Korean Journal Of Agricultural Science

pISSN : 2466-2402
eISSN : 2466-2410

PLANT&FOREST

Practical significance of plant growth-promoting rhizobacteria in sustainable agriculture: a review

Subhashini Wijeysingha[1], Buddhi C. Walpola[1,*], Yun-Gu Kang[2], Min-Ho Yoon[2,*], Taek-Keun Oh[2,*]

[1]Department of Soil Science, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya 81100, Sri Lanka

[2]Department of Bio-Environmental Chemistry, College of Agriculture and Life Sciences, Chungnam National University, Daejeon 34134, Korea

[*]Corresponding authors: bcwalpola@soil.ruh.ac.lk, mhyoon@cnu.ac.kr, ok5382@cnu.ac.kr

Abstract

Plant growth-promoting rhizobacteria (PGPR) are naturally occurring bacteria that intensively colonize plant roots and are crucial in promoting the crop growth. These beneficial microorganisms have garnered considerable attention as potential bio-inoculants for sustainable agriculture. PGPR directly interacts with plants by providing essential nutrients through nitrogen fixation and phosphate solubilization and accelerating the accessibility of other trace elements such as Cu, Zn, and Fe. Additionally, they produce plant growth-promoting phytohormones, such as indole acetic acids (IAA), indole butyric acids (IBA), gibberellins, and cytokinins.PGPR interacts with plants indirectly by protecting them from diseases and infections by producing antibiotics, siderophores, hydrogen cyanide, and fungal cell wall-degrading enzymes such as glucanases, chitinases, and proteases. Furthermore, PGPR protects plants against abiotic stresses such as drought and salinity by producing 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase and modulating plant stress markers. Bacteria belonging to genera such as *Bacillus, Pseudomonas, Burkholderia, Pantoa,* and *Enterobacter* exhibit multiple plant growth-promoting traits, that can enhance plant growth directly, indirectly, or through synergetic effects. This comprehensive review emphasizes how PGPR influences plant growth promotion and presents promising prospects for its application in sustainable agriculture.

Keywords: biofertilizer, phytohormone, rhizobacteria, sustainable agriculture

OPEN ACCESS

Citation: Wijeysingha S, Walpola BC, Kang YG, Yoon MH, Oh TK. Practical significance of plant growth promoting rhizobacteria in sustainable agriculture: A review. Korean Journal of Agricultural Science 50:759-771. https://doi.org/10.7744/kjoas.500414

Received: July 27, 2023

Revised: October 30, 2023

Accepted: November 02, 2023

Introduction

The human population has exponentially grown over the past few years. As estimated by the United Nations, the world population will reach 8.5 and 9.7 billion by 2030 and 2050, respectively (UN, 2019). With the increasing global population, the world faces challenges in sustaining the life on Earth. In this context, the agriculture sector is tasked with fulfilling the future food requirements of communities (Walpola and Yoon, 2012); however, the increasing demand needs to be met with great care considering environmental concerns (Sagbara et al., 2020).

The agricultural sector is a key contributor to many developing countries' economic and social development, where national food and nutritional security are top priorities (Singh, 2013). The rapid exploitation of natural resources, reckless development of agricultural land, and extensive use of synthetic compounds due to the increasing demand for agricultural products are frequently reported. These observed practices include managing agricultural land, reducing chemical fertilization, planting cover crops, applying eco-friendly management, and integrating ecosystems and agriculture (FAO, 2023). In this context, adopting environment friendly agricultural techniques, such as using favorable soil microorganisms, has been widely popularized owing to the high costs and negative environmental impacts associated with synthetic chemicals (Singh, 2013; Gupta et al., 2021; Ghani et al., 2022). For example, the excessive application of chemical fertilizers accelerates the degradation of soil organic matter, decreases soil fertility, and weakens the soil structure (Bhatt et al., 2019; Kang et al., 2019).

The purpose of this study was to review the practical significance of plant growth-promoting rhizobacteria (PGPR) in sustainable agriculture and the summarize their characteristics and mechanisms of plant growth promotion. Furthermore, this study revealed an eco-friendly agricultural approach to crop production.

What is the plant growth-promoting rhizobacteria (PGPR)?

Biotic and abiotic factors influence crop growth and yield (Saharan and Nehra, 2011). The actions of different microscopic forms, such as algae, bacteria, fungi, protozoa, and actinomycetes, are considered biotic factors, with 95% contribution from bacteria, which are the most common microorganisms in this context (Glick, 2012). Microorganisms generally have both beneficial and non-beneficial effects on crop growth and yield (Miransari, 2014). The rhizosphere is the area in the root zone of plants where many microorganisms reside. This thin soil layer is an important factor in the active zones of metabolism and root activity (Saharan and Nehra, 2011). Microbial activity in the rhizosphere influences the status of root exudates and, thereby, the availability of nutrients (Backer et al., 2018). Therefore, the absolute effect of microbes on plant performance can vary from positive to negative (Khalid et al., 2004). Plant growth-promoting bacteria (PGPB) are free-living organisms or members of specific symbiotic relationships. PGPBs have been identified as an indispensable component of the rhizosphere which enhances the growth of host plants through various direct or indirect mechanisms. Some are involved in nitrogen fixation (Rawat et al., 2021), solubilization of insoluble phosphate and potassium, and production of siderophores and phytohormones. Their role in heavy metal resistance has also been reported (Chu et al., 2019; Chen et al., 2021; Bennis et al., 2022). PGPBs have been recognized as biocontrol agents for plant diseases (Hosseini et al., 2021). Their stress responses include 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase production. PGPR promotes drought tolerance and halotolerance of plants through various mechanisms, as shown in Fig. 1 (Gupta et al., 2021; Mansour et al., 2021).

Bacterial genera such as *Bacillus*, *Brevibacillus*, *Burkholderia*, *Pseudomonas*, *Agrobacterium*, *Thiobacillus*, *Streptomyces* *Klebsiella*, *Acetobacter*, *Rhizobium*, *Azospirillum*, *Azotobacter*, and *Serratia* are known PGPR that enhance the growth of host plants (Radhakrishnan et al., 2017; Guo et al., 2020). They inhabit the roots of plants by colonizing the rhizosphere, root surface, or intercellular spaces of root cells (Miransari, 2014).

The close relationship between PGPR and host plants benefits the host plant primarily by making nutrients available for plant uptake (Verma et al., 2010). The effectiveness of this relationship depends on the population density of microorganisms and the period during which the PGPR remains in the rhizosphere. Therefore, inoculating host plants with PGPR could increase their population density for a certain period (Bhattacharyya and Jha, 2012). High population densities of bacteria in the rhizosphere, comprising different PGPR types that exhibit a wide range of effects on crop productivity, enhance the circulation and plant uptake of nutrients (Singh, 2013). Due to their rapid growth rate, adaptability to diverse environmental conditions, and ability to metabolize a range of natural, and xenobiotic compounds, PGPR are considered successful rhizobacteria in soil ecosystems (Bhattacharyya and Jha, 2012).

Commercial preparations of several PGPR inoculants have also been shown to promote plant growth through various mechanisms, such as the production of phytohormones, disease suppression, and improvement of nutrient acquisition (Saharan and Nehra, 2011).

As stated by Singh (2013) inoculation with PGPR induces plant growth, thereby enhancing yield through the enhancement of phosphorus or potassium solubilization and nitrogen and other element uptake (Fig. 1). They promote root growth while increasing the effective surface area of the root system. Table 1 shows the some of the PGPR tested for various crop species.

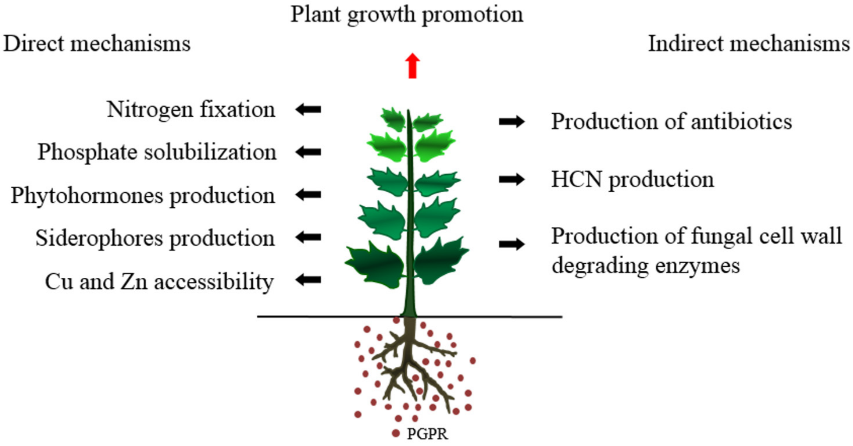

Fig. 1. Growth promotion characteristics by plant growth promoting rhizobacteria (PGPR). HCN, hydrogen cyanide.

Table 1. Plant growth promoting rhizobacteria tested for various crop species.

PGPR	Plant	Consequences of addition of PGPR	References
Bacillus subtilis subsp., *Bacillus megaterium*	*Oryza sativa*	Improve growth and productivity under drought stress	Abd El-Mageed et al. (2022)
Bacillus spp., *Mucilaginibacter* spp., *Pseudomonas* spp.	*Cannabis sativa*	Improve rooting speed of cuttings, yield attributes, and physiological variables	Lyu et al. (2022)
Bacillus licheniformis	*Solanum tuberosum*	Enhanced leaf gas exchange rates, including photosynthesis rate, stomatal conductance and transpiration rate at early seedling stage	Liu et al. (2022)
Azotobacter chroococcum, *Azospirillum brasilense*, *Pseudomonas brassicacearum*	*Fragaria* × *ananassa* (strawberry)	Enhance anti-herbivore defence system against two-spotted spider mites, improve nutritional status of plants	Hosseini et al. (2021)
Bacillus amyloliquefaciens, *Pseudomonas* spp.	*Piper nigrum*	Enhance anti-herbivore defence system against two-spotted spider mites and green peach aphids	Pappas et al. (2021)
Pseudomonas putida KT2440	*Glycine max*	Improve seed germination and stem length under saline conditions	Costa-Gutierrez et al. (2020)
Pseudomanas PS01	*Arabidopsis thaliana*	Improve seed germination and plant growth under salt stress	Chen et al. (2021)
Bacillus tequilensis SSB07	*Glycine max*	Improve shoot length, biomass, leaf area, and photosynthetic pigments under normal growth conditions and heat stress	Kang et al. (2019)
Rhizobium leguminismarum, *Pseudomonas* spp.	*Triticum* spp.	Increase the yield and phosphorus uptake	Singh (2013)

PGPR, plant growth-promoting rhizobacteria.

Use of PGPR in Agriculture and their Relevant Mechanisms

PGPR can be used as a bio-fertilizer

The increased use of chemical fertilizers in agriculture is a matter of great concern because of their possible environmental and health risks (Verma et al., 2010). Biofertilizers have received wide recognition as viable alternatives to chemical fertilizers (Hayat et al., 2012). When used as a biofertilizer, PGPR can colonize the rhizosphere or interior parts of plants, enhance nutrient availability, and further influence the plants by their involvement in nitrogen fixation and phosphate solubilization (Bhattacharyya and Jha, 2012). In addition to enhancing mineral and nitrogen availability in soil, some bacterial strains can directly regulate plant physiology by simulating plant hormone synthesis (Saharan and Nehra, 2011). A previous study reported that PGPR enhances soil fertility and promotes safflower growth by increasing the activity of soil urease, phosphatase, and invertase enzymes (Nosheen and Bano, 2014). Furthermore, it is recommended that PGPR treatment could potentially replace 50 - 75% of chemical fertilizers.

PGPR is involved in nitrogen fixation

Nitrogen, a key nutrient required for plant growth, is often reported as a limiting factor in many agricultural fields owing to heavy nitrogen losses (Perez-Montano et al., 2014). Nitrogen-fixing bacteria are important in agro-ecosystems because they can influence nitrogen availability and uptake by plants (Gopalakrishnan et al., 2017). Symbiotic nitrogen fixation through *Rhizobium* and *Bradyrhizobum* is significant in soils with low amounts of nitrogen because of nodule formation on the roots of species such as soybeans, peas, peanuts, and alfalfa (Hayat et al., 2012). Nitrogen-fixing rhizobacteria that colonize the rhizosphere are good examples of legume-rhizobial symbiosis (Verma et al., 2010). They convert atmospheric nitrogen to ammonia, which could subsequently act as a source of nitrogen for plants. Among the most studied rhizobia, the ability of *Rhizobium*, *Bradyrhizobium*, *Allorhizobium*, *Azorhizobium*, *Mesorhizobium*, and *Sinorhizobium* fix nitrogen in legumes has been proven (Verma et al., 2010). *Bradyrhizobium* is a common soil-dwelling microorganism that forms symbiotic relationships with legumes and exchanges nitrogen with carbohydrates from the host plant (Saharan and Nehra, 2011). During the signal exchange process of *Rhizobium*-legume symbiosis, flavonoids are released by the legume, providing signals to the bacterium to secrete Nod factors. Cereals grown in inter-cropping systems or crop species that rotate with legumes benefit from *Rhizobium*-legume symbiosis (Hayat et al., 2012). In these systems, plant root hairs induce root nodules, on which *Rhizobium* bacteria fix atmospheric nitrogen (Verma et al., 2010). Free-living nitrogen-fixing bacteria that associate with roots, such as *Azotobacter, Paenibacillus, Burkholderia, Bacillus, Azospirillum,* and *Herbaspirillum*, can facilitate nitrogen uptake (Goswami et al., 2016). These bacteria maintain close interactions with the plant roots and feed on root exudates containing proteins, amino acids, enzymes, vitamins, sugars, organic acids, and hormones (Tabassum et al., 2017). Furthermore, some rhizobia can enhance phosphorus availability by mobilizing inorganic and organic phosphorus (Saharan and Nehra, 2011).

PGPR affected phosphate solubilization

Phosphorus (P), a key element for plant growth (Rawat et al., 2021), is generally unavailable for plant uptake because of its insoluble form, which often limits the productivity of agricultural ecosystems (Singh, 2013; Lin et al., 2016). When a phosphate fertilizer is applied to the soil, a substantial portion of the phosphorus is rapidly converted into insoluble forms and forms complexes with Al and Fe in acidic soils and with Ca in calcareous soils (Walpola and Arunakumara, 2015). The accumulation of inorganic insoluble phosphates in the soil and their transfer to water bodies can have undesirable effects on the environment (Gatiboni et al., 2020). Microorganisms capable of converting insoluble phosphates into soluble forms are known as phosphate-solubilizing bacteria (Hayat et al., 2012).

Phosphate-solubilizing bacteria (PSB) produce and release low-molecular-weight organic acids (e.g., citric acid, lactic acid, gluconic acid, 2-ketogluconic acid, oxalic acid, tartaric acid, succinic acid, malonic acid, glutaric acid, malic acid, and acetic acid) that can lower the pH of the soil solution and facilitate solubilization (Patel and Saraf, 2017). In addition, some inorganic acids such as sulfuric acid, nitric acid, carbonic acid, and hydrochloric acid also contribute significantly to phosphate solubilization (Rawat et al., 2021). Mineralization of organic phosphates also occurs through the hydrolysis of phosphate esters by excreted extracellular enzymes such as acid and alkaline phosphatases, phytases, phosphatases, and C-P lysases (Alori et al., 2017). Strains belonging to the genera *Bacillus*, *Pseudomonas*, *Enterobacter*, *Rhizobium, Arthrobacter*, and *Burkholderia* are found the most efficient at promoting plant growth (Jha and Saraf, 2015; Islam et al., 2016; Kang et al., 2019). Their role in phosphate solubilization reduces the dependency on phosphatic fertilizers while minimizing environmental contamination. Plant growth promotion and increased phosphorous availability with the inoculation of phosphate-solubilizing bacteria have been assessed under green-house and field conditions; some are listed in Table 2.

Table 2. Plant growth promoting phosphate solubilizing bacteria with their host plants.

Phosphate-solubilizing microorganisms	Host plant	Plant growth promotion	References
Pseudomonas spp. JP233	*Zea mays*	Reduce P leachate loss, improve P absorption and use of soil available P	Yu et al. (2022)
Bacillus aryabhattai B8W22	*Zea mays* + *Glycine max*	Improve the plant growth, available P content and plant P uptake	Song et al. (2021)
Pseudomonas sp., *Burkholderia* sp., *Paraburkholderia* sp., *Novosphingobium* sp., *Ochrobactrum* sp.	*Cunninghamia lanceolata* (Chinese fir.)	Increased plant height, stem diameter and the biomass of roots, stems and leaves, increased total N, total P, total K, Mg and Fe contents in leaf	Chen et al. (2021)
Pseudomonas putida, *Pseudomonas fluorescens*, *Bacillus subtilis*	*Sorghum bicolor*	Increased plant growth as well as the content of Mn, Zn, Cu, and K	Abbaszadeh-Dahaji et al. (2020)
Bacillus xiamenensis PM14	*Saccharum officinarum*	Suppress red rot disease symptoms in sugarcane and enhance plant growth	Amna et al. (2020)
Bacillus subtilis 320	*Zea mays*	Improve yield and P in the plants	Lobo et al. (2019)
Azospirilum brasilense, *P. fluorescens*	*Zea mays*	Improved grain yield	Di Salvo et al. (2018)

PGPR, plant growth-promoting rhizobacteria.

PGPR induces siderophore production

Siderophores are high-affinity microbial iron-chelating low molecular weight (< 1.5 kDa) compounds that are metabolites of PGPR released into iron-limited rhizospheric soil (Khan et al., 2018; Wang et al., 2022). Siderophores produced by some PGPR can scavenge micronutrients such as iron, discouraging pathogenic microorganisms from maintaining their nutrition thereby reducing disease incidence (Saharan and Nehra, 2011). These PGPRs in the rhizosphere can increase the rate of Fe^{3+} availability, enabling absorption by plants (Kramer et al., 2020). These siderophilic bacteria are major assets to plants as they maintain and provide iron (Khan et al., 2018). *Bacillus* spp. are highly regarded in this context because they can produce different siderophores that maintain ionic balance and suppress the iron requirements of pathogenic microorganisms

(Radhakrishnan et al., 2017). Wang et al. (2022) that isolated 21 siderophilic bacterial species from the rhizosphere of *Paris polyphylla* var. *yunnanensis* found that *Bacillus* spp. were the dominant species. In addition, Xu et al. (2020) reported that siderophore-producing pathogenic bacteria such as *Mycobacterium tuberculosis* cause severe tissue damage and bleeding through the continuous chelation of their host’s iron.

PGPR regulates certain phytohormones

Certain bacteria stimulate plant growth by producing various substances, such as growth-stimulating phytohormones (Numan et al., 2018). Phytohormones are biochemical molecules that regulate various functions in plants (Miransari, 2014). They can stimulate the physiological activities of plants even at low concentrations (Hayat et al., 2012). Among the known phytohormones, auxins, such as indole-3-butyric acid (IBA), indole-3-acetic acid (IAA), cytokinins, gibberellic acid (GA_3), ethylene, and abscisic acid (ABA) have been extensively studied for their ability to enhance plant growth and development (dos Santos et al., 2020). IAA is the most common and widely studied auxin and is produced by more than 80% of bacteria isolated from the rhizosphere (dos Santos et al., 2020). IAA induces the growth and development of different plant parts, including stems, leaves, flowers, and roots (Phillips et al., 2011). It stimulates the mortification, elongation, and differentiation of plant cells, germination of seeds and tubers, pigment formation, metabolite biosynthesis, formation of lateral roots in dicotyledons, and formation of adventitious roots in monocotyledons. IAA can loosen cell walls and facilitate root exudation, which ultimately enhances the uptake of additional nutrients. This is further facilitated by the increased surface area and length of the roots, although higher concentrations of IAA may negatively affect plant root growth (Glick, 2012; Duca et al., 2014). *Azospirillum brasilense*, *Pantoea rodasii* LGM 26273, *Enterobacter ludwigii* DSM 16688, *Enterobacter hormaechei* ATCC 49162, *Burkholderia phytofirmans,* and *Bacillus subtilis* are efficient plant-growth-promoting bacterial species that synthesize IAA (Walpola and Arunakumara, 2015; Patel et al., 2016; Poupin et al., 2016).

Cytokinins and gibberellins are two others important phytohormones that are produced by rhizobacteria. Zeatin and kinetin are relatively abundant cytokinins (O’Brien and Benkova, 2013). Cytokinins stimulate shoot formation, root development, and cell division while regulating plant growth (Jha and Saraf, 2015; Khan et al., 2018). The combined effects of cytokinins and auxins are important for meristem function, root architecture, reproductive organ development, and lateral organ development in the shoots (Schaller et al., 2015). Gibberalins are involved in seed germination, shoot growth, flowering, and fruit setting (Saleem et al., 2015). They regulate the size of the root and leaf meristems (Martínez et al., 2018). Ethylene is another well-known hormone and the simplest molecule that can enhance plant biological activity (Glick, 2012). Table 3 depicts the different phytohormones produced by PGPR.

Table 3. Phytohormone produced by plant growth promoting rhizobacteria.

PGPR	Phytohormones	References
Bacillus tequilensis SSB07	Gibberellins GA_1, GA_3, GA_5, GA_8, GA_{19}, GA_{24}, GA_{53}, indole-3-acetic acid, abscisic acid	Kang et al. (2019)
Lysinibacillus sphaericus	Indole-3-acetic acid	Breedt et al. (2017)
Pseudomonas stutzeri, *Stenotrophomonas maltophilia*, *P. putida*	Indole-3-acetic acid, gibberellic acid, Cytokinins	Patel et al. (2016)
Azospirillum lipoferum	Abscisic acid	Cohen et al. (2009)

PGPR, plant growth-promoting rhizobacteria.

PGPRs act as biological control agents

Rhizobacteria can act as bio-control agents to alleviate various pathogenic diseases and are widely regarded as environmentally-friendly approaches (Qiao et al., 2017). PGPR facilitates antagonistic interactions between pathogens and bio-control agents (Table 4). The induction of host resistance is another mechanism by which PGPR protects plants (Singh, 2013). As bio-control agents, PGPR is effective in suppressing diseases in living plants, but their role in minimizing post-harvest diseases was also reported (Lugtenberg and Kamilova, 2009). Several bacterial genera, including *Pseudomonas*, *Bacillus*, *Burkholderia*, *Streptomyces*, and *Agrobacterium*, have been studied for their ability to act as bio-control agents. They could suppress plant diseases by inducing systemic resistance and producing siderophores, bacteriocins, hydrolytic enzymes, antibiotics, or other hydrolytic enzymes (Umer et al., 2021). The most widely recognized mechanism by which PGPR can suppress disease is by producing metabolites that can directly act on pathogens since they compete with pathogens for nutrients and specific niches in the roots (Figueiredo et al., 2010). Some anti-fungal metabolites, such as antibiotics, hydrogen cyanide, and fungal cell wall-lysing enzymes can improve plant growth by suppressing phytopathogens. Siderophores chelate iron, making it unavailable to pathogens. Additionally, they can induce systemic resistance (Singh, 2013). As reported Saharan and Nehra (2011), the growth of pathogens can be suppressed by PGPR through the antibiotic production. The use of PGPRs as bio-control agents is summarized in Table 4. A wide range of fungal diseases can be managed using PGPR and bacterial endophytes; however, an appropriate delivery system has yet to be established Singh (2013). Table 4 also summarizes the fungicidal activities of PGPRs.

Table 4. PGPR as bio-control agents against plant diseases.

PGPR and PGPF	Activity as the bio-control agent	References
Candida lusitaniae Cl-28, *Candida oleophila* Co-13, *Debaryomyces hansenii* Dh-67, *Hypopichia pseudoburtonii* Hp-54	Reduced post-harvest and wilt diseases severity caused by *Penicillium expansum* in grape and apple plants	Fernandez-San Millan et al. (2021)
Trichoderma spp.	Suppressed downy mildew disease caused by *Sclerospora graminicola* in pearl millet	Nandini et al. (2021)
Azotobacter chroococcum, *Azospirillum brasilense*, *Pseudomonas brassicacearum*	Exert adverse effects on life history and population dynamics of two-spotted spider mites in above ground tissue of strawberry plants	Hosseini et al. (2021)
Bacillus amyloliquefaciens B10W10, *Pseudomonas* spp. B11W11, *Bacillus amyloliquefaciens* B10W10, *Pseudomonas* spp. B11W11	Controlled brown rot disease caused by *Monilinia fructigena* in apple	Lahlali et al. (2020)
Pantoa agglomerans ACBP2, *Bacillus amyloliquefaciens* LMR2, Brevibacterium. *halotolerans* (SF3, SF4), *Bacillus mojarvensis* SF16	Inhibit fire blight caused by *Erwinia amylovora* in apple plants	Bahadou et al. (2018)
Pseudomonas fluorescens PF15, *P. putida* PP27	Reduce disease incidence of *Fusarium* wilt in tomato	Boukerma et al. (2017)
Methylobacterium aminovorans, *Methylobacterium rhodinum*, *Bradyrhizobium japonicum* St. 110, *Bacillus megaterium* var. *phosphaticum*, *Trichoderma viride*	Biocontrol of *Rhizoctonia Solani* in Soybean seedlings	Omara et al. (2017)
Bacillus subtilis LHS11 and FX2	Biocontrol agents in rapeseed plants rapeseed plants against *Sclerotinia sclerotiorum*	Sun et al. (2017)
Pseudomonas stutzeri, *Bacillus subtilis*, *Stenotrophomonas maltophilia*, *Bacillus amyloliquefaciens*	Suppression of the pathogen *Phytophthora capsici* in cucumber plants	Islam et al. (2016)

PGPR, plant growth-promoting rhizobacteria; PGPF, plant growth-promoting fungi.

PGPRs act as biotic elicitors

Elicitors are chemicals or biofactors of diverse origins (Glick, 2012; Breedt et al., 2017; Chu et al., 2019; Ghani et al., 2022). They induce physiological and morphological alterations in the targeted living creatures (Sekar and Kandavel, 2010). As stated by Bhattacharyya and Jha (2012), the accumulation of phytoalexin in plants could be triggered by elicitors. Furthermore, they augment the physiological and morphological responses of plants. Abiotic elicitors include inorganic compounds and metal ions, while biotic elicitors include chemicals released by plants, fungi, bacteria, and viruses. Biotic elicitors display an array of defense mechanisms, as they can induce the secretion of defensive bioactive molecules, such as phytoalexins (Bhattacharyya and Jha, 2012). A range of metabolites, including picrocrocin, ajmalicine, hyoscyamine, serpentine, crocetin, and scopolamine, have been reported to be produced by PGPR. These metabolites elicit both physiological and morphological responses in plants (Bhattacharyya and Jha, 2012).

PGPR is used for rhizoremediation

Under contaminated soil conditions, inoculation with PGPR strains has been shown to assist plant growth and development; hence, the application of PGPRs for rhizoremediation is very effective in polluted soils (Table 5). Degradation of organic pollutants can be facilitated with the use of PGPR rhizo-remediers (Saharan and Nehra, 2011). PGPR and arbuscular mycorrhizal fungi have been reported to be effective in enhancing the solubility of certain heavy metals in nutrient-deficient agricultural soils (Bhattacharyya and Jha, 2012).

Table 5. Plant growth promoting rhizobacteria as bioremediation agents.

PGPR	Pollutants	Rhizoremediation activity	References
Enterobacter cloacae MUG75	Agricultural area with repeated application of profenofos	Degraded 90% profenofos	Ghani et al. (2022)
Enterobacter cloacae	Soil samples polluted with crude oil	Hydrocarbon biodegradation	Ejaz et al. (2021)
Pseudomonas baetica B2, *Pseudomonas moraviensis* B1	Mercury-contaminated soils	In situ phyto-rhizoremediation mercury-contaminated soils.	Gonzalez et al. (2021)
Bacillus spp. PRB101	Endosulfan	Increase the decontamination of endosulfan stressed soil and decline endosulfan concentration in the plant tissues.	Rani et al. (2021)
Micrococcus luteus	As (III)	Decrease of $NaAsO_2$ toxic effect in *in vitro* grapevines inoculated with *M. luteus*	Pinter et al. (2017)
Alcaligenes feacalis RZS2, *Pseudomonas aeruginosa* RZS3	Heavy metal contaminated soil	Bioremediation of heavy metal ions like $MnCl_2.4H_2O$, $NiCl_2.6H_2O$, $ZnCl_2$, $CuCl_2$, $CoCl_2$	Patel et al. (2016)
Pseudomonas aeruginosa, *Bacillus subtilis*, *Acinetobacter lwoffii*	Egyptian crude oil	Bioremediation of oils spills individually	Al-Wasify and Aboelwafa (2009)

PGPR, plant growth-promoting rhizobacteria.

PGPRs act as multifunctional agents

The effectiveness of PGPR has been reported to differ according to the growing conditions of the crops; thus, the intended outcome is sometimes difficult to achieve (Ahemad and Kibret, 2014). *Azospirillum* sp. can withstand a certain degree of salinity or osmolarity, as the species can accumulate compatible salts and exhibit osmoadaptation (Saharan and Nehra, 2011). As reported by Saharan and Nehra (2011), *Pseudomonas. fluorescens* can withstand a certain level of drought and hyperosmolarity. PGPRs are ideal candidates for organic agriculture, where using synthetic plant growth regulators has been prohibited Singh (2013). Once seeds are inoculated before planting, PGPR is generally established in the rhizosphere of the crop Saharan and Nehra (2011).

Conclusion

Excessive use of inorganic fertilizers and pesticides for improved agricultural production severely contributes to the deterioration of soil fertility and negatively impacts the environment. This has become a matter of great concern, and there is an urgent need for alternative strategies to address these issues. Therefore, the use of plant-growth-promoting rhizobacteria to enhance soil fertility and plant growth via various mechanisms is vital. This review highlights the practical significance of PGPR, which can be effectively used in sustainable agriculture as biofertilizers and biocontrol agents for many crop species. However, it is important to note that specific studies have reported negative effects on soil health and plant growth when using PGPR under saline conditions. Therefore, further research is required to assess their performance under varying field conditions with specific crop species to broaden their application in sustainable agriculture.

Conflict of Interests

No potential conflict of interest relevant to this article was reported.

Acknowledgements

We are sincerely thankful to our advisor for their invaluable guidance throughout this research. We also extend my gratitude to the reviewers and editors in *Korean Journal of Agricultural Science* for their insightful feedback and valuable contributions. Their support and input have been instrumental in shaping and improving this work.

Authors Information

Subhashini Wijeysingha, Master student, University of Ruhuna
Buddhi C. Walpola, Professor, University of Ruhuna
Yun-Gu Kang, https://orcid.org/0000-0001-5368-5910
Min-Ho Yoon, Professor, Chungnam National University
Taek-Keun Oh, https://orcid.org/0000-0003-0215-0427

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