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Review Article

Plant growth promoting *Rhizobacteria*: a novel approach towards sustainable agriculture

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Agricultural sustainability is increasingly important in the modern era, as conventional agriculture will not be able to meet our future needs. In the area of agriculture, chemical fertilizers used in the control of pests, weeds and pathogens and for raising crop yields disrupt and damage the ecosystem. A viable alternative to conventional agriculture is the use of soil microorganisms that could promote plant growth and development. Plant growth-promoting Rhizobacteria (PGPR) reside in the rhizosphere and use a variety of mechanisms to contribute to plant growth. They can serve as biofertilizers (improves nutrition content), biostimulants (produces phytohormones), and biocontrol agents (provides against diseases). The use of PGPR provides promise of reducing food insecurity, keeping our environment clean, and mitigating public health risk, so there is a compelling reason to globally adopt biological agents. The objective of this review is to promote the use of PGPR, in the form of bio-inoculum, in our research and explore the formulation design of PGPR in sustainable agricultural practices.

Keywords: *Sustainable agriculture, PGPR, microbes, PGD, Rhizobia*

Introduction

The projected population of the world is up to 8.3 billion and 9.1 billion people by the years 2030 and 2050, respectively, which may result in food crises. Therefore, special attention has been paid to improving the yield of crops and achieving food security. In the modern cultivation process, fertilizers especially nitrogen and phosphorous fertilizers were used indiscriminately. The usage of these fertilizers significantly contaminated the soil, water, and air. Their excessive use harms the soil microbial community and adversely affects soil fertility (Youssef & Eissa, 2014). When these fertilizers are used continuously, the pH and the exchangeable bases decrease, making the nutrients inaccessible to crops. As a result, crop productivity is decreasing. Farmers are increasingly depending on the chemical sources of nitrogen and phosphorous. Their production is not only costly; it also wastes natural gas and oil (non-renewable resources) that are utilized in their production. Their usage is hazardous to both humans and the environment (Joshi et al., 2006). There is a need for the best alternative method that can solve this problem and improve crop yield. To use agrobiology to tackle food security issues, special attention must be paid to the engineering of beneficial soil microbes that have been associated with reducing issues in agricultural practices (Van Veen et al., 1997). Using biofertilizers to increase soil fertility is one of the main elements of sustainable agriculture (Zaidi et al., 2015). In the last few years, many studies have been conducted for the potential replacement of agrochemicals (pesticides and fertilizers) with PGPR

for the stimulation of plant growth. It is because they are easy to access, low-cost, and have a simple application method. Additionally, PGPR recognizes the best methods for managing soil and crops to increase soil fertility and promote more agricultural sustainability (Maheshwari et al., 2012). They have a significant impact on agricultural production, whether used alone or in the form of consortia (Dinesh et al., 2015). According to Ahemad & Khan (2009), they participate in a variety of biotic activities that keep the ecosystem of soil sustainable both for the cycling of nutrients and for the production of crops. They alter plant growth in various ways. These include the development of soil structure, recycling of important elements, breakdown of organic matter, root growth stimulation, solubilization of complex forms of nutrients, production of growth regulators essential for the fertility of the soil, as well as promoting vegetation changes (Sivasakthi et al., 2014). Since the 1950s, a large number of PGPR strains have been examined and tested in laboratories, field research, and greenhouses worldwide (Zehnder et al., 2001). Currently, PGPR as inoculants are utilized in underdeveloped countries. The right selection of the PGPR, which must be tailored to the crop and soil combination, is essential for the successful establishment of introduced bacteria. In this review, we examine PGPR's functional traits and their basic mechanisms for promoting plant growth. Their most recent uses in various agroecosystems have been fully discussed to acquire a comprehensive understanding of the functions and applications of these advantageous Rhizobacteria.

Rhizosphere and its classification

The area of the ground that surrounds a root system of plants is called the rhizosphere. (Walker et al., 2003). The rhizosphere is one of the ecological niches that has the highest population of bacteria and is affected by root exudates. There are three divisions within the rhizosphere. The exorhizosphere, which is related to soil that sticks to roots and stays there even after vigorous shaking, is the first division. The rhizoplane, which describes the thin layer of the root as well as any related soil particles, is the second division. The endo rhizosphere, which is an intracellular space in the tissues of the root where endophyte bacteria are present, is the third division (Bowen & Rovira, 1999).

PGPR and its classification

Rhizobacteria' are a class of bacteria that are associated with roots (Zablotowicz et al., 1991). The two distinct forms of organisms that might promote plant development are extracellular growth plants rhizobacteria (ePGPR) and intracellular plant health-stimulating rhizobacteria (iPGPR) (Martínez-Viveros et al., 2010). iPGPR resides inside the root cells, typically in the specialized modular structures, whereas the ePGPR may be found in the root cortex's cell spaces, in the rhizosphere, or the rhizoplane (Ahemad & Kibret, 2014). On the other hand, PGPR can be categorized according to their functional activities (Somers et al., 2004). They can be categorized as phytostimulators (which stimulate the production of phytohormones to promote plant development), rhizoremediators (which degrade organic pollutants), bio-fertilizers (which make nutrients more readily accessible to plants), and biopesticides (which produce antifungal metabolites as well as antibiotics for the cure of diseases) (Antoun & Prévost, 2006).

General characteristics of PGPR

The fundamental properties of Rhizobacteria are as follows

(i) They can colonize the surface of the root.
(ii) They can survive, proliferate, and engage in competition with other microorganisms at least long enough to exhibit their actions that promote plant growth or protection.
(iii) They must possess the capacity to encourage plant development (Kloepper, 1994).

Mechanism for promoting plant growth

Rhizobacteria are widely known for promoting plant development, and this plant development is because of their unique characteristics that make them so effective in their mode of action. PGPR employs some mechanisms for promoting growth in plants as shown in figure 1. These are often categorized as direct as well as indirect methods (Glick, 1995). Direct mechanisms take place inside plants and have a direct impact on plants' metabolism, whereas indirect mechanisms, as the name suggests, occur outside the plant and do not affect the plants directly. The direct mechanisms involve, biofertilization, rhizo-remediation, and phytohormones production (Bhattacharyya & Jha, 2012). PGPR benefits plants indirectly by controlling harmful microorganisms that hinder the growth of plants. This involves producing antibiotics, synthesizing extracellular enzymes needed to break the cell wall of fungi, lowering the toxicity of pollutants, competing with pathogens for resources and niches, and inducing systemic resistance (Bhattacharyya & Jha, 2012; Zahir et al., 2004). Generally speaking, PGPR works by producing phytohormones, promoting the uptake of environmental nutrients, and preventing plant diseases (Glick et al., 1998)

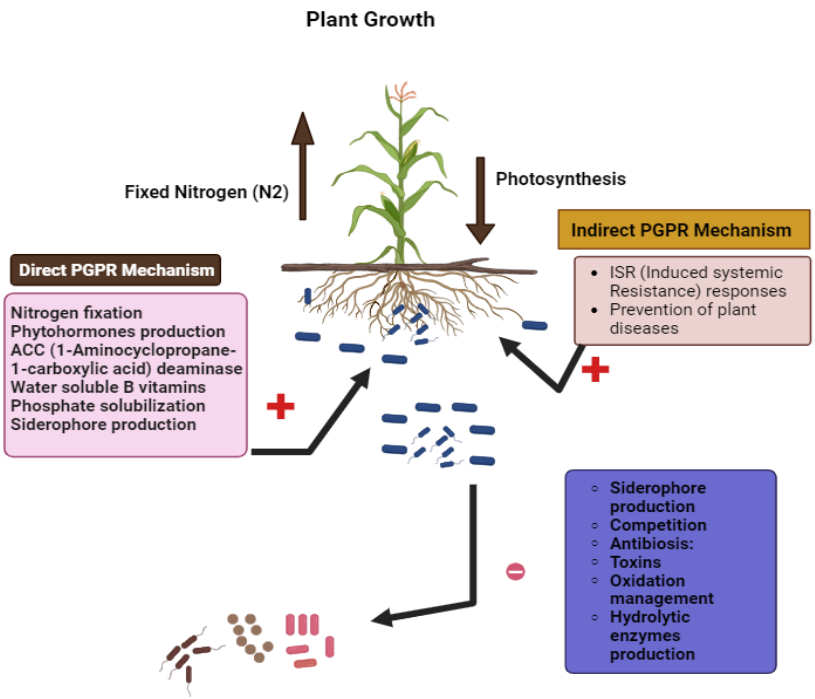

Figure 1. Mechanism for promoting growth by rhizobacteria

Biofertilization

Chemical fertilizers are generally used to increase soil fertility and crop productivity, but this often harms the complexity of the turnover of abiotic as well as biotic materials (Perrott et al., 1992; Steinshamn et al., 2004). This happens due to potential nutrient runoff, particularly of phosphorous and nitrogen. Biofertilizers contain cells of microorganisms that can fix nitrogen (N), solubilize phosphorous (P), oxidize sulfur (S), or break down organic matter. A scientist defined biofertilization as the packing of cultures of bacteria, algae and, fungi in a carrier material, either separately or in combination (Mahdi et al., 2010)**.** To induce rhizosphere or internal plant colonization, microbial base material or inoculant is given to soil, seeds, or plant surfaces. As a result, the availability of specific nutrients promotes plant development. Biofertilizers are essential components of organic agriculture because they help to produce safe and healthy food. Additionally, they Have a significant effect on long-term soil fertility and agricultural sustainability.

Fixation of nitrogen

The most vital element for plant health is nitrogen. All forms of life depend on nitrogen. Even though it makes up over 78% of the atmosphere, it is not easily absorbed by plants. Unfortunately, no plant species can turn (N_2) into ammonia. Bacteria that can fix nitrogen convert N_2 into plant-utilizable forms by using nitrogenize which is a hard enzyme system. This phenomenon is referred to as biological nitrogen (N_2) fixation (Kim & Rees, 1994). Two groups of bacterial strains can fix N_2 from the atmosphere. One group fixes dinitrogen by making a mutualistic relationship with plants (leguminous plants). This nitrogen fixation is known as symbiotic N fixation. This process begins with the introduction of bacteria into the roots, after which nodules are formed where N is fixed, e.g., strains of *Rhizobium* (Ahemad & Kibret, 2014). The genera identified in this group include *Rhizobium, Bradyrhizobium, Sinorhizobium,* and *Mesorhizobium* (Zahran, 2001) The other group of bacteria are free-living and lack specificity. These free-living nitrogen fixers belong to the following genera: *Azoarcus, Azotobacter, Acetobacter, Azospirillum, Burkholderia, Diazotrophicus, Enterobacter, cyanobacteria, Pseudomonas,* and *Gluconacetobacter* (Bhattacharyya & Jha, 2012; Vessey, 2003). Freely living and symbiotic bacteria both have the nitrogen-fixing gene (*nif* gene)

Solubilization of phosphate

After nitrogen, phosphate is another essential element for plants. It makes up about 0.2% of plants' dry weight, as it is a necessary component of phytin, phospholipid, and nucleic acid. It is essential to nearly every important metabolic function in a plant, including photosynthesis, energy transformation, etc. (Khan et al., 2010) but phosphate in soil is not easily accessible to plants. There are two main insoluble forms of P in soil: organic forms like phosphomonoesters, phosphodiesters, phosphodiester, and inositol phosphate (soil phytate) and mineral forms including apatite, oxy apatite,

and hydroxyapatite (Khan et al., 2002). Solubilizing and mineralizing phosphate through phosphate-solubilizing bacteria is one of the most significant physiological functions of bacteria in the biogeochemical cycle of soil (Figure 2). The most significant bacteria that possess this ability belong to following genera: *Azotobacter, Beijerinckia, Bacillus, Burkholderia, Erwinia, Enterobacter, Flavobacterium, Microbacterium, Pseudomonas, Rhizobium and Serratia* (Bhattacharyya & Jha, 2012). Phosphate solubilization occurs by a mechanism in which organic acid is produced and secreted by microbes, i.e., PGPR (Han & Lee, 2006). These microorganisms break down sugars (glucose, fructose, mannitol, and other types of carbohydrates) in root exudates to produce organic acids. The organic acids can effectively chelate divalent Ca cations or lower pH levels, which makes it easier for phosphates to be released from insoluble phosphatic compounds (Pradhan & Sukla, 2006). (Glick, 2012). Organic phosphorous is caused by the production of multiple phosphatases. Phosphoric esters are hydrolyzed by these enzymes. Agricultural microbiologists are very interested in the idea of increasing the uptake of P by crops through artificial inoculation with rhizobacterial strains that have phosphate-solubilizing traits.

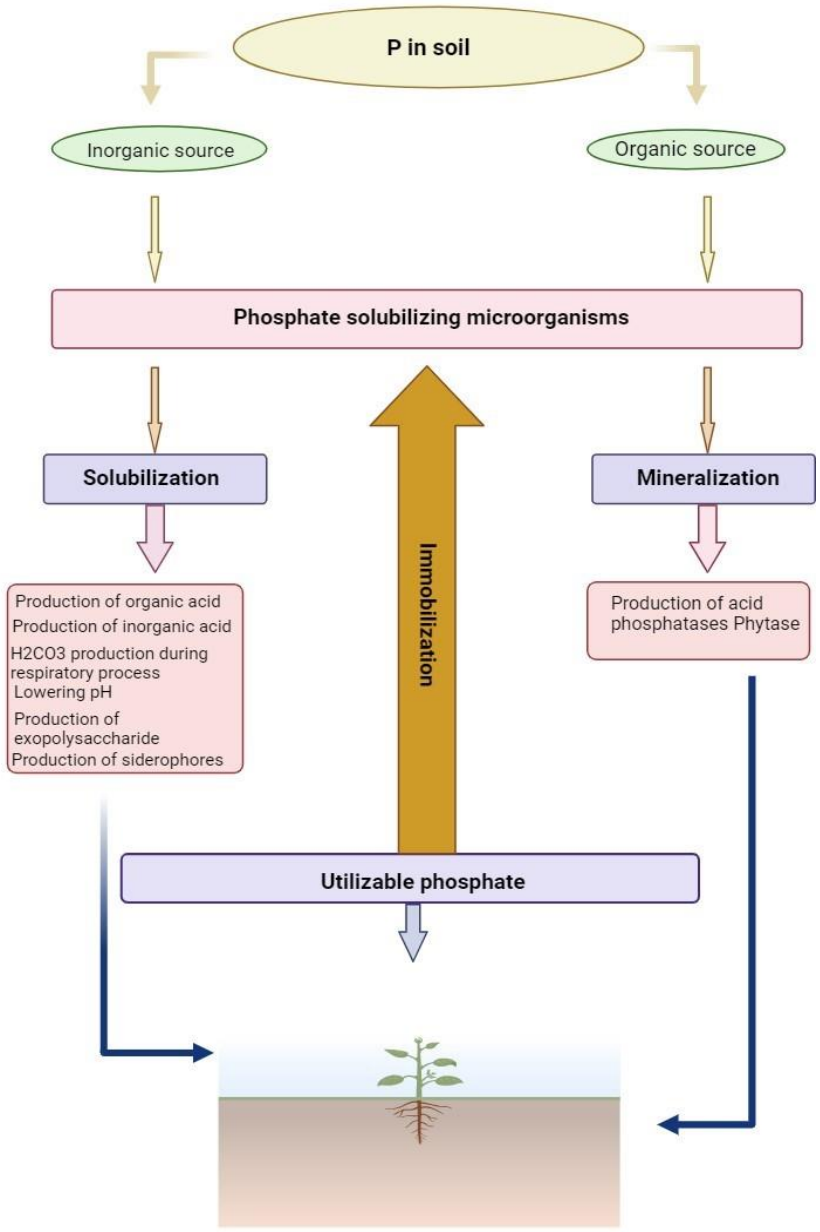

Figure 2. Solubilization and mineralization of phosphate by Soil rhizobacteria

Solubilization of potassium

The third essential micronutrient required by plants is potassium. Over 90% of potassium is found in the form of silicate minerals and rocks, and there is often a relatively low amount of potassium in the soluble form (Parmar & Sindhu, 2013). Currently, one of the biggest obstacles to agricultural productivity is a potassium deficit due to an imbalanced

application of fertilizer. Plants that are deficient in potassium grow slowly, generate little seeds, have low yields, and have poorly developed roots (Kumar & Dubey, 2012). This demonstrated that there is a need to discover another source of potassium that could meet the potassium deficiency in plants and improve their growth and productivity. PGPR can solubilize potassium by producing organic acids (Han & Lee, 2006). It has been discovered that rhizobacteria that can solubilize potassium include *Acidothiobacillus ferrooxidans, Bacillus edaphicus, Bacillus mucilaginosus, Burkholderia, Paenibacillus* sp., and *Pseudomonas*, releasing potassium from minerals in soils (Potassium source) (Liu et al., 2012). To improve agriculture, PGPRs that have potassium solubilizing traits are used as biofertilizers. This reduces the need for agrochemicals and supports the production of eco-friendly crops.

Production of siderophores

Siderophores are low molecular weight, iron-chelating compounds that are produced by rhizobacteria. Iron is an essential micronutrient that plays an essential role by acting as a cofactor for many enzymes having redox activity. Primary physiological activities in plants such as nitrogen fixation, photosynthesis, respiration, etc. all depend on it. Iron is the fourth element that is found abundantly on the earth, but in aerobic soils, assimilation of iron for both bacteria and plants is difficult. This is because ferric ion (Fe^{3+}), which is the most prevalent form of iron in nature is not easily soluble and hence leaves very little iron available for uptake by living organisms. Plants and microbes have developed specific strategies to meet their iron deficiency. These mechanisms involve the release of siderophores for the chelation of insoluble forms of iron and then iron-siderophore complexes are taken up by certain receptor proteins that are present in the plant's outer membrane (Sharma & Johri, 2003).

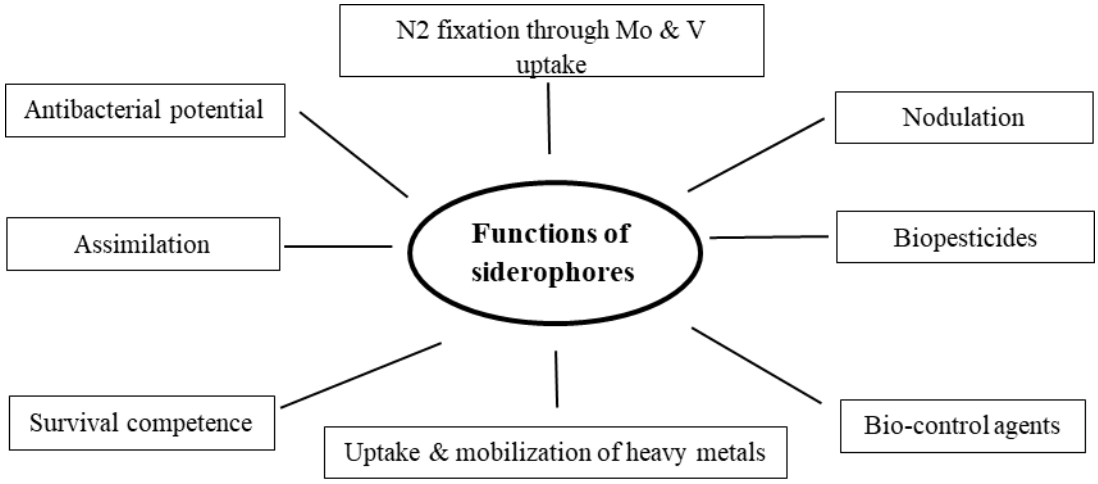

Figure 3. Impact of siderophores on plant growth secreted by microbes

Biostimulants

These are the organic compounds that have an impact on the growth of plants. Generally, we called them growth regulators, like auxin (indole 3-acetic acid), cytokinin, gibberellin, and ethylene. Over the years, these chemical substances have been identified as the four main hormones required for plants' morphological, physiological, and biochemical development. These phytohormones are produced by a variety of rhizosphere microbes. Numerous PGPR species, including those from genera*, Azospirillum, Acetobacter, Alcaligenes, Rhizobium, Enterobacter, Bradyrhizobium, Klebsiella, Pseudomonas, and Xanthomonas,* as well as the species *B.licheniformis, Bacillus pumilus, Aspergillus sp, Penicillium niger, Glucanoacetobacter sp, Phosphobacteria sp* and*, Paenibacillus polymyxa,* capable of producing these to plant hormones (Shobha & Kumudini, 2012; Chatzipavlidis et al., 2013).

Auxin synthesis

Auxin is an important hormone that controls plant processes, either directly or indirectly. Indole acetic acid (IAA) is the most prevalent form of natural auxin that promotes root growth. It is essential for plant's cell division, increases tuber and seed germination, enhances the development of the roots and rate of xylem, initiates the formation of lateral as well as adventitious roots, regulates responses of plants to gravity and light, has an impact on photosynthesis and pigment formation, and makes plants more resistant to adverse environmental conditions (Spaepen & Vanderleyden, 2011). Even though plants can synthesize this chemical molecule naturally, they nevertheless rely heavily on exogenous sources so that they can perform optimally. The majority of this external demand is managed by rhizobacteria and other soil-related microorganisms (Patten & Glick, 2002 ; Khalid et al., 2006). The species and strain type, culture conditions,

developmental stage, and nutrient availability in the rhizosphere are crucial factors in PGPR's ability to synthesize IAA efficiently (Ashrafuzzaman et al., 2009). Bacteria that can produce IAA are found abundantly in auxin pools of soil or plants. Moreover, L-tryptophan helps in the production of auxin by functioning as a precursor. Root exudates contain tryptophan, an amino acid that occurs naturally. Findings demonstrate that as the L- Tryptophan level rises, metabolic and biochemical activities of the auxin-producing bacteria rise as well. As a result, root length and root architecture change (Bartel, 1997).

Synthesis of gibberellic acid

A class of tetracyclic diterpenes called gibberellic acid has a major impact on biological processes, including leaf expansion, seed germination, stem elongation, the development of flowers as well as fruits, and trichome initiation (Yamaguchi, 2008). Under stress conditions, Gibberellin and its producing genera are the main targets because they are essential for promoting effective photosynthetic processes. Because of this, they function as an important growth regulator, enhancing crops' resistance to adverse conditions. Gibberellin-producing rhizobacteria have been documented (Kang et al., 2009). However, their exact mechanism of growth improvement through the synthesis of gibberellin is not fully understood yet. These growth hormones may be used exogenously to amend contaminated soil and enhance crop overall performance (Iqbal et al., 2011).

Cytokinin synthesis

It is essential to several important plant processes. These include mobilization of nutrients, differentiation of shoot as well as vascular tissues (xylem and phloem), production of anthocyanin, chloroplast biogenesis, apical dominance, leaf senescence, and photomorphogenic development (Davies, 2004). Studies have demonstrated that cytokinin perfectly regulates plants' adaptability during growth, particularly in soil that has been polluted with salt. According to research, inoculating seedlings with *Bacillus subtilis* strains that can produce cytokinin makes plants resistant to environmental stress.

Ethylene synthesis

This particular phytohormone has a broad range of biological effects, including initiation of root, germination of seed, ripening of fruit, and abscission of leaves (Kaur et al., 2016). It plays beneficial roles at low concentrations. When its concentration is high, it inhibits some important processes of plant development, like root elongation, induces leaves to fall off or be destroyed, and also influences other cellular processes negatively. As a result, crop performance is reduced (Bhattacharyya & Jha, 2012). That's why it is categorized as a senescence hormone. 1-aminocyclopropane-1 carboxylic acid (ACC) deaminase is an enzyme needed to overcome these concerning effects. 1-aminocyclopropane-1 carboxylic acid (ACC) is the primary precursor used by plants to synthesize ethylene. The role of this enzyme (ACC deaminase) is to convert ACC into ammonium and α- ketobutyrate (Glick et al., 2007). In plants, ethylene level is regulated by PGPR which produces ACC deaminase enzyme. This prevents inhibition of growth caused by excessive ethylene levels (Noumavo et al., 2016). Rhizobacteria that have ACC deaminase activity belong to the following genera: *Achromobacter, Acinetobacter, Agrobacterium, Azospirillum, Alcaligenes, Burkholderia, Bacillus, Enterobacter, Serratia, Pseudomonas,* and *Rhizobium* (Dell'Amico et al., 2008). The activity of the ACC deaminase enzyme, which is produced by soil rhizobacteria, has been demonstrated to be a determinant of *Brassica napus* plant growth.

Biocontrol mechanism

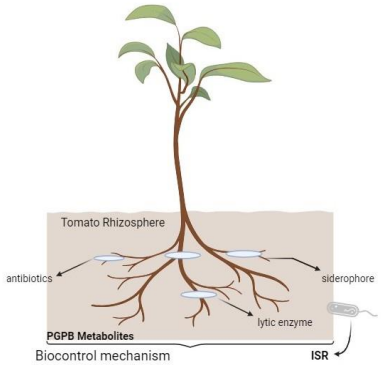

Figure 4. Rhizobacteria's biocontrol mechanism

It has been determined that PGPRs are biocontrol agents that can suppress the growth of phytopathogens. These plant pathogens were previously managed with chemical pesticides, but this method has raised concerns about environmental pollution. This has led to a condition known as the "pesticide treadmill," in which phytopathogens become resistant to these chemical pesticides over time, necessitating the creation of new pesticides (Fernando et al., 2006). Therefore, a new strategy for controlling plant diseases must be developed. This method of plant disease prevention (using PGPR as a biocontrol agent) uses beneficial rhizobacteria or their metabolites to reduce or neutralize the negative impacts of the pathogens while enhancing the health of the plants (Junaid et al., 2013).

Antibiotic production

Antibiotic production is one of the most efficient and extensively studied biocontrol methods for controlling phytopathogens (plant pathogens). Antibiotics are substances with a small molecular weight that prevent the growth of harmful bacteria in plants. PGPR produces a variety of antibiotics that have shown efficacy against phytopathogens under laboratory conditions (Bowen & Rovira, 1999). The antibiotics produced by PGPR include amphibian, ionomycin A, 2,4-diacetyl phloroglucinol (DAPG), phenazine, pyrrolnitrin, pyoluteorin, tropolone, tensin, and the synthesis of cyclic lipopeptides (Loper & Gross, 2007). Additionally, oligomycin A, zwitterion A, xanthobaccin, and kanosamine are also produced (Compant et al., 2005). *Bacillus, Pseudomonas* strains, *Streptomyces,* and *Stenotrophomonas* species possess the ability to synthesize these antibiotics. One issue with relying too much on antibiotics produced by PGPR is that as a result of their increased use, some plant pathogens have the potential to become resistant to particular antibiotics. To avoid this, some researchers have used those strains as biocontrol agents that can produce one more antibiotic (Glick, 2012).

Hydrogen cyanide (HCN) producing rhizobacteria

Pseudomonas species are mostly linked with the production of hydrogen cyanide (cyanogeneis) quantitatively (Lorck, 1948). Hydrogen cyanide, an extensively studied biocontrol agent is widely known for being a volatile compound. Most metalloenzymes are inhibited by their cyanide ion, particularly cytochrome c oxidases (Blumer & Haas, 2000). In gram-negative bacteria, it is synthesized as a secondary metabolite formed from glycine that is mediated by the enzyme HCN synthase. *Thielaviopsis basicola* (Laville et al., 1998), which causes tobacco black root rot, was controlled by *P. fuorescens* strain CHAO (Voisard et al., 1989). The presence of glycine in the culture media of several rhizobacteria still seems to make them cyanogenic.

Nutrients and niche competition

Soil rhizobacteria must possess a certain capacity to effectively compete for the available resources and niche to claim dormant status over the other microorganisms residing in the soil. This is essential to reduce the occurrence of phytopathogens (Kamilova et al., 2005). As a result of rapid colonization of PGPR, this kind of adaptation makes the roots unfit for the phytopathogens. Other characteristics include the use of exudates secreted by roots, the presence of lipopolysaccharide, flagellum, and chemotaxis, which enhance PGPR's ability to survive in addition to their natural growth that they acquire through competition when sufficient nutrients are available (Lugtenberg & Kamilova, 2009). A good example is the fact that iron cannot be accessed by phytopathogenic fungi when it has been chelated by siderophores produced by PGPR. In Niche competition, by delaying pathogen colonization until the available substrate is depleted, these delay strategies are used by PGPR to enhance the occupation of the physical site.

Induced systemic resistance (ISR)

A physiological condition known as "induced resistance" arises in response to particular environmental stimuli and involves an increase in the defensive capacity. As a result, the natural defense system of plants is strengthened against upcoming biotic threats (Avis et al., 2008). To combat plant pathogens, rhizobacteria induce the production of a protective response. This could make the plant a far more powerful and well-adapted species (Van Loon, 2007). This type of biological phenomenon is not extensively studied in terms of the gene and gene product that controls it. Induced systemic resistance increases the host plant's mechanism against several pathogens by the use of organic acids and plant hormones, namely salicylic acid, ethylene, and jasmonic acid (Beneduzi et al., 2012; Niranjan Raj et al., 2006; Pieterse et al., 2014). In response to ISR, rhizobacteria typically modify the metabolic and physical responses of cell walls to environmental stress in addition to strengthening them mechanically and physically (Labuschagne et al., 2011). The mechanism of induced systemic resistance in PGPR is the synthesis of siderophores, lipopolysaccharide, flagella, antibiotics, salicylic acid, and N-acyl homoserine lactone (AHL) molecules (Schuhegger et al., 2006; Van Loon, 2007). This type of biocontrol mechanism involves the participation of *Bacillus pumilus, Pseudomonas species, and enterobacteria* (Jourdan et al., 2009).

Defense enzymes

Various rhizobacterial strains are capable of secreting enzymes that destroy the cell wall. β 1,3-gluconase, protease, chitinase, lipase, and cellulase, are among the enzymes that smash down the cell wall of harmful fungi (Chet & Inbar, 1994). The defense enzyme β 1,3- gluconase, produced by *Bacillus cepacian,* is capable of rupturing the cell wall of *P. ultimum, S. rolfsii,* and *R. solani* (Compant et al., 2005). When *Serratia marcescens* B2 (a biocontrol agent) is combined with mycelia of pathogenic fungi *Fusarium oxysporum* and *Rhizoctonia solani,* this alters the proliferation of the hyphae, causing the hyphal cell to swell, curl, and burst (Someya et al., 2000).

Role of PGPR in Phytoremediation

Human health as well as the ecosystem are badly affected over time as garbage and hazardous materials are continually deposited on the soil. Heavy metals including mercury, cobalt, zinc, lead, cadmium, and nickel are the most prevalent of these contaminants. In the context of agricultural development, human activities, including the use of insecticides and herbicides, the overuse of fertilizer, and the careless dumping of sewage and municipal waste, have all been linked to soil pollution. Even though these agricultural chemicals initially promote growth and development, they also leave behind metal residues that hinder microbial metabolism and plant growth. It becomes very difficult to remediate them because they are not biodegradable. They can only change from one state to another state. Phytoremediation with PGPR has emerged as a viable option for detoxifying sites. It is because it is affordable, aesthetic, and eco-friendly (Odoh et al., 2017). The heavy-metal-polluted soil is chelated, solubilized, and mineralized by a vast array of rhizosphere-dwelling soil microbes, which facilitates plant bioaccumulation and bioavailability.

Commercialization of Soil Rhizobacteria

The collaboration between industries and scientific institutes is crucial to the advancement and marketing of PGPR. Various studies have demonstrated different phases of the commercialization process. These include antagonistic strains' isolation and screening, formulation methods, mass manufacturing, toxicity, formulation viability, field efficacy, and quality control (Nandakumar et al., 2001). Additionally, for PGPR strains to be commercially successful, there must be profitable market demand, stability and safety, low capital costs, a longer shelf life, and easy access to carrier materials.

Formulation Design of Soil Rhizobacteria

For inoculants containing bacterial strains with effective activity, the formulation design is a vital factor that can decide how well or poorly a biological agent can perform. A preferred method for transferring microbial cells to soil or the rhizosphere is by using inoculant formulations that involve carrier materials. The use of inoculant formulations containing carrier materials is a desirable solution for the transfer of microbial cells to soil or in the rhizosphere. Generally, carrier materials are designed in such a way that they provide a safe habitat to microbial inoculants in the soil. They do this either physically, through pore space by providing a protective surface, or nutritionally, by providing a particular substrate. Soil rhizobacteria should be bio-formulated using a superior carrier material that has properties that support the growth as well as the survival of bacteria. These properties include a large capacity for holding and retaining water, sterility, chemical, and physical uniformity, no heat produced from wetting, nontoxic in nature, having neural or easily adjustable pH, and biodegrading easily. In addition to these materials, several other inert and synthetic substances have also been examined, these include ground rock phosphate, alginate, polyacrylamide gels, and vermiculite (Domenech et al., 2006).

Conclusion

In the past century, farmers have relied on pesticides, herbicides, and chemical fertilizers to improve crop yield. Initially, their usage improves plant growth, but then it exerts harmful effects. The soil fertility and productivity decrease due to an increase in soil pollution, soil-borne pathogens, and overuse of land. They not only affect soil and beneficial microorganisms residing in the soil but also humans and ecosystems over time. Thus, with growing environmental concerns and the understanding that the period of extensive chemical use must come to an end, the use of soil rhizobacteria is the best alternative that offers the potential for creating more sustainable agricultural methods. The identification of different mechanisms underlying the interactions between plants and soil rhizobacteria has created new ways for the development of strategies to improve crop yield. Additionally, strains exhibiting PGPR traits can be further enhanced using biotechnology to create transgenic strains that combine various modes of action. Conclusively, when properly utilized, genetic engineering of PGPR as a vital component of modern food production would minimize ecosystem disruption, soil pollution, and loss of the soil's flora and fauna. To increase the production of food and avoid

future famine in areas devastated by war and terrorism, it is crucial to implement and use this technology, especially in developing countries.

Author contributions

All authors contributed to the study conception and design. The study was created and the protocol was written by author Amina Zia and Umar Azam.Material preparation, data collection and analysis were performed by Amina Zia and Ali Haider.The first draft of the manuscript was written by Ali Haider and Amina Zia commented on previous versions of the manuscript. Author Rabia Talat Mehmood, Natasha Shahzadi, Noor Ul Huda and Uzma Ambreen the literature searches and contributed a lot in Biocontrol mechanism. The final part of manuscript that is related Role of PGPR in Phytoremediation by Aniqah Akhter, Ayesha Hafeez, and Syeda Maria Majid. References and citations were managed by Ali Haider. All authors read and approved the final manuscript.

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Ethics approval

Not applicable

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