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REVIEW

Plant Growth-Promoting Bacteria (PGPB) for Sustainable Agriculture: Current Prospective and Future Challenges

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Abstract

Sustainable agriculture is a global imperative to meet the challenges of food security and environmental protection. Plant Growth-Promoting Bacteria (PGPB) have emerged as key players in sustainable agricultural practices due to their diverse roles in enhancing plant growth, nutrient uptake, stress tolerance, and disease resistance. This review explores the diverse facts about PGPB and their potential applications in sustainable agriculture. The review begins by elucidating the mechanisms underlying PGPB-plant interactions, including phytohormone production, nutrient solubilization, and biocontrol activities. This review delves into the intricate signalling networks involved in PGPB-induced systemic resistance. In addition, this review discusses the pivotal role of PGPBs in mitigating abiotic stresses such as drought, salinity, and heavy metal toxicity, highlighting their contributions to climate-resilient agriculture. The ecological implications of PGPB application in sustainable agriculture are discussed, emphasizing the need for responsible and environmentally friendly practices. Furthermore, the use of PGPB for sustainable agriculture holds great promise for addressing the challenges of food security and environmental sustainability. In addition, this review provides a comprehensive overview of the multiple roles, mechanisms of action, and potential applications of PGPB, while emphasizing the importance of responsible and environmentally sound approaches in realizing the full potential of PGPB for a resilient and sustainable agricultural future.

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Statement of Sustainability: The use of plant growth promoting bacteria (PGPB) in agriculture holds great promise for sustainable agricultural practices, as these beneficial microorganisms have the potential to increase crop yields, reduce the need for chemical fertilizers and pesticides, and improve soil health. PGPB can enhance nutrient uptake, increase resistance to pests and diseases, and mitigate the negative environmental impacts associated with conventional agricultural practices. Effective implementation requires addressing issues. In addition, it is critical to educate and engage farmers in adopting PGPB-based strategies, and to conduct ongoing research to further elucidate the environmental and agronomic implications of PGPB use to ensure its integration into a truly sustainable and resilient agricultural future.

1. Introduction

Sustainable agriculture is essential in a growing world because it attempts to meet agricultural demands in a way that traditional agriculture cannot (Singh et al., 2017). This type of agricultural activity adopts a unique growth approach to maximize the use of available natural resources (Abdelkrim et al., 2018). This strategy benefits the environment and ensures safe agricultural products. However, the continuous use of chemical pesticides, herbicides, and fertilizers has reduced soil fertility and resulted in substandard agricultural production, while food contamination, soil degradation, biodiversity loss, and poor economic returns are all important environmental issues (Akhtar et al., 2018). According to the discussion of the linkages between agriculture and the environment, the use of such chemicals in agricultural activities affects both the quantity and quality of agricultural products (Singh et al., 2017).

Plant Growth-Promoting Bacteria (PGPB) are used in a range of activities including formation of soil structure, decomposition of organic matter, recycling of elements, solubilization of mineral nutrients, synthesis of plant growth regulators, and decomposition of organic matter to replace these compounds (Ali et al., 2021). Biological control of plant diseases, faster root development, improved soil fertility, etc. (Gupta et al., 2023). Due to their remarkable ability to stimulate plant development and enhanced ability to respond to stress, PGPBs have the potential to play a significant role in sustainable food production (Yadav et al., 2020). The PGPB, which also provides a mechanism to enhance nitrogen supply and control diseases spread through the soil, is the key player in our efforts to maintain soil fertility (Singh et al., 2017).

Beneficial microorganisms, also known as microbial and/or soil inoculants, can increase the host plant's access to nutrients and improve plant growth and health when added to soil, but to introduce living microorganisms into soil or growing plants, a substance called an inoculant is used (Bruno et al., 2021). The microorganisms can then have the desired effects on plant growth, such as improved mineral absorption, nitrogen fixation in legumes, weathering of soil minerals, biocontrol of soil-borne diseases, or effects on nutrient uptake or hormones (Bruno et al., 2020). They also help promote the production of growth hormones, which are then administered to plants to help them absorb nutrients and tolerate biotic and abiotic stresses (Yadav et al., 2020). However, they don't harm the environment or soil in any negative way (Begum et al., 2019). Only a small dose is required to achieve the desired results, as each gram of the biofertilizer carrier contains at least 10 million live cells of a particular strain (Yadav et al., 2020). To be produced from a sustainable agricultural standpoint, crops need to be resistant to heavy metal stress, drought, and disease, and one way to bypass the aforementioned ideal crop characteristics is to use soil microorganisms that enhance plant water and nutrient uptake (Zhang et al., 2022). This allows the use of PGPB to enhance plant health and promote development without damaging the environment (Abdelkrim et al., 2018).

However, the widespread use of PGPBs in agriculture may have potential environmental impacts and unintended consequences. One concern is the introduction of non-native bacterial strains into ecosystems, which could disrupt native microbial communities and alter soil biodiversity (Pandey et al., 2019). The persistence and spread of engineered PGPB raises questions about unintended ecological consequences and the potential for these organisms to become invasive. In addition, the use of PGPB may lead to shifts in the dynamics of nutrient cycling, affecting nutrient availability in ways that could have cascading effects on ecosystem functions (Zhang et al., 2022). There is also a risk of horizontal gene transfer between introduced PGPB and native bacteria, potentially leading to the spread of genetic traits with unforeseen consequences. Rigorous research, risk assessment, and adherence to best practices in application are essential to mitigate these potential environmental impacts and ensure the responsible use of PGPB in agriculture (Begum et al., 2019).

Therefore, reviewing the prospects and challenges of PGPB in sustainable agriculture is essential to advance environmentally friendly and productive agricultural practices while addressing the complex issues associated with their implementation. For this current review, the literature survey was conducted in the world's leading biological databases such as NCBI, Scopus, and Web of Science. from the time frame year 2014 to the year 2023. In addition, the literature review is focused on synthesizing the current knowledge, assessing the potential benefits and barriers associated with PGPB, and providing guidance for the advancement of sustainable and productive agricultural practices.

2. Beneficial Soil Microbes

Soil is a dynamic part of the Earth's lithosphere. It is the boundary that separates all living and non-living geologic materials, water supplies, and the gas pores that hold the latter two components and support all terrestrial ecosystems (Pandey et al., 2019). Beneficial soil microbes play a pivotal role in supporting plant health and ecosystem sustainability by contributing to nutrient cycling, disease suppression, and overall soil fertility. By secreting a variety of metabolites, they enhance nutrient uptake, form complex soil matrices, and support plant defenses, all of which lead to increased plant development (Lee et al., 2023). In addition, it can strengthen a plant's defenses against harmful environmental factors such as heavy metal contamination, weed infestation, salt stress, drought stress, and nutrient deficiencies (Tanwir et al., 2021). Recent research has shown that soil microorganisms have both beneficial and detrimental effects on the soil ecosystem (Finkel et al., 2017). In addition to their ability to promote plant growth, beneficial soil microbes have attracted interest for other functions, including their role in decomposing organic waste and detoxifying hazardous materials such as pesticides (Sharma et al., 2020).

The function of beneficial soil microbes is summarized in Figure 1. The soil microflora, particularly bacteria and fungi, play a central role in the ecological processes within the soil environment. They are the primary agents responsible for the decomposition of soil organic matter, a critical function in the regulation of carbon cycling (Finkel et al., 2017). In addition, soil microbes play essential roles in nutrient cycling. They convert mineral nutrients such as phosphate and zinc into forms that are readily available to plants. They also provide plants with nitrogen, a key nutrient, through both symbiotic and non-symbiotic fixation processes. Beyond nutrient cycling, soil microorganisms engage in activities that promote plant growth (Rashid et al., 2017). The role of soil microflora extends to the inhibition of soil-borne plant pathogens. This is achieved through a variety of mechanisms, including antibiotic secretion, extracellular lytic enzymes, parasitism, and competitive interactions. In addition, soil microorganisms play a critical role in bioremediation, aiding in the remediation of contaminated sites, whether the contaminants are inorganic or organic in nature (Pineda et al., 2010). Soil microorganisms are integral components of complex food webs, acting as decomposers, parasites, saprophytes, and pathogens. These diverse roles allow them to mediate nutrient cycling in a vital and intricate manner (Mishra et al., 2016).

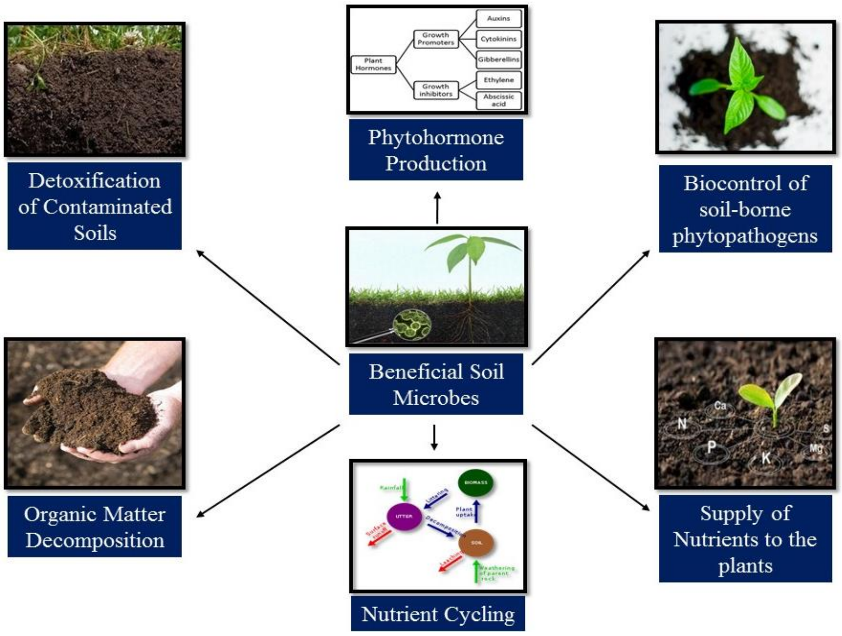

Figure 1. The significance of beneficial microbes in the soil ecosystem.

2.1. Cyanobacteria

Cyanobacteria, also known as blue-green algae, are a group of photosynthetic bacteria that play an important role in the environment by producing oxygen through photosynthesis and contributing to nitrogen fixation; some species are also used in various biotechnological applications, while others can form harmful algal blooms in aquatic systems (Mahdi et al., 2021). Their ability to fix nitrogen makes them a suitable natural source for improving soil fertility. Free-living or symbiotic blue-green algae (BGA) have a well-established history in sustainable agriculture (Zhang et al., 2022). Free-living or symbiotic cyanobacteria, such as those associated with the water fern Azolla, are estimated to fix 46 billion kg of nitrogen annually (Sharma et al., 2020).

2.2. Plant Growth-Promoting Rhizobacteria (PGPR)

Microbes in the rhizosphere help plants grow. Bacteria that can improve soil fertility and plant development include *Azospirillum*, *Rhizobium*, *Azotobacter*, *Arthrobacter*, *Bacillus*, *Pseudomonas*, and other species of rhizobacteria that promote plant growth (Burges et al., 2017). Phytohormone synthesis, nitrogen fixation, siderophore synthesis, solubilization of inorganic elements (such as P, K, and Zn), and easy access to the plant are all part of the growth-promoting pathway (Begum et al., 2019). One way to look at the indirect pathway from a different angle is to use growth inhibition, which works against phytopathogens using a variety of techniques, including iron deficiency in the rhizosphere, production of chemicals that are antibiotics or antifungals, and production of enzymes that break down plant walls, such as chitinase (Huang et al., 2021). However, PGPR represent a sustainable agricultural strategy because they enhance plant growth, nutrient uptake, and stress tolerance through beneficial interactions with plant roots, contributing to improved crop yields and reduced reliance on chemical inputs.

3. Role of PGPB in Soil Fertility

Ants, termites, earthworms, and especially microorganisms are just a few of the insects that contribute to the processes of soil mineralization and nutrient cycling that directly affect plant growth (Vishnupradeep et al., 2022). However, the majority of the many biomolecules that improve soil health are produced by rhizobacteria associated with roots, while interactions between organic molecules and plant residues cause mineralization and degradation (Vejan et al., 2016). In addition to the methods mentioned above, chemicals necessary for plant growth are produced. The plant roots are formed in some way (Huang et al., 2021). Soils can be improved by improving the rhizosphere by increasing the availability of nutrients through the use of microbes (Begum et al., 2019). Plants need nitrogen to make proteins and amino acids through biological N_2 fixation (Singh et al., 2017). However, increased phosphorus availability to plants is the result of the P solubilization activity of PGPRs (Ke et al., 2021). In addition, PGPRs are known to produce a number of volatile compounds and metabolites that are beneficial to soil and plant health (Zhang et al., 2022). Nevertheless, the rhizosphere secretes a variety of enzymes that limit pathogen growth and subsequently support biocontrol strategies (Zhang et al., 2022).

4. Mechanism of Growth Promotion by PGPB

PGPRs can directly aid plant growth by providing easy access to nutrients such as N, P, and Fe, as well as higher concentrations of phytohormones. These bacteria do this by utilizing the mineralization and solubilization processes of the available nutrients (Yadav et al., 2020). The main chemical produced by PGPRs is indole-3-acetic acid (Mahdi et al., 2021). PGPRs are important disease suppressors from both economic and environmental safety perspectives through the synthesis of substances such as pyoluteorinare and 2,4-diacetylphloroglucinol (Mahdi et al., 2021). Through induced systemic resistance or systemic acquired resistance, PGPRs provide plants with protection against phytopathogens and pests (Vejan et al., 2016). However, the mechanism of growth promotion by plant growth promoting bacteria is indexed in Figure 2.

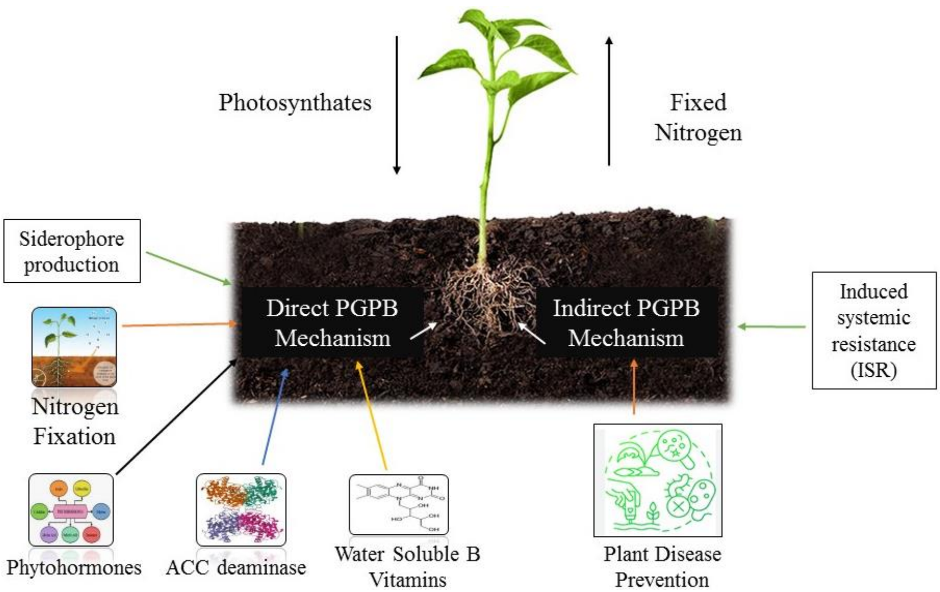

Figure 2. Mechanism of plant growth promoting bacteria

4.1. Mineral Solubilization

Through the synthesis of siderophores, many organic acids, and hydroxyl and carboxyl groups, phosphate-solubilizing bacteria (PSBs) solubilize Ca, Fe, and Al inorganic soil phosphates while chelating the bound phosphates with accessible calcium (Akhtar et al., 2018). While some strains of *Enterobacter* sp., *Pantoea* sp., and *Klebsiella* sp. have been shown to solubilize calcium phosphates more than iron and aluminum phosphates, this relationship is not always found (Bruno et al., 2021). Soils in India are sufficiently potassium-rich, but potassium fertilizers are still critically needed. It's important to make use of local resources such as phlogopite, muscovite, biotite and potassium feldspar (Singh et al., 2010). There is significant potential for potassium solubilization in potassium solubilizing bacteria, potassium solubilizing bacteria, and potassium solubilizing rhizobacteria (Bruno et al., 2021). Microorganisms that solubilize potassium serve as bioinoculants and support sustainable agriculture (Zhang et al., 2022).

One of the minerals most critical to the survival of all living things is iron. Fe^{3+} is a common ionic form when oxidized, but it is not easily accessible because it can form insoluble oxyhydroxides and hydroxides (Abdelkrim et al., 2018). On the other hand, the ionic form of Fe^{2+}, which has a lower pH and is more easily absorbed by plants, is readily accessible to both microorganisms and plants (Ma et al., 2011). Siderophores, which have the specificity and affinity to chelate iron, allow bacteria and fungi to take up iron (Ma et al., 2011). Siderophores are non-protein amino acids smaller than 1000 Da that are associated with rhizosphere bacteria (Choudhary et al., 2009). Similarly, phytosiderophores found in plants are useful for obtaining cationic micronutrients from the rhizosphere (Abdelkrim et al., 2018).

4.2. Heavy Metal Toxicity

Soil contamination with heavy metals, one of the greatest environmental problems of our time, is caused by the increasing infiltration of industrial effluents into water bodies and is detrimental to both agriculture and human health (Tanwir et al., 2021). The already serious situation is exacerbated by the excessive use of nitrogen, phosphorus, and potassium fertilizers, as well as other forms of agrochemicals such as herbicides, insecticides, pesticides, and fungicides (Ma et al., 2011). Trace elements and Cd in phosphate are particularly problematic (Mahdi et al., 2021). Since such metal-stressed soils are unsuitable for cultivation, remediation has become crucial. Soil contamination by heavy metals has long-term adverse effects on all living things, including humans (Ke et al., 2021). Of all the heavy metal contaminants, lead and cadmium are the two most prevalent and pose the greatest risk of poisoning (Lee et al., 2023).

4.3. Microbe-Induced Bioremediation

Soil phytoremediation outcomes are greatly influenced by the degree of contamination as well as the contaminants. In addition, the amount of contaminant taken up by neighboring plants or bacteria affects the rate of remediation (Ali et al., 2021). When rhizospheric metal concentrations are too high, plants that are good at accumulating metal tend to grow at the slowest rate (Ke et al., 2021). Physicochemical and biological techniques can be used to remove heavy metal contaminants from soil (Shi et al., 2018). Due to its low cost and environmental friendliness, biological remediation is considered the most efficient approach to eliminate hazardous metals (Shafi et al., 2015). BSMs often exhibit increased plant growth and a high survival rate under stressful conditions, demonstrating their potential for remediation by converting complicated chemicals into simple and harmless molecules. PGPRs have the potential to be resistant to harmful heavy metals (Nazil et al., 2020).

4.4. Remediation of Heavy Metals

Heavy metal toxicity is reduced by soil bacteria in the rhizosphere by providing a vital microflora (Khan et al., 2021). Growth regulators produced by soil microorganisms help plants absorb nutrients, promote development, and increase plant production (Lee et al., 2023). Metal pollutants are limited by the formation of metal complexes from siderophore complexes, metabolites produced by bacteria, and transporter proteins (Ahmed and Holmstrom, 2014). Overexpression of target genes or introduction of gene transfer are two novel ways to obtain the desired microorganisms with higher throughput metal sequestration capacity (Chuck et al., 2011). One of the many microorganisms that live in the rhizosphere are mycorrhizal fungi. Mycorrhizae that colonize roots have the ability to significantly increase nutrient availability and heavy metal ion uptake (Kumar et al., 2017). Soil metal bioavailability can be rapidly altered by microbes, and heavy metal accumulation can be reduced by using ecological trophic level adaptation approaches (Lee et al., 2023).

There are mycorrhizal fungi with different microbial culture systems. The primary function of arbuscular mycorrhizal fungi (AMF) in soil is to promote the growth of soil microorganisms near the rhizosphere of the host plant (Yadav et al., 2020). As a result, the association between plants and vesicular arbuscular mycorrhiza (VAM) has been recognized for its ability to promote growth because of the huge mycelial mats that bind the soil and collect and deliver minerals, particularly phosphorus, to plants (Smith and Smith, 1997; Tanwir et al., 2021). However, AMF also form a significant portion of the soil microflora and create one-to-one connections between the roots of soil plants, and by increasing root surface area, nutrients can be more easily taken up (Singh et al., 2017). AMF has also been associated with practices in industrial facilities such as PGPR, metal cleaning, and metal allocation (Wani et al., 2023), in addition to vacuolar deposition, chemical metal binding, and their sequestration through the root apoplasm and the formation of phytochelatins or metallothioneins (Jan and Parray, 2016).

Some plants accumulate more heavy metals when surviving in contaminated soils, which can be attributed to the local soil flora improving the plant's habitat (Singh et al., 2017). This improved efficiency can be considered a critical tool for nutrient recycling, hazardous waste removal, and soil restoration (Ullah et al., 2015). The use of rhizospheric bacteria for soil remediation can complement or replace the use of green plants, which is now considered an antiquated practice. Both immobilization of excreta and perspiration accelerate the detoxification process. Despite many investigations, the method for sequestration of heavy metals from contaminated soils is still unknown (Singh et al., 2017). However, some studies on heavy metal remediation by plant growth-promoting bacteria are indexed in Table 1.

Table 1. Remediation of heavy metals by plant growth-promoting bacteria

Metal	PGPB spp.	Host Plant	Target Trait	Reference
Pb	*Pseudomonas fluorescens*	*Lathyrus sativus*	Photosynthetic pigments biosynthesis, Membrane stability	Abdelkrim et al. (2018)
Ni	*Bacillus* sp.	*Raphanus sativus*	Increased plant biomass, chlorophyll and nitrogen contents	Akhtar et al. (2018)
Cd, Cu, and Zn	*Streptomyces pactum*	*Triticum aestivum*	Increased plants biomass, Decreased antioxidant activities	Ali et al. (2021)
Pb, Zn, Ni, Cu, and Cd	*Bacillus cereus*	*Zea mays*	Increased plant biomass, chlorophyll, carotenoid and protein contents	Bruno et al. (2021)
Cr	*Bacillus cereus*	*Sorghum bicolor*	Increased the root length, plant dry weight, and antioxidant activity	Bruno et al. (2020)
Zn, Cd	*Microbacterium* sp.	*Noccaea caerulescens*	Increased chlorophyll, carotenoid contents, and soil nutrient cycling	Burges et al. (2017)
Cu, Cd	*Acinetobacter* sp.	*Perennial ryegrass*	Increased the shoot and root biomass	Ke et al. (2021)
Cu, Cd	*Bacillus atrophaeus*	*Chenopodium quinoa*	Improved the germination rate, and seedling biomass and growth vigor index	Mahdi et al. (2021)
Cd	*Serratia* sp.	*Zea mays*	Increased plant biomass, and photosynthetic pigments	Tanwir et al. (2021)
Cr	*Providncia* sp.	*Zea mays*	Increased plant growth, pigments, protein, phenolics and relative water content	Vishnupradeep et al. (2022)
Cr and Zn	*Brevibacillus parabrevis OZF5*	Bean	Protect plants against oxidative damage	Wani et al. (2023)
Cu	*Sphingomonas sp.* PbM2	*Zea mays*	Remediation performance of contaminated soil	Lee et al. (2023)

4.5. Induced Systemic Resistance (ISR)

Induced resistance in plants is a massively complex system that is only partially understood in a number of model plant species, including Arabidopsis (Pandey et al., 2019). There are three widely recognized induced resistance mechanisms in Arabidopsis, two of which involve the direct synthesis of pathogenesis-related (PR) proteins. In one pathway, pathogenic bacteria typically attack, whereas in the other, plant pathogens that cause necrosis or injury typically induce the production of PR proteins (Sharma et al., 2020). The pathogen-induced pathway often uses salicylic acid (SA), which is produced by the plant, whereas the wounding pathway typically uses jasmonic acid (JA) as the signaling molecule (Pandey et al., 2019).

The term "induced systemic resistance" (ISR), which refers to the JA-induced pathway, is also used to refer to numerous different processes initiated by rhizobacteria (Pandey et al., 2019). After an extensive screening for plant growth promoting and antimycelial activity against Pythium and Phytophthora strains, bacterial isolates from the central Himalayan region were reported (Singh et al., 2010). The molecular characterization of rhamnolipid, which is believed to be a predictor of biocontrol activity, was one of the outcomes (Vishnupradeep et al., 2022). Researchers have also shown that the use of fluorescent pseudomonad (FLP) strains that produce siderophores can help address the problem of iron unavailability, especially in calcareous soils where siderophores are one of the factors affecting ISR and impacting plant nutrition (Vejan et al., 2016).

5. Significance of PGPB in Sustainable Agriculture

Modern agriculture faces a critical problem caused by contaminated and dry soils. Despite the fact that the soil rhizosphere is a crucial area for microbial bioremediation, varying soil atmospheres can make it impossible for many rhizosphere bacteria that can digest certain types of organic contaminants to proliferate (Mahdi et al., 2021; Bruno et al., 2021). Using modern molecular biology and genetic techniques, it is possible to create bacteria that can both improve soil fertility and solve soil problems. Chemical degradation processes for soil contaminants such as trichloroethylene have long been known (Scheidegger and Sparks, 1996). Cloning beneficial genes into a powerful bacterial vector will also accelerate soil remediation (Bruno et al., 2020). Application of nanoparticle adhesion to BSMs and enhancement of surface activity are two other critical strategies (Pandey et al., 2019). Bioinoculants, which have a growth and survival rate in the rhizosphere, can also utilize nanoparticles (Ullah et al., 2015).

The soil ecosystem is supplemented with these bacterial-based microorganisms to improve its physicochemical properties, microbial diversity, and overall health (Bhardwaj et al., 2014). Due to its wide range of metabolic capabilities, ability to produce plant hormones such as indoleacetic acid, gibberellins and cytokinins, and vitamins such as thiamine and riboflavin, *Azolotobacter* plays an important role in the nitrogen cycle in nature (Bhardwaj et al., 2014). In addition to promoting seed germination and improving root architecture, *A. chroococcum* suppresses agricultural plant pathogens around root zones (Chennappa et al., 2017). *A. armeniacus*, *A. beijerinckii*, *A. chroococcum*, *A. nigricans*, *A. paspali*, and *A. vinelandii* are the species that make up this genus. Barley, castor, cotton, coffee, coconut, jute, linseed, oat, maize, mustard, rice, rubber, safflower, sunflower, sorghum, sugar beet, tobacco, tea, and wheat are some of the crops that use them as biofertilizers (Ullah et al., 2015).

Studies conducted in greenhouses and in the field have shown that *Azospirillum* has a positive effect on plant growth and agricultural production (Sivasakthivelan and Saranraj, 2013). According to one study, *Azospirillum* inoculation can change the structure of the roots by releasing substances that control plant development, as well as increasing the number of lateral roots and root hairs, which increases the surface area of the roots that can absorb nutrients (Ke et al., 2021). A robust root network improves the plant's water status and helps the nutrient profile to accelerate plant growth and development (Chuck et al., 2011). Triticum aestivum produced more grain and had higher NPK content after co-inoculation with *Rhizobium meliloti* (Hosseinkhani et al., 2015). By converting atmospheric nitrogen into forms that plants can utilize, Rhizobium has been used as an effective nitrogen fixer to promote crop development (Vishnupradeep et al., 2022). With a wide range of temperature tolerance. However, researchers have also found that rhizobium inoculants significantly increase the grain yield of berseem (Chandra et al., 2018).

6. Plant Microbe Interactions

Depending on the type of bacteria involved and how they interact with plants, plant-microbe interactions can be beneficial or detrimental (Ali et al., 2021). PGPB can promote plant development, increase agricultural production, and act as a biocontrol agent against plant diseases caused by phytopathogenic microorganisms (Tanwir et al., 2021). Furthermore, new research shows that PGPB can improve plant resistance to abiotic conditions such as salt, temperature, pH, and drought, but due to their multifunctionality, PGPB can replace polluting chemical fertilizers and pesticides (Kumar et al., 2017). Endophytes can then enter plant tissues through the root zone and invade plant cells to benefit the host (Lee et al., 2023). Parasitism, competition, and antibiosis are examples of biological controls that negatively affect nematode fitness, survival, and reproduction (Zhang et al., 2022). Biodiversity, which is the diversity of living organisms at the species, interspecies, and intraspecies levels, is highly useful in employing microorganisms to generate income for sustainable agriculture and improve human health (Burges et al., 2017; Wani et al., 2023). Meanwhile, bacteria have positive ecological relevance as they have been shown to be widespread, niche or host specific, however, the niche of host specific microbes may be essential for the growth of certain plants under different abiotic stress situations (Begum et al., 2019).

6.1. Actinobacteria

Actinobacteria are critical to agriculture because they can improve plant nutrition and development by directly promoting plant growth. Actinobacterial colonization has been associated with improved nutrient uptake, drought tolerance, and plant vigor in a number of studies (Sharma et al., 2020). It also makes humans more resilient to biotic and abiotic challenges. A study of actinobacteria associated with different crops, whose phylogenetic analyses mostly focused on 16S rRNA gene sequences, discovered all six species of actinobacteria (Begum et al., 2019). The study of several crops revealed the presence of bacteria from all six species. *Arthrobacter*, *Brevibacterium*, *Cellulomonas*, *Corynebacterium*, *Kocuria*, *Microbacterium*, *Micrococcus*, *Mycobacterium*, *Rhodococcus*, and *Streptomyces* were found in all crops studied (Vejan et al., 2016). In rhizospheric soils, actinobacteria make up a significant proportion of the microbial biomass (Ma et al., 2011). They can be found at 109-106 bacteria per g of soil and make up more than 30% of the total population of soil microbiomes (Zhang et al., 2022). Actinobacteria and other taxa contribute significantly to the rhizosphere of many plants, including wheat, rice, soybean, maize, sugarcane, chickpea, pea, and sunflower (Choudhary et al., 2009).

6.2. Firmicutes

Sequencing of DNA bands seen on a denaturing gradient gel electrophoresis gel has been widely used to distinguish between similar species such as *Paenibacillus* and *B. mycoides* (Huang et al., 2021). The most common bacteria are those belonging to the genus Bacillus (Huang et al., 2021). *Bacillus subtilis*, *B. mycoides*, *B. pumilus*, *B. megaterium*, *B. thuringiensis*, and *B. firmus* are some of the *Bacillus* species found in the rhizosphere soil (Tanwir et al., 2021). From surface-sterilized wheat var. HS507 roots and culms growing in the NW Indian Himalayas, 41 endophytic bacteria were found (Chunk et al., 2011). The ability of these bacteria to fix nitrogen, produce siderophores, hydrogen cyanide, indoleacetic acids, and gibberellic acid was studied in vitro, but at low temperatures (4°C), their ability to biocontrol *Rhizoctonia solani* and *Macrophomina phaseolina* was also studied by some researchers (Singh et al., 2010). Then, a significant amount of potassium solubilization in one isolate, IARI-HHS2-30, was evaluated in vivo under low temperature control conditions. The endophytic nature of IARI-HHS2-30 and its ability to accelerate plant growth were qualitatively assessed prior to injection into wheat seedlings grown at low temperatures (Sharma et al., 2020).

Wheat plants treated with *Bacillus amyloliquefaciens* IARI-HHS2-30 30 days after inoculation showed significant improvements in root/shoot length, fresh weight, and chlorophyll concentration (Singh et al., 2010). Due to its ability to promote plant growth and its psychrophilicity, this endophytic bacterium has the potential to be used as a bio-inoculant for a variety of crops grown at high altitudes and freezing temperatures (Ali et al., 2021). In the northwestern Indian Himalayas, scientists collected and characterized psychrotrophic bacteria from a number of sites. A total of 247 morphotypes were recovered from various soil and water samples, and 43 clusters were discovered using 16S rDNA-RFLP analysis (Sharma et al., 2020). Sequencing was used to identify representative isolates from each cluster (Sharma et al., 2020). *Desemzia*, *Exiguobacterium*, *Jeotgalicoccus*, *Lysinibacillus*, and *Virgibacillus* were among the 11 genera represented by the 43 bacilli found (Zhang et al., 2022).

6.3. Proteobacteria

The phylum Proteobacteria contains a large class of Gram-negative bacteria known as Proteobacteria. The two most common species in the Proteobacteria class are *Pseudomonas* and *Azotobactor* (Vishnupradeep et al., 2022). A gram-negative, aerobic, heterotrophic, rod-shaped nitrogen-fixing bacterium called Azotobactor is found in alkaline and neutral soils (Pandey et al., 2019). They are free-living organisms that are occasionally found around certain plants as well as in soil and water. *Azotobacter* have been found in a variety of plants, including *A. agilis*, *A. chrococcum*, *A. beijerinckii*, *A. vinelandii*, and *A. ingrinis* (Huang et al., 2021). One of the most common and beneficial genera of proteobacteria is Pseudomonas, a genus of aerobic, gram-negative proteobacteria with 191 validly recognized species (Vejan et al., 2016). To prevent the spread of agricultural diseases, certain members of the Pseudomonas genus have been applied directly to cereal seeds or soils (Jan and Parray, 2016). Pseudomonas sp. with biocontrol capabilities is one that produces a phenazine-type antibiotic that is effective against certain fungal plant diseases (Ullah et al., 2015). However, scientists have used 16S rRNA gene sequencing to investigate thermotolerant wheat-associated microorganisms that promote plant growth (Zhang et al. 2022).

7. Biocontrol

Phytopathogenic microorganisms pose a serious and ongoing threat to sustainable agriculture and ecosystem stability worldwide because they alter soil ecology, negatively impact the environment, reduce soil fertility, threaten human health, and contaminate groundwater (Mahdi et al., 2021). The use of microorganisms that promote plant growth is an environmentally benign and sustainable way to inadvertently increase soil fertility and plant development (Bruno et al., 2021). This strategy produces antibiotics, siderophores, and hydrolytic enzymes, among others, to improve soil fertility and reduce the need for agrochemicals (fertilizers and pesticides) (Chuck et al., 2011). Using microbes to treat disease appears to be one of the more promising approaches. The natural soil flora is excellently preserved by biocontrol systems, which are also good at improving soil consistency and are ecologically benign (Akhtar et al., 2018). The biocontrol agent needs to function well under a variety of conditions, such as those that involve variations in pH, temperature, and ion concentration (Ke et al., 2021). Recent research suggests that hostile microbes could be used to biologically cure bacterial wilt disease (Shi et al. 2018; Khan et al., 2021).

8. Effects of Soil Ecosystem

Soil bacteria, including numerous species and fungi, can enhance the availability of various nutrients through a variety of strategies (Tanwir et al., 2021). According to PGPB studies, *Rhizobium* sp. can fix atmospheric N_2 in symbiosis with its legume host, while *Azospirillum* can do so in non-symbiotic association with its host (Mahdi et al., 2021). PGPB such as *Arthrobacter*, *Bacillus*, and *Pseudomonas* produce phosphatase enzymes and organic acids by forming siderophores (Lee et al., 2023). In addition, PGPB can increase the solubility of Fe, which improves plant uptake (Vishnupradeep et al., 2022). However, of all the biochemicals produced by soil bacteria, polysaccharides are the most effective in binding soil particles together (Smith and Smith, 1997). Mineralization of organic matter by soil bacteria can affect soil structure (Akhtar et al., 2018). Increased rhizodeposition and root exudates caused by stimulation of plant growth by soil microorganisms may have a direct or indirect effect on soil structure by increasing microbial activity and population (Bruno et al., 2021). Many biochemicals are produced by soil bacteria and affect the soil environment (Mahdi et al., 2021). These include substances that have a negative effect on the development and functioning of soil fungi and bacteria (Tanwir et al., 2021). In addition, soil microorganisms can make plants more resistant to disease by promoting systemic resistance in plants (Ali et al., 2021). By producing antibiotic substances, preventing plant-induced systemic resistance, and preventing pathogens from inhibiting plant growth, PGPB, which are primarily related to Pseudomonas and Bacillus, typically have negative effects on soil pathogens (Wani et al., 2023).

9. Challenges and Future Prospects

Despite their promising benefits, the use of PGPB in agriculture faces certain limitations and drawbacks. A major challenge is variability in performance, as the efficacy of PGPB can be influenced by factors such as soil type, climate, and the presence of other microbial communities. Achieving consistent results in different agricultural environments remains a hurdle (Ke et al., 2021). In addition, competition with native soil microorganisms for resources and niche occupancy may affect the establishment and persistence of introduced PGPB. Regulatory hurdles and the need for standardized protocols for large-scale application pose additional challenges (Vishnupradeep et al., 2022). There are also concerns about the potential ecological impacts of introducing non-native bacterial strains into ecosystems. In addition, the cost of production and application may limit the accessibility of PGPB technologies to small-scale farmers (Kumar et al., 2017). Addressing these limitations will require further research, technological innovation, and a comprehensive understanding of the complex interactions between PGPBs, plants, and the environment (Kumar and Saxena, 2019).

PGPB in sustainable agriculture are promising, as they have the potential to significantly increase crop productivity while reducing dependence on chemical inputs. PGPBs can contribute to stress tolerance, improved soil health, and increased nutrient availability, addressing key challenges in the face of climate change and global food demand (Lee et al., 2023). Tailored microbial consortia, biotechnological applications, and ongoing research advances can further optimize the efficacy of PGPB for specific crops and environmental conditions. However, challenges such as field application scalability, regulatory approval, and a comprehensive understanding of plant-microbe interactions must be addressed to ensure the successful integration of PGPB into mainstream agricultural practices. Overall, the continued exploration of PGPB holds great promise for sustainable and environmentally friendly agricultural systems (Abdelkrim et al., 2018). For growers considering the use of PGPB, the first step is to conduct a soil analysis to understand soil composition and nutrient levels. This includes selecting PGPB strains that match your specific crops and local conditions and follow recommended application rates and methods from reputable suppliers (Tanwir et al., 2021). This integrated and informed approach will help realize the potential benefits of PGPB for improved crop yields and sustainable agricultural practices (Vishnupradeep et al., 2022).

However, researchers have identified various bacterial strains that exhibit beneficial effects on plant growth through mechanisms such as nitrogen fixation, phosphate solubilization, and plant growth hormone production (Abdelkrim et al., 2018). In addition, PGPB can enhance plant resistance to abiotic stresses and suppress pathogenic microorganisms. Ongoing research is exploring the complex interactions between PGPB and plants at the molecular level, with the goal of unlocking the full potential of these bacteria for sustainable agriculture (Akhtar et al., 2018). Techniques such as metagenomics and advanced molecular biology tools are being used to characterize and optimize PGPB strains for specific crops and environmental conditions (Ali et al., 2021). Investigating the signaling pathways involved in plant-bacteria interactions and understanding the impact of PGPB on soil microbial communities are emerging areas of interest. It's recommended to consult recent scientific literature and updates from reputable sources to stay abreast of the latest discoveries and avenues for further investigation in the field of plant growth promoting bacteria (Bruno et al., 2021).

10. Conclusion

PGPB holds great promise for promoting sustainable agriculture by enhancing plant growth, improving nutrient uptake and increasing resilience to environmental stresses. Harnessing the beneficial interactions between plants and these bacteria has the potential to reduce reliance on chemical fertilizers and pesticides, mitigate environmental impacts, and contribute to more environmentally friendly agricultural practices. The ability of PGPB to improve soil fertility and plant health represents a valuable tool for sustainable agriculture, particularly in the face of the challenges posed by climate change and increasing global food demand. Continued research and practical implementation of PGPB-based strategies, tailored to specific crops and agroecosystems, are essential to maximize their positive impact on crop yields and overall agricultural sustainability.

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