosystem. Therefore, it is important to discover a natural and harmless method to increase crop yields in low Phosphorus soils. Multiple PGPR have been identified, each with a unique mechanism for transforming insoluble phosphate complexes [85].

By solubilizing and mineralizing insoluble forms of phosphorus, PGPR makes the element accessible to plants [86]. Phosphorus is made more soluble into organic compounds produced by soil microbes. These compounds reduce the pH of the medium by chelating mineral ions, which allows them to enter the soil solution. [87]. Phosphate-solubilization can also occur via mineralization, the process by which soil bacteria use enzymes like phosphatases and phytases to convert insoluble phosphate molecules into soluble ones that plants can use [88]. Phosphatases are a family of extracellular enzymes that convert organic Phosphorus substrates into inorganic Phosphorus. Phosphate is a key component of organic phosphorus in soil, and phytases are crucial to getting the phosphate out of the phytic acid. [89]. Phosphates are easily absorbed by plants once their organic and inorganic forms have been simplified. This phosphate solubilizing enzyme development is extremely desirable as it may have significant applications in sustainable agriculture [90].

4.3 POTASSIUM SOLUBILIZATION

Economically significant crops like cotton, rape, pepper, cucumber, peanut, and maize have benefited from PGPR's ability to solubilize potassium and raise soil potassium levels, boost plant potassium intake, and stimulate crop development [91]. Plant requires a steady supply of potassium to control cell growth processes such hair root expansion, pollen tube expansion, osmotic pressure regulation, and chemical compounds transportation [92]. Insoluble potassium in the soil can be converted into forms that plants can use by potassium-solubilizing bacteria [93]. There are more potassium-solubilizing rhizobacteria (KSR) in rhizospheric soil than in bulk soil. Soil feldspar and aluminosilicate minerals contain potassium, which can be extracted by potassium-solubilizing bacteria [94]. Inoculating maize with *Azotobacter* has been shown to boost growth in saline stress conditions by increasing the plant's ability to exclude sodium and absorb potassium [95,96]

Minerals in the soil can be decomposed by organic acids like citrate, oxalate, and acetate. These minerals include clay silicates, mica, feldspar, sandstone, granite, calcite, and dolomite from limestone. This process increases plant nutrient availability by changing insoluble potassium to a soluble form that can be easily absorbed by plants. Soil fertility and agricultural yields can be improved with the help of Bacillus species, which generate carboxylic acids that dissolve potassium complexes [16,97]. Based on these facts, potassium-solubilizing rhizobacteria may significantly contribute to long term high yield, enhanced productivity, and escalating soil fertility.

4.4 PRODUCTION OF PHYTOHORMONES

Plants produce substances called phytohormones, which function as signalling molecules and have a profound effect on a wide range of physiological processes, such as cell elongation, apical dominance, tissue differentiation, cell division, and intracellular communication, even at very low concentrations [98]. Auxins, gibberellins, cytokinins, ethylene, and abscisic acid are the five main classes based on their structural makeup and reactivity to physiological processes in plants. It is common for plants to keep their levels of endogenous hormones constant under harsh environmental conditions [99]. Bacteria found in and around plants and soil create phytohormones, which are essential to the development and growth of plants. They are also essential in reducing the effects of biotic and abiotic stress. Plant growth is controlled and responses to stress are triggered by auxins, gibberellins, and cytokinins [100]. The effects of bacterially generated phytohormones on plant growth are discussed in detail. *Pseudomonas fluorescence* PGPR-7 and *Trichoderma* sp., under cadmium-stressed conditions, tolerated cadmium (Cd) up to 2000 µg/mL and produced several plant growth-regulating chemicals (IAA, siderophore, ACC deaminase ammonia and HCN), respectively [101]

4.4.1 AUXINS

Auxins are bioactive substances involved in a wide range of physiologic activities in plants. Numerous studies have shown that plants treated with auxins producing PGPR, grows much faster than untreated plants [102]. The essential processes such as cell Extension, proliferation, and differentiation are all facilitated by auxins. Auxins trigger signalling pathways in root epidermal hair cells, leading to an expansion of root hairs in response to the auxin gradient. [103]. According to an examination of transcriptome sequencing data, 90% of the genes associated with root growth are favourably regulated by auxins [104]. In addition, auxin synthesis by plant growth-promoting rhizobacteria can modify and enhance the antioxidant system in economically significant crops such as wheat [105]. *Rhizobium, Pantoea, Agrobacterium, Pseudomonas, and Bacillus* species have been identified as PGPR for auxin synthesis [106]. Indole-3-acetic acid (IAA)-producing PGPR have also been involved in mitigating metal stressors by inhibiting metal sorption and boosting antioxidant enzymes [107]. Despite the availability of a number of strategies for reducing the effects of stress, IAA synthesis by PGPR may prove to be the best long-term strategy for increasing crop and biofertilizer yields. The most important auxin, IAA, is created in several different ways. Microbial IAA synthesis largely involves four tryptophan-dependent pathways. Based on the intermediate molecules produced, these reactions are known as the indole-3-

Acetamide pathway, the indole-3-pyruvic acid pathway, the indole-3-acetonitrile pathway, and the indole-3-tryptamine pathway [108]. IAA is mostly synthesised via the indole-3-pyruvic acid pathway in PGPR. It is challenging to identify and characterize separate IAA production pathways since the enzymes involved are often encoded by large gene families. L-tryptophan is a key precursor for IAA production in both plants and microorganisms. The first step in this pathway involves the conversion of tryptophan to indole-3-pyruvate via an aminotransferase. Flavin-containing monooxygenases catalyse the second step, wherein indole-3-pyruvate is converted into IAA [109]. The principal method for the production of auxin, which is essential for many aspects of plant development, involves the conversion of tryptophan to isoamylamine.

4.4.2 GIBBERLLINS

The gibberllin family of tetracyclic diterpenoid carboxylic acid derivatives plays important roles in many aspects of plant development and physiology. For both stressed and non-stressed host plants, gibberellins act as signalling molecules [110]. By reducing superoxide dismutase, flavonoids, and radical scavengers, the gibberellin-producing PGPR protects plants from biotic and abiotic stress [110]. Regulation of salt stress through decreased lipid membrane peroxidation is achieved through the action of gibberellins, which promote calcium ion and other nutrient intake [111]. Soybean development is stimulated by the exogenous application of gibberellins, which play a protective role under stressful conditions by elevating daidzein and genistein levels [112]. Dry weight, fresh weight, and moisture content of crops were all improved after being inoculated with GA-producing Bacillus and Pseudomonas species.

The 5-carbon precursor to all terpenoid molecules, geranyl-geranyl diphosphate (GCPP), and isopentenyl diphosphate (IDP) combine to form gibberellin [113]. Both the mevalonic acid pathway (in the cytoplasm) and the methyl erythritol phosphate pathway (in the plastid) contribute to the production of the basic isoprenoid unit (IPP) in most plant chloroplasts. The process can be broken down into three distinct stages according to the involvement of various enzymes and subcellular structures. Enzymes localised in proplastids catalyse the initial stage in ent-kaurene synthesis. Subsequently, monooxygenases at endoplasmic reticulum sites catalyse the oxidation of ent-kaurene to GA12-aldehyde, the general GA precursor. Di-oxygenases in the cytosol catalyse the last step of the process [114].

In addition, gibberellins promote blooming, stem elongation, fruit set, and germination in a wide range of higher plants [115]. Sensitive reactions to hormones and other signalling components are crucial for the proper development of sessile plants. As a result, it is crucial for plants to maintain strict control over their hormone signalling pathways..

4.4.3 CYTOKININ

Cytokinins are a class of growth regulators that play important roles in a wide range of plant activities, from gametogenesis to root meristem specification to vascular development to shoot and root growth to meristem homeostasis to senescence. They also control reactions to things like light, stress, and nutrient availability in the environment [116]. Cytokinin concentrations in soil and plants are raised because most bacteria can synthesise cytokinins [117]. Soil health and plant productivity can both benefit from inoculating the root environment with cytokinin-producing rhizobacteria. Plants lose cytokinins when subjected to stresses like drought, and it has been shown that applying cytokinins encourages stomatal opening, possibly through interacting with stored abscisic acid (ABA) [118]. Plant cytokinin levels are said to rise in response to microorganisms [119]. As a result, plant growth-promoting cytokinin-producing microorganisms can be used as markers in plant health management.

4.5 SIDEROPHORES

Only by using PGPR, which is a powerful bioprotectant, can natural soil health be preserved [120]. The creation of iron-chelating chemicals, also known as siderophores, is one of the earliest-described methods for preventing plant disease. [121]. Several PGPR produce siderophores (of various types, such as *bacillibactins, pyoverdines, cephalosporins*) in response to low ironlevels in the soil, thus when it is limiting, PGPR can form Fe3-siderophores complexes, making it unavailable for other pathogenic microorganisms, such as pathogenic fungi. Iron is unavailable to plants unless chelated by rhizobacterial (or plant) siderophores.[122]. Since siderophores, which are iron-chelating compounds, have been involved in antifungal action by depriving plant pathogens of this vital element (Fe), they have been used in a number of studies as potential biocontrol agents [123].

4.6 VOLATILE ORGANIC COMPOUNDS (VOCS)

During interactions with plants and other rhizosphere microorganisms, PGPR (and other organisms) produce volatile organic compounds (VOCs) with distinct roles and functions [124]. There is substantial evidence that VOCs have dual direct and indirect action during plant growth promoting activities [125], i.e., rhizosphere VOCs can induce plant growth directly or indirectly by limiting the development of potential phytopathogens. *Arthrobacter agilis* UMCV2 is a rhizobacterium that produces the volatile compound N,N-dimethylhexadecylamine (DMHDA), which protects plants from the pathogens *Botrytis cinerea* and *P. cinnamomi* in vitro. Furthermore, the DMHDA compound induces the Fe-uptake mechanisms of *M. truncatula* seedlings in Fe-deficient conditions [126,127]. *Pseudomonas pseudoalcaligenes'* volatile organic compounds induced the highest levels of germination, growth promotion, and drought tolerance in maize plants [128]. Dimethyl disulfide (DMSD) is another volatile compound produced by the PGPR that has been shown to stimulate growth in Arabidopsis plants by increasing their sulphur nutrition. DMSD also acts as an antagonistic agent against major plant pathogens like *B. cinerea* and as an elicitor of defence responses in plants [129,68]. When PGPR (and other organisms) interact with plants and other rhizosphere microorganisms, they produce volatile organic compounds (VOCs) that serve a variety of purposes [124]. There is substantial evidence that VOCs have dual direct and indirect action during plant growth promoting activities [125], i.e., rhizosphere VOCs can induce plant growth directly or indirectly by limiting the development of potential phytopathogens. *Arthrobacter agilis* UMCV2 is a rhizobacterium that produces the volatile compound N,N-dimethylhexadecylamine (DMHDA), which protects plants from the pathogens Botrytis cinerea and P. cinnamomi in vitro. Furthermore, the DMHDA compound induces the Fe-uptake mechanisms of *M. truncatula* seedlings in Fe-deficient conditions [126,127]. Dimethyl disulfide (DMSD) is another volatile compound produced by the PGPR that has been shown to stimulate growth in Arabidopsis plants by increasing their sulphur nutrition. DMSD also acts as an antagonistic agent against major plant pathogens like *B. cinerea* and as an elicitor of defence responses in plants [129,68].

In a groundbreaking study by [130], The volatile chemicals, especially 2,3-butanediol and acetoin, generated by helpful Bacillus bacteria play a critical role in encouraging the growth of *Arabidopsis thaliana*. Hydrogen cyanide (HCN), on the other hand, has the opposite impact on disease-causing organisms. By blocking the electron transport pathway, this chemical aids in the suppression of infections [131]. HCN can be produced by a wide variety of bacteria [29], including *Bacillus* and *Pseudomonas species*. The ability of bacteria to produce HCN is very useful in preventing the spread of fungal infections, which aids in the development of new plants [132]. PGPR-produced For example, HCN helps with metal chelation and geochemical processes in the substrate as a biocontrol factor against phytopathogens. The related plants benefit from the increased availability of phosphate in the rhizosphere as a result of this volatile organic molecule [133,134].

4.7 HYDROLYTIC ENZYME PRODUCTION

Cellulases, pectinases, proteases, catalases, and chitinases are only some of the hydrolytic enzymes that PGPR generates and secretes. These enzymes have been shown to exhibit defense-related activity against a wide range of phytopathogens. Fungi rely on chitin, a structural component of their cell wall, to maintain their integrity. The chitin in fungal cell walls is degraded by chitinases, which are secreted by rhizobacteria that promote plant development. Chitinolytic bacteria work in this way to prevent the spread of *Botrytis cinerea* and other plant-harming fungi. As a result, chitinolytic PGPR mitigates the effects of fungal and oomycete infections on plants, hence promoting plant growth [135,136]. Rhizobacteria that produce cellulase hydrolyze cellulose to glucose via the synergistic actions of enzymes, including glucanases, hydrolases, and glucosidases [137]. Cellulase-producing bacteria have long been recognised as potential antifungal agents [138]. Cellulosic bacteria, by their degradation of cellulosic wastes, supply carbon to the rhizosphere, where it is used to boost soil health and keep nutrients in check [139]. Cellulose-making bacteria are also useful for making biofuels from plant matter [137]. Cellulase-mediated conversions are eco-friendly and sustainable alternatives to chemical processes.

5. PGPR AS GREEN BIOINOCULANTS

The term "bioremediation" describes the practise of eliminating environmental hazards by employing living organisms and natural processes [140]. The green belt plants' air pollution tolerance index can be lowered and dust dangers mitigated with the use of PGPR. Three essential desert plants (*S. rosmarinus*, *H. aphyllum*, and *N. schoberi*) are vulnerable to dust stress, whereas PGPR (*Z. halotolerans* SB and *B. pumilus* HR) may mitigate its effects [141]. As an alternative to more traditional procedures, bioremediation has allowed for the cleanup of metal-contaminated soil. The natural role of rhizobacteria in supporting plant growth is even more important in metal-contaminated soils than in traditional agricultural practices [142]. While many metals have negative connotations, the actual toxicity can range from mild to lethal. Soil organisms are harmed by cadmium and lead because these metals bind to respiratory proteins and cause oxidative damage by releasing reactive oxygen species [143]. Even at low concentrations, these metals are toxic to the soil microbes that call it home. Bulk and rhizosphere bacteria play crucial roles in the biogeochemical cycling of heavy metals, leading to the cleanup of polluted ground.

5.1 DEGRADATION OF POLLUTANTS BY PGPR

Oxidative degradation by aerobic bacteria and dechlorination by anaerobic bacteria are researched as potential pathways for the biodegradation of persistent organic pollutants (POPs). PGPR are used in aerobic bioremediation, where oxygen from the air is used to break down pollutants [144]. The use of biphenyl by bacteria has been shown to increase aerobic remediation of contaminated soil [145]. Several genes and the enzymes they code for work together to oxidise polychlorinated biphenyl (PCB) during this process [146]. Major enzymes involved in POPs degradation are dehydrogenases, dioxygenases, hydrolases, hydratases, aldolase [147]. Bacterial strains that degrade POPs via aerobic oxidation include, to name a few, *Pseudomonas, Bacillus, Achromobacter, Rhodococcus, Ralstonia,* and *Corynebacterium* [148].

Anaerobic bacterial species degrade chemical substances in the soil to release the energy they need for their metabolic processes; this process is known as anaerobic degradation. Anaerobic bacterial respiration using electron acceptors like sulphate and nitrates occurs in uncontaminated soils. Reductive dehalorespiration occurs in PCB-contaminated soils [149]. Bacterial species engage in dehalorespiration, in which chlorine substituents at the para and meta positions are attacked and subsequently replaced by hydrogen atoms [150]. Through a process called dechlorination, bacteria reduce the toxicity of chlorinated compounds and make them more amenable to aerobic degradation [151].

Pesticides persist in soil because they are not degraded quickly enough in response to high rates of application [152]. The microbial community and plants suffer because of the pesticides that are loaded into the soil's rhizosphere [152]. These compounds pose serious health hazards since they are not biodegradable and have a lengthy half-life in the environment [153]. The biomagnification effect causes the entire ecosphere to deteriorate due to the rise in pesticide levels [154]. Biotransformation, biomineralization, bioaccumulation, biodegradation, bioremediation, and cometabolism can break down pesticides [155]. Pesticides in the environment can be degraded by bacteria in the rhizosphere of soil, in groundwater, and in industrial systems [156]. Because of this, the PGPR greatly reduces the amount of pesticides in the environment, boosts soil health, and encourages plant development.

6. CONCLUSION AND FUTURE PERSPECTIVE

In order to boost plant development and yield, it is crucial to take use of PGPR's possible modes of action and the positive interactions it has with plants. The global population is predicted to reach 10 billion by 2050, with a peaking between 2070 and 2080, making PGPR indispensable [157]. Consequently, one of the goals of this initiative is to highlight the various mechanisms of PGPR and their enormous potential to create ideal conditions for sustainable agricultural production. A better understanding of ecological roles played by rhizoacteria in a microecosystem like rhizozphere is required for PGPR inoculation [125]. The effectiveness of a bioinoculant with stimulatory or protective effects depends on a number of factors, such as the colonising capacity of PGPR, interaction with other beneficial soil microorganisms, tolerance, and adaptive mechanisms to abiotic and biotic stresses, and the regulation at the molecular level of genes involved in the production of diffusible and volatile compounds and enzymes in the rhizosphere. Nonetheless, the discovery of new bacterial strains (or even species) with plant growth augmenting activities emerged, revealing the shadow side of well-studied and little-explored ecosystems with potential agricultural applications. More recently, molecular and genomic approaches have shed light on the distinct but crucial roles played by bacterial consortiums in direct and indirect activities of plant growth promotion [158]. Despite these advances, a significant gap remains between laboratory and field application, which is typically the bottleneck that limits the potential for expanding the use of PGPR in agriculture. In this stage, scientists and other business and political actors, especially in developing countries, must create optimal and legal conditions to benefit agricultural and economic production while also taking into account sustainable agriculture and an environment health for the population.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTIONS

Author a : Conceptualization, literature search, writing - reviewing and editing.
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