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Review Article

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Mechanisms used by plant growth-promoting rhizobacteria to boost plant growth - A Review

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ABSTRACT

Several decades after the green revolution, the agricultural industry depended on artificial chemical fertilisers to achieve higher crop yields. This practice, however, contributes to a hazardous impact on the farming ecosystem, causing a smaller deposit of arable land for crop cultivation and production worldwide. Since the 2000s, people, industries, and governments are aware that it is time for everyone to shift to new technology which promotes responsible land use for agriculture. One of the technologies is plant growth-promoting rhizobacteria to enhance crop productivity and potentially rehabilitate soil health directly or indirectly. This review paper outlines the mechanisms used by plant growth-promoting rhizobacteria to promote plant growth. The tools could be opening up new ideas to address one of the recent and urgent world agriculture issues, food security.

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INTRODUCTION

Over recent years, an increase in the world population has triggered an increasing demand for food production. The current world population is 8.04 billion as of May 2023. It is estimated that 9.7 billion people will be inhabiting the earth by 2050 (Worldometers, 2023). This phenomenon has alarmed our ability to feed the accelerating demand for food in the long term without putting enormous pressure on the world's resources and damaging environmental health. Advanced farming techniques are introduced to provide the world's need for food products. Efforts to increase agriculture productivity were hinged on synthetic-based fertilisers and plant growth regulators. The significant dependence on mineral fertilisers accounted for more than 90% of the fertilisers used to 'feed on crops' is becoming standard practice.

This ill-conceived and extensive reliance on chemical input in our farming system would intimidate the environmental sustainability and the agribusiness connected with agricultural products. Improper application of chemical, and agricultural inputs, including chemical fertilisers and pesticides (organophosphate, organochlorines, carbamates/dithiocarbamates, and synthetic pyrethroids), could lead to detrimental effects on the environment through excessive soil erosion, surface water and groundwater pollution caused by the associated transport of sediment, chemical fertilisers and pesticides runoff and greenhouse gas emission (Opoku-Kwanowaa *et al.*, 2020). Moreover, an ever-increasing amount of fertilisers and pesticides commonly used in conventional practices and the energy requirements for tilling to aerate soils and increasing irrigation have accelerated production costs. Of late, there has been a new interest in introducing safe, cost-effective, environment-friendly, sustainable and organic farming practices. By using organic plant growth regulators and bio-fertilisers containing beneficial microbes in place of agricultural chemical inputs, plant growth

can be improved, and the soil's productivity sustained for better environmental health.

The term 'Plant growth-promoting rhizobacteria' was coined by Joe Kloepper in the late 1970s. In 1978, Kloepper and Schroth briefly defined them as "the soil bacteria that colonise the plant's roots by the following inoculation onto the seed and enhancing plant growth". They are commonly known as rhizobacteria, which encompasses naturally occurring soil bacteria inhabiting rhizosphere soil, rhizoplane, and internal root tissue that biologically interact with plants through direct or indirect mechanisms. They belong to the genera *Agrobacterium*, *Azospirillium*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Micrococcus*, *Pseudomonas*, and other extracellular PGPR (Verma *et al*., 2019); and intracellular PGPR includes the *Rhizobium* and *Frankia* species which perform symbiotic relationships with plant roots (Verma *et al*., 2019). They exert beneficial effects on plant growth and development through the recycling of essential elements (da Silveira *et al*., 2016), solubilisation of nutrients such as potassium and phosphorus (Meena *et al*., 2015), producing numerous plant growth regulators (Jiang *et al*., 2012), degrading organic pollutants (Nonnoi *et al*., 2012; Sharma & Archana, 2016), biocontrol of soil-borne pathogens (Hong *et al*., 2016; Niu *et al*., 2020) and assisting plant to tolerate environmental stress (Kaushal & Wani, 2016). Figure 1 illustrates the benefits of applying plant growth-promoting rhizobacteria as a biofertiliser, biopesticide, and phytostimulator (or biostimulant).

MECHANISMS OF PLANT GROWTH-PROMOTING RHIZOBACTERIA

Biological Nitrogen Fixation

Nitrogen (N) is one of the essential yield-limiting macronutrients in the agricultural ecosystem (Bhattacharjee *et al*., 2008) that occurs in the soil in both organic and inorganic forms (Richardson *et al*., 2009). It is a crucial element for all living organisms for their amino acid synthesis, proteins, and other organic nitrogenous compounds (Reddy, 2014). Microorganisms play important roles in increasing N availability for plant use through biological nitrogen fixation and mineralisation of nitrogen. Meanwhile, biological nitrogen fixation (BNF) is the process of fixation of unreactive atmospheric dinitrogen molecules. It converts them into ammonia, readily utilised by a plant (Bhattacharjee *et al*., 2008). It is catalysed by a complex enzyme system known as nitrogenase that exists within the bacteria. BNF can be done by PGPR either symbiotically between symbiotic N_2-fixing bacteria from genera *Rhizobium*, *Sinorhizobium*, *Bradyrhizobium*, *Mesorhizobium* and *Azorhizobium* with leguminous plants; or through free-living N-fixing bacteria (Bishnoi, 2015).

BNF is a critical process for enhancing N availability biologically for plant uptake since no plant species can do that. N's high fixation is achieved through a symbiosis between rhizobia with a leguminous plant, which involves most of the 18,000 species are legumes (Sharma *et al*., 2023), such as cowpea, pigeon, peas, etc. This symbiotic relationship can fix 50-100 kg N per hectare (Reddy, 2014) and provide up to 90% of the plant's N requirements (Franche *et al*., 2009). This rhizobium-legume interaction has significantly contributed to the N fixation in the agricultural ecosystem. The yield of crops increased up to 70% after inoculation with *Rhizobium* inoculants compared to uninoculated crops (Reddy, 2014). Inoculation of *Rhizobium or Bradyrhizobium* in legume and pasture crop production is seen to be more economical and practical to provide sufficient N sources than the application of chemical fertilizer-N (Zahran, 1999).

Besides symbiotic rhizobium-legume interactions, BNF also can be carried out by non-symbiotic N fixing bacteria. In contrast to symbiotic N fixation, N_2 is significantly less fixed by free-

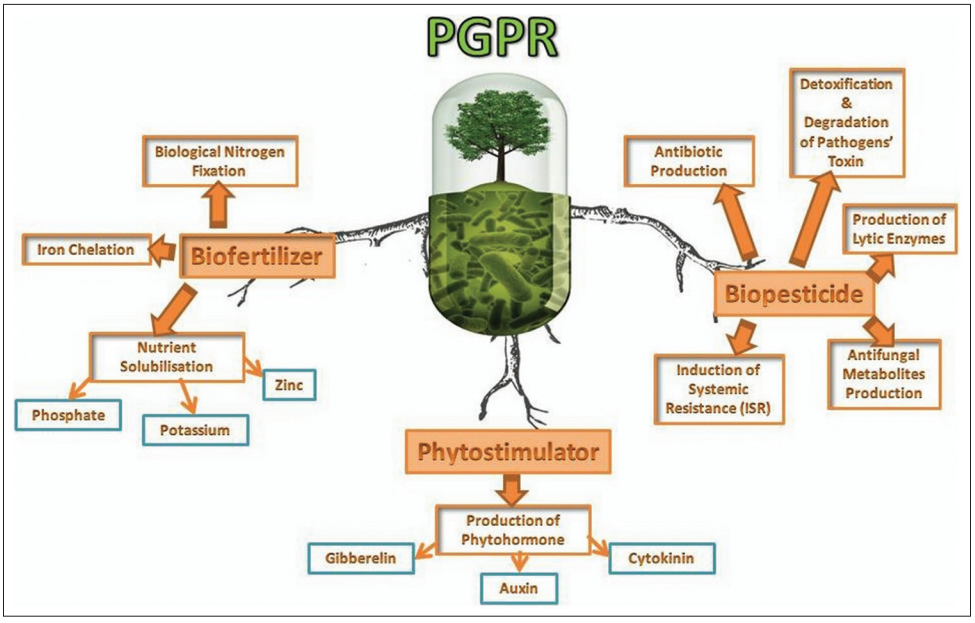

Figure 1: Plant growth-promoting rhizobacteria as biofertilisers, biopesticides, and phytostimulator. Single or multiple combinations of traits promote plant growth and conserve the environment

living diazotrophs due to the shortage of glucose equivalents in the soil to cover the high energy requirements of nitrogenase. More energy is required to protect the enzyme from oxygen since nitrogenase is oxygen-sensitive (Olivares *et al.*, 2013). For example, *Azotobacter* requires 100 g of carbon to reduce one molecule of N_2. In contrast, rhizobia only need 12 g of carbon to do the same reduction process (Phillips, 1980), thus limiting BNF to be used industrially (Olivares *et al.*, 2013).

On the other hand, *Azospirillium* is a well-studied diazotroph by numerous researchers. *Azospirillium* sp. is an aerobic heterotrophic N fixing bacterium that fixes N_2 under microaerophilic conditions (Kennedy *et al.*, 2004) and is grown extensively in the rhizosphere of important agricultural non-leguminous crops. They can save chemical fertilisers by 15-20 kg N ha^{-1} (Reddy, 2014). Zakry and his co-workers reported that *Bacillus sphaericus* inoculation to field-grown young oil palm uptakes 63% of nitrogen derived from the atmosphere (Zakry *et al.*, 2012). Other important free-living diazotrophs that form an association with plant rhizosphere and fix dinitrogen into a convenient form for plant uptake come from genera *Azoarcus*, *Azotobacter*, *Bacillus*, *Burkholderia* and *Pseudomonas* (Saharan & Nehra, 2011). At present, 13 genera of prokaryotes have been classified able to fix nitrogen such as Anabaena, Anabaenopsis, Azospirillum, Azotobacter, Bacillus, Frankia, Methanobacteriales, Methanococcales, Methanomicrobiales, Mycobacterium, Nostoc, Rhizobium, and Tolypothrix (Soumare *et al.*, 2020).

Solubilisation of Phosphorus

Phosphorus (P) is one of the crucial macronutrients for the requirement of plant growth and development (Sharma *et al.*, 2013). However, global P resources are limited and decreased gradually (Cordell *et al.*, 2009), with more than two billion hectares reduction in agriculture (Oberson *et al.*, 2001). It exists at levels of 400-1200 mg/kg of soil (Rodríguez & Fraga, 1999), but the concentration of soluble P is very low, generally present at levels one ppm or less (Richardson *et al.*, 2009). This low P efficiency is due to the P fixation and immobilisation caused by hydrated oxides ferum and aluminium in acid soils. In contrast, in alkaline soil, it is fixed by calcium (Rodríguez & Fraga, 1999). Thus, microorganisms such as phosphate-solubilising bacteria (PSB) need to solubilise the P pools in the soil for plant uptake. Since PSB is a heterogeneous and naturally abundant rhizospheric bacteria (Pereira & Castro, 2014), it can trigger P availability for plant requirements through (i) conversion of insoluble phosphates into available form (Sharma *et al.*, 2013); and (ii) mineralisation of organic phosphorus via synthesis of several phosphatase enzymes (Richardson & Simpson, 2011).

Several reports showed that inoculation of PSB on the plant had increased plant growth and P uptake in laboratory and pot studies. Still, PSB use in field trials showed inconsistent results (Richardson & Simpson, 2011). Inoculation of bacterial strain *Pseudomonas* sp. EAV and *Arthrobacter nicotinovorans* strain EAPAA with corn have increased available soil P and promoted corn growth in P-deficient soils (Pereira & Castro, 2014). Krey *et al.* (2013) found that *Pseudomonas flourescens* increased available P and improved root colonisation by mycorrhiza in corn. Combining PSB with other beneficial substances or organisms such as silicon and arbuscular mycorrhizal fungi may be useful strategy to improve further the plant growth and yield (Etesami *et al.*, 2021).

Potassium Solubilisation

Besides N and P, potassium (K) is the third essential macronutrient needed for plant growth and development to maintain plant turgidity, resist an unfavourable environment like drought and salinity stress, and assist plant defence against pests and pathogens attack (Abdelaal *et al.*, 2021). An inadequate supply of K during plant growth will lead to a poorly developed root system, slower growth, reduction in yields, and increased susceptibility to diseases (Meena *et al.*, 2014). This phenomenon may happen when a plant cannot access available K from the soil since its availability depends on the K dynamics and total K content (Parmar & Sindhu, 2013). Even though soil generally has large reserved K, only a tiny amount (1-2%) can be absorbed by the plant through soil solution K, representing only 0.1-0.2% of the total soil K (Meena *et al.*, 2014). The rest of the total K is incorporated in the crystal lattice structure of minerals such as mica and feldspar; thus, it is not directly available for plant use (Zörb *et al.*, 2014). Therefore, the K source added through fertilisation increases available K for plant uptake.

Even though the application of K through fertiliser was reported to enhance the water holding capacity of the soil and improves the structural stability of sandy soil in particular (Holthusen *et al.*, 2010), unbalanced fertilisation due to lower K-fertilization may lead to a significant reduction of available K reserves, thus reduced soil fertility (Zörb *et al.*, 2014). Moreover, low awareness of K-fertilization among farmers only a few of them applying K-fertilizer in their crop production (Meena *et al.*, 2014), has caused the reduction of plant-accessible K due to loss of K through the removal of the crop, runoff, erosion and/or leaching (Sheng & He, 2006; Parmar & Sindhu, 2013). Regarding increasing available K without compromising environmental health, the use of soil bacteria capable of solubilising K-minerals could provide a promising approach to tackle this issue (Parmar & Sindhu, 2013).

In 1890, Muentz discovered the first evidence of the involvement of microorganisms in solubilising rock potassium (Sammauria *et al.*, 2020). Various soil microorganisms have been found to solubilise silicate minerals such as silicate bacteria from genera *Pseudomonas*, *Burkholderia*, *Bacillus* and *Paenibacillus*. K-bearing minerals release into soluble form for plant uptake generated by producing various organic acids (Meena *et al.*, 2014). Production of organic acids such as acetic, citric, propionic, glycolic, oxalic, and tartaric acid has been identified among K-solubilizing bacteria (KSB) (Wu *et al.*, 2005). Therefore, the mechanisms for K solubilisation induced by KSB are initiated through pH reduction, enhancement of chelation of cations bounded to K and acidolysis of the surrounding area of the microorganism (Meena *et al.*, 2014).

Various researches such as *in vitro*, greenhouse or field trials have been conducted to discover bacterial strains that can

solubilise mineral K. Meena *et al.* (2015) investigated the influence of KSB, namely *Agrobacterium tumefaciens* OPVS 11 and *Rhizobium pusense* OPVS6, on the K release and pH dynamic under waste mica (muscovite and biotite). Both strains significantly reduced media pH via acidolysis and efficiently solubilised insoluble K when examined under *in vitro* conditions. KSB strain isolated from rhizospheric soil of tobacco viz. strain GL7, JM3, XF4, and XF11 promoted tobacco growth under a greenhouse study (Zhang & Kong, 2014). All the strains had triggered the uptake of K and N and increased the plant dry weight of tobacco seedlings.

Production of Phytohormones

Phytohormones are organic compounds synthesised in one part of the plant and are translocated to another location. They effectively promote physiological responses, such as growth or fruit ripening at a poor concentration (Reddy, 2014). Each reaction is often the result of two or more hormones acting together on the specific target tissue. Since hormones could stimulate or inhibit a plant's growth, many botanists also denote them as plant growth regulators (Saharan & Nehra, 2011). Phytohormones available to the plant naturally come from two primary sources; endogenous production by the plant tissues and exogenously produced by associated microorganisms, including numerous soil bacteria and fungi. Five major groups of hormones, regarded as the "classic five", are auxins, gibberellins, cytokinins, ethylenes, and abscisic acid (Baca & Elmerich, 2007). Among these hormones, the most studied in PGPR's role is indole-3-acetic acid (IAA) production.

IAA is generally considered the most important native auxin (Saharan & Nehra, 2011) that functions in root initiation, cell division and cell enlargement (Reddy, 2014). It is commonly synthesised and released as secondary metabolites by rhizospheric bacteria due to root exudates (Ahmad *et al.*, 2005), for instance, amino acid tryptophan (Lugtenberg & Kamilova, 2009). It has been identified that tryptophan acts as a primary precursor for IAA biosynthesis pathways in bacteria (Spaepen *et al.*, 2007). The effects of auxin on plant seedlings are concentration-dependent, where high concentrations may be inhibitory (Saharan & Nehra, 2011) and lead to disease susceptibility (Duca *et al.*, 2014).

Approximately 80% of soil bacteria-produced IAA, including streptomycetes, methylobacteria, cyanobacteria, and archaea. The most well-studied phytohormone producers are PGPR belonging to the genera *Azospirillium, Azotobacter, Aeromonas, Bacillus, Pseudomonas, and Rhizobium* (Etesami *et al.*, 2014). Numerous researches have been conducted to determine the effect of bio-inoculation of phytohormone-PGPR towards plant growth. Inoculation of the crop with a strain capable of IAA production significantly increases the uptake of macro-nutrients (N, P, and K). The access of plants to the nutrients in the soil can be enhanced by increasing root growth through IAA production (Etesami *et al.*, 2014). The exogenous IAA secreted by *B. cereus* UPMLH1 showed a significant effect on the induction of shallot adventitious roots compared to non-IAA-producing *B. cereus* UPMLH24. However, both inoculation promotes the mustard plant's primary roots and shoot growth (Aziz *et al.*, 2012). Thus, the potential of IAA biosynthesis by rhizobacteria can be used as a tool for the screening of promising PGPR strains.

Siderophore Production

Iron (Fe) is considered a rich element that is found abundantly on the earth and can exist in two oxidation states; ferrous iron (Fe^{2+}) and ferric ion (Fe^{3+}) (Chu *et al.*, 2010). However, the scarcity of available Fe in soil habitats such as microorganisms and for plant assimilation encourages fierce competition (Loper & Henkels, 1997) due to the rapid conversion of Fe^{2+} into lower soluble form Fe^{3+} in the presence of oxygen and at neutral pH conditions (Joshi *et al.*, 2006). Thus, the availability of Fe is made biologically by an iron-chelating compound called siderophore. Siderophores are low molecular weight (normally exist below 10,000 Da) (Tian *et al.*, 2009), with high-affinity iron-chelators that are biosynthetically produced and secreted by plants and microorganisms such as bacteria and fungi (Chu *et al.*, 2010) to competitively acquire Fe^{3+}. Microbes released siderophores to scavenge iron by forming soluble Fe^{3+} complexes that can be taken up by active transport mechanisms (Saharan & Nehra, 2011). Three major groups of siderophores are catecholates, hydroxamates, and carboxylates. Numerous factors modulate the synthesis of siderophores, in particular pH, the level of iron and its ion form, a sufficient supply of carbon, nitrogen, and phosphorus, and also the presence of other trace elements (Duffy & Défago, 1999).

Primarily, the application of siderophore-producing bacteria can help to increase iron availability, improve plant growth and the yield of economically important crops (Westover *et al.*, 1997), and may perform in biocontrol of pathogens through iron competition. Specific native microflora like pathogenic fungi cannot compete for iron since extracellular siderophores efficiently sequester it from PGPR (Kloepper *et al.*, 1980). Inoculation of PGPR from two most studied genera, namely *Bacillus* (Rais *et al.*, 2018; Sarwar *et al.*, 2018), *Pseudomonas* (Borah *et al.*, 2018; Prabhukarthikeyan *et al.*, 2018), have the potential for biocontrol of diseases.

Biological Control of Plant Diseases

The use of microbes in deterring soil-borne disease, which is a form of a biological approach, is a safe and environmental-friendly approach (Lugtenberg & Kamilova, 2009). This approach is looked to be more convenient to be applied in production systems over the use of genetically engineered resistance plants and synthetic agrochemicals. PGPR mediates several mechanisms of biocontrol to suppress plant diseases such as antibiosis, iron-chelation via siderophore production, lytic enzyme and antifungal production, induction of systemic resistance, detoxification and degradation of pathogen's toxin, and production of biochemical compounds associated with host defence (Reddy, 2014). Disease-causing pathogens can be antagonised by various members of PGPR such as *Pseudomonas* and *Bacillus* (Saharan & Nehra, 2011) before and during primary

Table 1: The role of PGPR as a biological control agent for the control of various plant diseases

PGPR	Crops	Diseases (Cause)	Application mode	References
Pseudomonas sp.	Tomato	Root-knot nematodes (*Meloidogyne spp.*)	By dipping roots for 30 min in water suspensions of bacterial cells adjusted at 107 cells/mL	Colagiero *et al.* (2018)
		Early blight (*Alternaria solani*)	Polymer-coated seeds were soaked in 25 mL of pre-screened PGPR suspensions, namely, TN Vel-35, KR Tri-17, AN Rai-27, KA Mys-39 and MA Rah-43, at the rate of 1×10^8 CFU/mL	Babu *et al.* (2015)
	Apple	Fire Blight (*Erwinia amylovora*)	Wounded fruits were treated with antagonists by dipping in 100 ml of antagonist suspension (1×10^8 CFU/mL) for 20 min and then placed in separate plastic boxes	Bahadou *et al.* (2018)
Pseudomonas sp. strain CMR12a	Chinese cabbage (*Brassica chinensis*)	Damping-off (*Rhizoctonia solani*)	The heated seeds were immersed in 50 ml of inoculum solution 10^7 CFU/mL for 2 hours at room temperature	Olorunleke *et al.* (2015)
Pseudomonas putida	Tomato	Bacterial wilt & Cancer (*Clavibacter michiganenensis*)	The heated tomato seeds were immersed in 40 ml of inoculum suspension at 10^7 CFU/mL for 2 hours at room temperature	Aksoy *et al.* (2017)
	Patchouli (*Pogostemon cablin*)	Root-knot (*Meloidogyne incognita*)	By dipping roots for 30 min in water suspensions of bacterial cells adjusted at 10^7 cells/mL	Borah *et al.* (2018)
Pseudomonas fluorescens	Canola (*Brassica napus*)	Crown rot (*Sclerotinia sclerotiorum*)	Spray to the surface of plant with suspensions of bacterial cells adjusted at 10^7 cells/mL	Sun *et al.* (2017)
	Onion	*Tip blight (Alternaria sp.)*	Each plant's root was drenched with 100 ml of PGPR spore suspension (10^6 CFU/mL) at transplanting	Gao *et al.* (2017)
Pseudomonas veronii	Tomato	Bacterial speck (*Pseudomonas syringae pv. tomato*)	Bacterial cells were centrifuged and resuspended in sterile 0.01 mol/L $MgCl_2$ pH 7.0. Bacterial density was adjusted to 10^8 CFU/mL (OD600= 0.1) and bacterial suspensions thus obtained were sprayed on leaf surface	Romero *et al.* (2016)
Bacillus sp.	Tomato	Early blight (*Alternaria solani*)	Polymer-coated seeds were soaked in 25 ml of prescreened PGPR suspensions, namely, TN Vel-35, KR Tri-17, AN Rai-27, KA Mys-39 and MA Rah-43, at the rate of 1×10^8 CFU/mL	Babu *et al.* (2015)
		Root-knot nematodes (*Meloidogyne spp.*)	The root immersion for 30 minutes in the bacterial solution set at a concentration of 10^8 cells/ml	Xiong *et al.* (2015)
	Paddy	Rice bakanae (*Gibberella fujikuroi*)	Seeds are soaked with bacterial inoculum containing 1×10^8 CFU/mL	Sarwar *et al.* (2018)
Bacillus subtilis	Tomato	Post –harvest disease (*Penicillium dan Rhizopus*)	Inoculum was applied to the fruit and foliage of established 6-month-old tomato plant (rate of 1.45 L product/100 L water, product contains 1-10^9 CFU/g) using a finemist high-pressure nozzle	Punja *et al.* (2016)
	Pepper (*Capsicum annuum L.*)	Fusarium wilt (*F. oxysporum f. sp. capsicum*)	Seed soaked with the bacterial inoculum containing 1×10^7 colony forming units (CFU) per ml	Wu *et al.* (2015)
	Castor (*Ricinius communis L.*)	Fusarium wilt (*F. oxysporum* f. sp. *capsicum*)	One day after transplanting the seedlings, pots were inoculated with 30 ml of bacteria (10^8 CFU/mL)	Janga *et al.* (2017)
Bacillus subtilis B99-2	Tomato	Tomato rot (*Rhizoctonia solani*)	Spray on the surface of the plant with a solution containing bacterial cell fluid at 10^7 cells/mL	Ma *et al.* (2015)
Bacillus mojavensis	Chinese cabbage (*Brassica chinensis*)	Black rot (*Xanthomonas campestris* pv. campestris)	Spray on the surface of the plant with a solution containing bacterial cell fluid at 10^7 cells/mL	Liu *et al.* (2016)
Bacillus amyloliquefaciens	Tomato	Bacterial spot (*Pseudomonas syringae pv. tomato*)	Bacterial cells have been centrifuged and sterilised with $MgCl_2$ pH 7.0. Approximately 10^8 CFU/mL (OD600 = 0.1) of the bacterial solution was applied by spraying to the leaf surface	Romero *et al.* (2016)
		Fusarium wilt (*Fusarium oxysporum*)	Seeds were soaked in bacteria inoculum containing 1×10^8 CFU/mL with a mixture of carboxymethyl cellulose (CMC)	Gowtham *et al.* (2016)
	Common bean	Damping-off and Web blight (*Rhizoctonia solani*)	Seeds were soaked in 10^7 CFU/g bacteria solution for 30 minutes	Martins *et al.* (2018)
Bacillus cereus S42	Tomato	Fusarium wilt (*Fusarium oxysporum f. sp. lycopersici*)	Seedling root (first two leaves) was soaked for 30 minutes with bacterial cell concentration at 10^8 cells/mL	Abdallah *et al.* (2016)
Bacillus velezensis	Chinese cabbage (*Brassica chinensis*)	Black rot (*Xanthomonas campestris pv. campestris*)	Seeds were soaked in 10^7 CFU/mL bacteria solution	Liu *et al.* (2016)

infection and during secondary spread on and in root tissue (Mendes *et al.*, 2013). Disease attacks on the plant often occur and are responsible for the destruction of about one-third of crop yields worldwide (Lugtenberg & Kamilova, 2009). PGPR has biological control features that can be considered an alternative to compensating for the high dosage of pesticides used in the plant to kill pathogens and reduce the disease rate (Fernando *et al.*, 2005). Production of siderophores, bacteriocins and antibiotics are the most effective and well-known strategies used by PGPR to minimise or prevent phytopathogenic proliferation. Some PGPR has been identified as a potential catalyst for an induced systemic resistance (ISR) system due to its ability to promote endurance to plant against pathogenic, bacterial, and viral fungi (van Loon, 2007).

Induced Systemic Resistance (ISR), resistance booster is an enhanced protection proportion situation caused by PGPR such *Pseudomonas putida*, *Serratia*, *Flavomonas oryzihabitans*, *Bacillus pumilus*, for example a potential plant defensive potential for the subsequent biotic challenge a popular way of protecting the plant from pathogens through ISR (Vallad & Goodman, 2004). Several identified bacteria that can produce these mechanisms act as foreign compounds and activate plant resistance, such as siderophore, pyoverdin, SA bacteria, fucose, rhamnose (lipopolysaccharides) and flagellin reported so far. Transmissions of plant signals by biocontrol fungi (BCF) leading to disease resistance (De Vleesschauwer & Höfte, 2009). The relationship between pathogenic and non-pathogenic microorganisms will cause many kinds of defence mechanisms in the plant. Two primary mechanisms are Systemic Acquired Resistance (SAR) and Induced Systemic Resistance (ISR). SAR is generally caused by local infections, providing longstanding systemic resistance to consequent pathogenic attacks, related with activation of PR genes and requiring salicylic acid (SA) intake (van Loon, 2007).

ISR is also caused by roots inhabited by some rhizosphere bacteria that are not pathogenic to plants. ISR does not rely on SA but instead requires a jasmonic acid (JA) followed by the presentation of ethylene signals (Pieterse *et al.*, 2001). Most potential bacteria can be forced the ISR like siderophores pyocyanin and pyocholin, flagella, lactone N-acyl homoserine (Mandal & Ray, 2011), antibiotics such as Phl (Iavicoli *et al.*, 2003), salicylic acid and LPS (van Loon, 2007) 2,3-butanediol bacteria produced by *Bacillus spp.* (Ryu *et al.*, 2003) and lipopeptide cycle (Ongena *et al.*, 2007). In addition, the ISR associated ethylene signals and jasmonate in plants and these hormones prompt plant defence response to numerous plant pathogens (Glick, 2012). Antibiotics associated with polyketides, lipopeptides, and nitrogenous heterocyclic compounds have a vast spectrum of action opposed to phytopathogens, affecting the plant. Furthermore, to direct antipathogenic action, they also behave as a determinant in causing SAR in plant systemic (Mandal & Ray, 2011).

Antibiotic production is the major mechanism of biological control by PGPR committing the making of antibiotics such as pyoluteorin, pyrrolnitrin, phenazine-1-carboxyclic acid, oomycin, zwittermycin-A, canosamine, 2,4-diacetyl phloroglucinol, and pantocin. Endogenous signal transmission such as sensor kinase, lactone N-acyl homoserine, and sigma factor controls antibiotic production (Matilla *et al.*, 2018). The genes liable for acquiring antibiotics are very conservative. Through the production of specific metabolites or not specifically with antibacterial activity. Pseudomonas antibiotics have been identified (Loper & Gross, 2007) with biocontrol properties including phenazine derivatives, phoroglucinols, pyrrolnitrin, pyoluteorin, hydrogen cyanide and cycle lipopeptides. Apart from others antibiotics are herbicolin A (*Erwinia sp.*), iturin A, surfactin, agrocin 84 (*Agrobacterium sp.*), xanthobacin (*Stenotrophomonas sp.*) and zwittermicin A (*Bacillus* sp.) (Fernando *et al.*, 2005).

Hydrolytic enzymes; bio-phyto-pathogens control using rhizospheric microbes involve cell wall damage by hydrolytic enzymes (Kobayashi *et al.*, 2002). Almost all rhizobia can produce this extracellular enzyme which can hydrolyse various polymer compounds like chitin, protein, hemicellulose, cellulose, and phytopathogens DNA. Diverse types of microbes like *B. subtilis*, *S. marcescens*, *B. subtilius*, *B. thuringiensis*, *B. cereus* and many others can make hydrolytic enzymes for phytopathogens biocontrol such as *P. ultimum*, *F. oxysporum*, *R. solani*, *S. rolfsii*, and so on by swelling in hyphae and at the extremities of the hyphal, hypocal curve or broken at the tip (Felse & Panda, 2000; Someya *et al.*, 2002). This hydrolytic enzyme affects the integrity of the target cell wall structure (Budi *et al.*, 2000). Their potential to prevent phytopatogenation makes them more important in the biological control process (Mabood *et al.*, 2014).

Lytic enzyme action; some characteristics of bacteria with biocontrol capability involve direct damage to the pathogenic cell wall material or interruptions at certain stages of development. For example, the production of chitinase by *Serratia plymuthica* was proclaimed to constrain the germination of spores and the extension of germ tubes in *Botrytis cinerea*. At the same time, *Streptomyces* sp. and *Paenibacillus* sp. was produced ß-1,3-glucanase and attempted to destroy the cell wall of *Fusarium oxysporum f. sp. cucumerinum*. Other enzymes made by bacteria with biological control activities include laminarinase, hydrolase, and protease (Budi *et al.*, 2000). Table 1 shows the application of plant growth-promoting rhizobacteria with biocontrol capacity and also indicates several approaches were used to introduce the inoculants to the plant for successful colonisation.

CONCLUSION

The exploitation of beneficial microorganisms such as PGPR in agriculture has been studied extensively over the last forty years. The positive impact of PGPR on plants can be seen through direct and indirect mechanisms such as plant growth hormone production, triggering plant growth and development, enhancing nutrient uptake by plants, acting as a biological agent of the disease, and assisting plant to mitigate abiotic stress. Various studies have been conducted to assess the effect of PGPR on the plant *in vitro*, greenhouse, and in field studies. In general, most inoculations with PGPR exhibit significant

increases in plant height and root elongation, plant biomass, and nutrient absorption. The resistance of the plant inoculated with PGPR against biotic (phytopathogen) and abiotic stress (drought, salinity and heavy metal toxicity) indicates the potential of PGPR to be used in a variety of conditions including extreme conditions. However, the selection of PGPR strains with multi-trait characteristics is very important in ensuring the efficacy of PGPR application on plants.

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