The Pharma Innovation Journal 2022; SP-11(7): 3956-3969

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277-7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2022; SP-11(7): 3956-3969
© 2022 TPI
www.thepharmajournal.com
Received: 01-04-2022
Accepted: 06-05-2022

PGPR-beneficial microbes in agro forestry ecosystem

C Ushamalini, A Balasubramanian, KS Anjali, M Tilak, N Indra, Dr. G Swathiga and Manimaran V

C Ushamalini
Department of Silviculture &
NRM, Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

A Balasubramanian
Department of Silviculture &
NRM, Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

KS Anjali
Department of Silviculture &
NRM, Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

M Tilak
Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

N Indra
Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

Dr. G Swathiga
Forest College and Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

Manimaran V
Forest College and Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

Corresponding Author
C Ushamalini
Department of Silviculture &
NRM, Forest College & Research
Institute, Mettupalayam, Tamil
Nadu Agricultural University,
Coimbatore, Tamil Nadu, India

Abstract

Plant growth promoting rhizobacteria (PGPR) are a diverse set of bacteria found in the rhizosphere, on root surfaces, and in close proximity to roots that can directly or indirectly promote the extent or quality of plant development. Rhizobacteria that promote plant growth include rhizosphere-colonizing N2-fixing rhizobacteria that provide nitrogen to plants, as well as the well-known symbiosis of legume rhizobia. Several bacteria, including *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Klebsiella*, *Enterobacter*, *Alcaligens*, *Arthobacter*, *Burkholderia*, *Bacillus*, and *Serratia*, have been found to improve plant development in recent decades. *Rhizobium* is the most important PGPR, which is able to develop a symbiotic association with its specific host plant and increase its growth and yield by biologically fixing atmospheric nitrogen. However, the other PGPR, such as *Pseudomonas* and *Bacillus*, are able to increase plant growth and yield production by colonizing the host plant roots in a nonsymbiotic manner. PGPR's direct promotion entails either providing the plant with a plant growth promoting substance or providing the plant with a plant growth promoting substance. When PGPR inhibits the harmful effects of one or more phytopathogenic microorganisms, it indirectly promotes plant growth. In response to PGPR inoculation, significant increases in growth and yield of agronomically important crops have been recorded. Bacterial inoculants can boost plant growth and germination, improve seedling emergence, improve responses to stress, and protect plants from disease. When compared to farmed crops, the impact of PGPR on trees has received the least attention. The current review focuses on PGPR's mode of action and growth-promoting activities in trees.

Keywords: Plant growth promoting rhizobacteria, rhizosphere, nitrogen fixation, phytopathogens

Introduction

Plant Growth Promoting Rhizobacteria are symbiotic free-living soil microorganisms that live in the rhizosphere of many plant species and have a wide range of beneficial impacts on the host plant (Raza *et al*. 2016a,b) [152] through several processes such as nitrogen fixation and nodulation (Gouda *et al*. 2018; Oleńska *et al*. 2020) [78, 139]. The term "plant growth promoting rhizobacteria (PGPR)" was coined by Kloepper and Schroth (1978) [111] to describe these beneficial microbes. Furthermore, various microbial-based approaches, such as biofertilizers, biostimulants, and/or biopesticides, are currently being proposed as alternatives for increasing crop yield. Plant growth promoting rhizobacteria (PGPR) positively influence plant growth and represent promising long-term solutions for increasing plant biomass production. (Thijs and Vangronsveld 2015; Lindemann *et al*. 2016; Umesha *et al*. 2018; Liu *et al*. 2020) [186, 122, 190]. Plant health and soil fertility are highly influenced by beneficial soil microorganisms and their interactions (Jeffries *et al*. 2003) [99]. Without understanding the chemistry or the vital functions played by microorganisms, Middle Eastern farmers practised crop rotation about 6000 BC, sowing legumes and cereals alternately. Hellriegel and Wilfarth (1888) [85] researched rhizosphere root colonisation and proposed that soil microorganisms could transform atmospheric N_2 into plant-usable forms and that the introduction of legumes on cultivated areas resulted in enhanced soil fertility (Chew 2002) [45]. Plant Development Promoting Rhizobacteria is such a group of beneficial bacteria that boosts plant growth (Bajracharya 2019) [20]. The use of rhizospheric bacteria to promote plants in nutrient uptake and solubilization of fixed nutrients such as phosphorus has become more important in the paradigm of sustainable agriculture (Hayat *et al*. 2010) [92]. The plant is always associated with a well-structured and controlled colony of microbes (Turner *et al*. 2013; Chaparro *et al*. 2014; Lebeis 2014) [189, 44, 118].

Plant growth-promoting rhizobacteria (PGPR) can directly interact with plants by improving the availability of important nutrients (e.g. nitrogen, phosphorus, iron), the generation and regulation of plant-growth-related compounds (e.g. phytohormones) and the stress hormonal factors (Oleńska *et al*. 2020) [139].

The ability of PGPR to aid plant growth is critical, especially in the case of abiotic stress, when bacteria can enhance plant resilience, stress tolerance and/or even help with contaminant remediation (Bulgarelli *et al*. 2015; Smith *et al*. 2015b; Oleńska *et al*. 2020) [34, 173, 139]. PGPRs contain bacteria from the genera *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Klebsiella*, *Enterobacter*, *Alcaligenes*, *Arthobacter*, *Burkholderia*, *Pantoea*, *Bacillus*, *Serratia* and *Rhizobium*, among others (Kloepper *et al*. 1992; Fernando *et al*. 2005) [109, 64]. *Pseudomonas*, *Bacillus*, *Azospirillum*, Agrobacterium, *Azotobacter*, *Arthrobacter*, *Alcaligenes*, *Serratia*, *Rhizobium*, *Enterobacter*, *Burkholderia*, *Beijerinckia*, *Klebsiella*, *Clostridium*, Vario-Vovax, *Phyllobacterium* and *Phyllobacterium* are among the PGPR genera (Lucy, Reed & Glick 2004) [125]. *Pseudomonas* and *Bacillus* are the two most commonly reported PGPRs (Podile & Kishore 2006) [150]. Commercial applications of PGPR and their interactions with plants exist, as well as scientific applications for sustainable agriculture (Gonzalez *et al*. 2015).

Mechanism of PGPR action

Plant roots release a wide range of organic nutrients (organic acids, phytosiderophores, sugars, vitamins, amino acids, nucleosides, mucilage) and signals that attract microbial communities, particularly those that can metabolise and grow in this microbial habitat (Ahemad and Kibret 2014; Hasan *et al*. 2014) [6]. Three distinct traits describe the PGPR:

1. They must be able to colonise the root.
2. They must be able to survive and multiply in microhabitats associated with the root surface, in competition with other microbiota, for at least the time required to express their plant promotion/protection activities.
3. They must promote plant growth (Bishnoi, 2015) [33].

The rhizospheric soil bacteria that surround the plant root compete for this nutritional benefit and as a result, have an impact on the plant's growth, yield and defence mechanisms, either as free-living microbes or in a mutualistic connection with the plant root (endophytic/epiphytic) (Vejan *et al*. 2016) [199]. Rhizobacteria have an impact on plant development. When reintroduced by plant inoculation in a soil harbouring competitive microflora, about 2-5% of rhizobacteria have a good influence on plant development and are referred to as plant growth-promoting rhizobacteria (PGPR). The direct mechanism (Table 1), which directly encourages plant development in a direct form, is the most common method of action for PGPR. Nitrogen fixation, phytohormone synthesis, phosphate solubilization and increased iron availability are all part of this plant growth promotion mechanism. By removing pathogens or triggering plant defensive responses, PGPR can indirectly boost plant growth.

Many PGPR have many mechanisms of action (Narasimhan *et al*. 2003; Gupta and Dikshit 2010; Haymer 2015; Thijs *et al*. 2016; Delshadi *et al*. 2017) [136, 82, 93, 184, 51]. In the absence of pathogens, bacterially mediated phytohormone production is the most likely explanation for PGPR activity (Tien, Gaskins & Hubbell 1979) [187], whereas siderophore production by PGPR is thought to be more important for plant growth stimulation when other potentially deleterious microorganisms are present in the rhizosphere (Kloepper, Leong, Teintze, & Schroth 1980) [108]. PGPR influence plant physiology and development, either directly or indirectly (Table 2) and hence play an important role in plant function. Direct stimulation includes biological nitrogen fixation (Zahran 2001) [204], the production or alteration of phytohormones such as auxins, cytokinins, gibberellins (GA) (Vacheron *et al*. 2013; Tien *et al*. 1979) [191, 187] or ethylene (Glick, Karaturovic, & Newell 1995) [76], the solubilization of minerals such as phosphorus and iron. The manufacture of antibiotics, chelation of Fe in the rhizosphere, synthesis of extracellular enzymes to hydrolyze fungal cell walls and competition for niches within the rhizosphere are all examples of indirect plant growth promotion (Van Loon 2007) [194]. *Pseudomonas* fluorescens and *Bacillus* subtilis, in particular, are frequently explored as the most promising candidates for indirect stimulation (Damayanti, Pardede, & Mubarik 2007) [49]. Experimental evidence reveals that plant growth stimulation is the consequence of many pathways that may be triggered simultaneously, suggesting that PGPR may use more than one method to boost plant growth (Martínez-Viveros, Jorquera, Crowley, Gajardo, & Mora 2010) [130].

Several plant growth promoting (PGP) mechanisms of PGPR, according to Podile and Kishore (2006) [150], include root hair modification and increased branches, improved seed germination, increased leaf area per plant, release of certain phytohormones, increased nutrient and water uptake by plants, increased biomass of plants with more vigour growth, and better carbohydrate accumulation, all of which contribute to plant growth. Glick (2003) [74], on the other hand, divides bacterial supported plant development into three categories: plant hormone synthesis (Dobbelaere, Vanderleyden, and Okon 2003) [54], bacterial assisted enhanced nutrient uptake by plants and biological control of plant diseases (Saravanakumar *et al*. 2008) [162]. Dey *et al*. (2004) [52] suggest the need of exploring other mechanisms of plant growth promotion by PGPR apart from the list already studied. Listing all the explored and investigated mechanisms of PGPR, following can be included:

a) Solubilization and mineralization of nutrients notably phosphorus (Richardson 2001; Banerjee and Yesmin 2006) [156, 22].
b) Nitrogen fixation through symbiosis and asymbiosis (Kennedy, Choudhury and Kecskes 2004) [105].
c) Release of certain plant hormones such as gibberellic acid and cytokinins (Dey *et al*. 2004) [52], indole acetic acid (Patten and Glick 2002) [145] and abscisic acid (Dobbelaere, Vanderleyden and Okon 2003) [54].
d) Production of 1-aminocyclopropane-1-carboxylate (ACC)-deaminase helping to lower ethylene level in roots this increasing length and vigor of roots (Penrose and Glick 2001) [148].
e) Antagonism toward plant pathogens by producing substances such as cyanides and antibiotics (Glick and Pasternak 2003) [74].
f) Increasing the availability of nutrients specifically of iron through chelating by producing siderophores (Glick and Pasternak 2003) [74].
g) Tolerance against deveral abiotic stresses such as oxidative (Štajner *et al*. 1995) [175] and drought stress (Alvarez, Sueldo and Barassi 1996) [9].
h) Water soluble vitamin production including biotin, niacin, thiamine and riboflavin (Revillas *et al*. 2000) [155].
i) Detoxification of heavy metals (Ma *et al*. 2011) [126].
j) Tolerance of salinity (Tank and Saraf 2010) [182].
k) Biological control of pests and insects (Russo *et al*. 2008) [159].

Table 1: Direct mechanisms and PGPR (Verma *et al.* 2019)

Mechanism		PGPR	Crops	References
Nitrogen fixation	Symbiotic	*Rhizobium* andallied genera	Legumes, e.g., Soybeans, Peanut,Chickpea etc.	Lucas-Garcia *et al.* (2004) [124], Vargas *et al.* (2010) [197], Laranjo *et al.*(2014) [116] and Abd-Alla *et al.* (2017) [1]
		Frankia	Higher Agiospermic plants (Actinorhizalplants), e.g., *Alnus, Casurina*	Crannell *et al.* (1994) [48], Santi *et al.* (2013) [161], Diagne *et al.* (2013) [53] and Ballhorn *et al.* (2017) [21]
	Free-living	Cyanobacteria, *Azotobacter, Azospirillum, Beijerinckia*	Cereals, e.g., Wheat,Rice, Maize	Steenhoudt and Vanderleyden (2000) [176], Cassán *et al.* (2009) [39] and Shariatmadari *et al.* (2013) [166]
Phosphate solubilisation		*Pseudomonas, Bacillus, Rhizobium*	*Stevia rebaudiana*	Mamta *et al.* (2010) [130], Schoebitz *et al.* (2013) [163] and Oteino *et al.* (2015) [141]
Iron sequestration		*Alcaligenes, Pseudomonas,Bacillus*	Pigeon pea	Gamit and Tank (2014) [68]
Zinc solubilisation		*Burkholderia,Pseudomonas, Bacillus*	Maize, rice	Goteti *et al.* (2013) [77], Vaid *et al.* (2014) [192] and Sunithakumari *et al.* (2016) [178]
Potassium solubilisation		*Bacillus, Pseudomonas*	*Pinus canariensis, Cucumis sativus*	Bagyalakshmi *et al.* (2012) [19], Parmar and Sindhu (2013) [143] and Prajapati and Modi (2016) [151]
Phytohormone production		*Bacillus, Rhizobium,Pseudomonas*	Chick pea, onion	Khare and Arora (2010) [106], Reetha *et al.* (2014) [154] and Pandya and Desai (2014) [142]

Table 2: Indirect mechanism of PGPR (Deka *et al.* 2015) [52]

Mechanism	Effect	References
Plant growth regulator production	Biomass (aerial partand root)	Gutierrez Manero *et al.* (1996) [83]
Flowering		Gutierrez Manero *et al.* (2001) [84]
Ethylene synthesis inhibition	Root length	Glick *et al.* (1994) [73]
Induction of systemic resistance	Health	Van Loon *et al.* (1998) [193]
Root permeability increase	Biomass and nutrientabsorption	Sumner (1990) [177]
Organic matter mineralization (nitrogen,sulfur, phosphorus)	Biomass and nutrientcontent	Liu *et al.* (1995) [123]
Mycorrhizal fungus association	Biomass and phosphorus content	Germida and Walley (1996) [70]
Insect pest control	Health	Zehnder *et al.* (1997) [207]

Interactions between PGPR and conifers have been studied in the genera Araucaria, Picea (spruce), Pinus, Pseudotsuga (Douglas fir) and Tsuga (hemlock) by number of workers (Bent *et al.* 2001; Brunetta *et al.* 2007; Vasconcellos and Cardoso 2009; Singh *et al.* 2010) [28, 33, 198, 171]. The best-studied PGPR belong to *Arthrobacter*, *Curtobacterium*, *Bacillus*, *Burkholderia*, *Chryseobacterium*, *Enterobacter*, Paeni *Bacillus*, Phosphoro *Bacillus*, *Pseudomonas*, *Staphylococcus*, *Serratia* and Streptomyces (Enebak *et al.* 1998; Garcia *et al.* 2004; Barriuso *et al.* 2005) [63, 69, 25]. An extensive screening of PGPR in conifers was carried out by Barriuso *et al.* (2005) [25] in the rhizosphere of *Pinus pinea* and *Pinus pinaster*, when these were colonized by ectomycorrhizal fungus (EMF) *Lactarius deliciosus*. Earlier, growth promotion of P. pinea by PGPR was reported by Garcia *et al.* (2004) [69].

PGPR and plant growth regulation

Plant growth regulators (PGRs) are phytohormones that are generated in certain organs of the plant and then translocated to other regions, where they trigger unique biochemical, physiological and morphological roles in plant growth and development (Hayat *et al.* 2012) [91]. Auxins, gibberellins, cytokinins, ethylene and abcisic acid are five well-known phytohormones and soil microorganisms, particularly rhizosphere bacteria, are potential producers of these hormones (Patten and Glick 1996; Arshad and Frankenberger 1998) [144, 16]. By managing and modifying phytohormones and growth regulators, PGPR promotes drought-stressed plant growth (Bresson *et al.* 2014) [32]. Gibberellins and cytokinins promote plant development while ET and abscisic acid prevent it (Taiz and Zeiger 2010) [180]. In both symbiotic and nonsymbiotic roots, phytohormones are known to mediate processes such as plant cell expansion, division, and extension. Among these hormones, auxins have received the greatest attention, with indole-3-acetic acid (IAA) being the most common and well-studied. IAA is known to drive both short-term (e.g., cell elongation) and long-term (e.g., cell division and differentiation) responses in agricultural plants (Govindasamy *et al.* 2010) [79]. Root-associated microbes, such as symbiotic or endophytic bacteria, play an important role in the production of plant growth hormones (phytohormones), which affect seed germination, root system development for better nutrient uptake, vascular tissue development/elaboration, shoot elongation, flowering and overall plant growth (Sgroy *et al.* 2009) [165]. Hormone levels in plants can be controlled by microbe-produced plant growth regulators, which have effects similar to exogenous plant phytohormonal treatments (Egamberdieva, 2009; Turan *et al.* 2014) [58, 188]. Microbe-produced phytohormones like auxins and cytokinins are similar to plant-produced phytohormones in that they regulate plant hormone levels, regulating photosynthetic processes to promote plant growth and development and activating pathogen defence responses (Backer *et al.* 2018) [18]. Auxins are a category of hormones that help plants grow and develop. Indole Acetic Acid (IAA) is the most frequent and physiologically active phytohormone in plants, and it regulates gene expression by upregulating and downregulating it. IAA is produced by plant shoot apical meristems as free/diffusible auxins and is detected in practically all plant tissues (Maheshwari *et al.* 2015) [127]. More than 80% of rhizospheric bacteria have been found to be capable of synthesising and releasing auxins. *Aeromonas*, *Azotbacter*, *Bacillus*, Brady *Rhizobium*, *Burkholderia*, *Enterobacter*, Meso *Rhizobium*, *Pseudomonas*, *Rhizobium* and Sino *Rhizobium* all produce IAA, which is produced by a variety of bacterial genera including *Aeromonas*, *Azotobacter*, *Bacillus*, Brady *Rhizobium*, *Burkholderia*, *Enterobacter*, Meso *Rhizobium* (Ahmad *et al*. 2008; Celloto *et al*. 2012; Sharma *et al*. 2016; Çakmakçı *et al*. 2020) [7, 41, 168, 35]. A single bacterial strain can create IAA via many pathways in some situations. These biosynthesis routes can be independent of or dependent on tryptophan, a key IAA precursor molecule (Kashyap *et al*. 2019) [104], with mechanisms sourced from degraded roots or bacterial cell exudates (Spaepen *et al*. 2007; Egamberdieva *et al*. 2017) [174, 59]. The capacity of rhizospheric beneficial bacteria to manufacture IAA under salinity stress conditions could be critical for balancing and controlling IAA levels in the roots, resulting in enhanced plant responses to salinity stress (Egamberdieva *et al*. 2015) [60]. Microbe-produced IAA has recently been shown to boost root and shoot biomass output in water-stressed situations (Kumar *et al*. 2019). Many PGPR-produced phytohormones, including indole lactic acid (ILA), indole-3-butyric acid (IBA), indole-3-propionic acid (IPA), indole-3-pyruvic acid (IPA), 2,4-dichlorophenoxy acetic acid (2,4-D) and 2-methyl-4-chlorophenoxy acetic acid (MCPA) and tryptophol (TOL), can control various physiological processes (Ijaz *et al*. 2019; Swarnalakshmi *et al*. 2020) [97, 179]. PGPR with the ability to produce plant growth-regulating hormones, like auxins and cytokines, were tested on *P. contorta* (lodgepole pine) (Bent *et al*. 2002) [29].

Cytokinins are a type of hormone that affects plant growth and development by regulating physiological processes such as seed germination, cell division, apical dominance, root and shoot growth, flower and fruit production, leaf senescence, pathogen interactions and nutrient mobilisation and assimilation (Egamberdieva *et al*. 2015; Akhtar *et al*. 2020) [60, 8]. It has been observed that cytokinin, either alone or in combination with other phytohormones like auxin and abscisic acid, can enhance the growth of salt-stressed plants while also improving tolerance via modifying gene expression (Kang *et al*. 2012; Kunikowska *et al*. 2013) [102]. PGPR such *Arthrobacter*, *Bacillus*, *Azospirillum* and *Pseudomonas* have been shown to manufacture cytokinins, which have been shown to have beneficial effects on the root system. Plant growth and development are aided by cytokinin-producing PGPR, which are also powerful biocontrol agents against a variety of diseases (Naz *et al*. 2009; Maheshwari *et al*. 2015) [138, 127]. Plants and plant-associated microbes are known to have more than 30 growth-promoting cytokinin chemicals that are produced at varied quantities (Hayat *et al*. 2012; Amara *et al*. 2015) [91, 11]. In the past two decades, several studies have reported the effects of cytokinin producing PGPR on root system architecture, plant growth and tolerance to biotic and abiotic stresses including drought (Arkhipova *et al*. 2007; Dodd *et al*. 2010; Egamberdieva *et al*. 2015) [15, 55, 60], salinity (Naz *et al*. 2009; Cordero *et al*. 2018) [138, 47], bacterial pathogens (Naseem *et al*. 2014) [137], fungal pathogens (Mishra *et al*. 2018) [132] and insect pests (Giron and Glevarec 2014; Zhang *et al*. 2019) [72, 208].

Alexandre *et al*. 2021 reported that Arbuscular Mycorrhizal Fungi (*Rhizophagus clarus*) and Rhizobacteria (*Bacillus subtilis*) can improve the clonal propagation and development of Teak for Commercial Plantings. Aditya (2009) [5] reported on co-inoculation effects of nitrogen fixing and phosphate solubilizing microorganisms on teak (*Tectona grandis*) and Indian redwood (*Chukrasia tubularis*) that the effect of nitrogen fixing *Azotobacter* and phosphate solublising *Bacillus megaterium* on the growth of two trees; Teak (*Tectona grandis*) and Indian redwood (*Chukrasia tubularis*) were tested under nursery condition. Seed priming with beneficial micro-organisms including fungi and bacteria (*Trichoderma, Pseudomonas, Bacillus, Rhizobia* etc.) ameliorates a good sort of biotic, abiotic and physiological stresses to seed and seedlings (Sharma *et al*. 2015) [169]. PGPR had a wide range of impact on conifers (Table 3). These biological seed treatments may provide an alternate to chemical control of the pests and diseases and also increase the plant growth. Seed biopriming allows the bacteria to enter/adhere the seeds and also acclimatization of bacteria within the prevalent conditions (Mahmood *et al*. 2016) [128]. PGPR are a good range of root colonizing bacteria which may produce IAA like compounds (Kandoliya and Vakharia 2013) [101], enhance plant growth by increasing seed emergence, plant growth and crop yield (Kloepper 1992) [109].

Table 3: The most studied PGPR in conifers, their mode of action, the host plants (Cardoso *et al.* 2011)

Action	PGPR	Effects on plants	Conifer species	References
Hormones	*Bacillus* sp. *Pseudomonas fluorescens* M20; *P. fluorescens* BSP53a; *P. polymyxa* L6; *Chryseobacterium balustinum*;	Root length; shoot dry weight; root weight; seed germination	*Pinus pinaster*; *P. pinea*; *P. roxburghii*	Barriuso *et al*. (2005) [25]; Bent *et al*. (2001) [29]; Dubeikovsky *et al*. (1993) [56]; Singh *et al*. (2008, 2010) [172]
Siderophores	*Arthrobacter oxydans Bacillus* sp *Pseudomonas fluorescens*; *Staphylococcus* sp;	Root length; shoot dry weight; root weight; seed	*P. pinaster*; *P. pinea*;	Barriuso *et al*. (2005) [25]; Singh *et al*. (2008, 2010) [172]
Phosphate solubilization	*Arthrobacter oxydans Curtobacterium* sp.; *Burkholderia* sp.; *Staphylococcus* sp.; *Pseudomonas fluorescens*	Germination Shoot height and dry Mass	*P. roxburghii* *P. pinaster*; *P. pinea*; *P. halepensis*; *P. roxburghii*	Barriuso *et al*. (2005) [25]; Rincón *et al*. (2008) [157]; Singh *et al*. (2008, 2010) [172]
MHB	*B. cereus*; *B. sphaericus*; *P. fluorescens*; *Streptomyces* sp.	Root length; Shoot length; No. leaves initiated; Shoot dry weight; Root dry weight	*P. sylvestris*; *P. contorta*; *P. taeda*; *P. elliottii*; *Pseudotsuga menziesii*;	Bending *et al*. (2002) [27]; Frey-Klett *et al*. (1999) [67]; Schrey *et al*. (2005) [164]
Induced systemic resistance	*Streptomyces* sp. *P. fluorescens*; *Chryseobacterium balustinum*; *Enterobacter intermedius*; *PhosphoroBacillus latus*	Root length; shoot dry weight; root weight; neck root diameter; stem length; Incorporation of thymidine and leucine	*Picea abies* *Picea abies* *P. pinea*;	Lehr *et al*. (2008) [120] Garcia *et al*. (2004) [69]
Antagonism	*B. subtilis*;	–	*P. roxburghii*	Singh *et al*. (2008, 2010) [172]

ACC degradation	*P. aeruginosa* *Staphylococcus* sp.	–	*P. pinaster*; *P. pinea*	Barriuso *et al*. (2005) [25]

PGPR and Nitrogen fixation

Nitrogen is a fundamental requirement for the synthesis of nucleic acids, proteins, and other organic nitrogenous substances in all forms of life. Despite the fact that the atmosphere contains roughly 78 percent nitrogen, it is very inert and unavailable to growing plants. The process of biological N_2 fixation (BNF), in which nitrogen-fixing bacteria convert elemental nitrogen into ammonia utilising a complicated enzyme system known as nitrogenase, converts atmospheric N_2 into plant-usable forms (Kim & Rees 1994) [107].

Nitrogen fixing organisms are generally categorized as

1. Symbiotic N_2-fixing bacteria including members of the family rhizobiaceae (*Rhizobium*, Sino*Rhizobium*, Brady *Rhizobium*, Meso *Rhizobium* and Azo *Rhizobium*, collectively termed rhizobia) which forms symbiosis with leguminous plants (Zahran 2001) [204] and nonleguminous trees (e.g. Frankia).
2. Non-symbiotic (free living, associative and endophytes) nitrogen fixing forms such as cyanobacteria (Anabaena, Nostoc), *Azospirillum*, *Azotobacter* and Azocarus, etc.

(Bhattacharyya & Jha, 2012) [30]. In the rhizobia legume symbiosis, the signalling pathways (Long 2001), evolutionary history (Henson, Watson, & Barnum 2004) [94] and molecular features affecting host specificity (Young, Mutch, Ashford, Zeze & Mutch 2003) have all been reviewed. BNF contributes 106 metric tonnes per year globally, with symbiotic nitrogen fixation accounting for 80% and free-living nitrogen fixation accounting for the remaining 20%. As a result, BNF represents a cost-effective and environmentally friendly alternative to the current agricultural practise of using high doses of chemical fertilisers (Adesemoye, Torbert, & Kloepper 2009) [4].

Biological inoculants have gained popularity in recent years for sustainable crop production in various parts of the world, and biological nitrogen fixation is a key source of N input in agricultural soils, especially those in arid regions. The cyanobacteria *Rhizobium*, Azo *Rhizobium*, Brady *Rhizobium*, Sino *Rhizobium*, Allo *Rhizobium*, Meso *Rhizobium* and Frankia are symbiotic nitrogen-fixing bacteria (Paul and Clark 1996) [146]. The mechanisms of *Rhizobium*-legumes symbiotic N_2 fixation have been extensively researched. Frankia's symbiosis with non-leguminous actinorhizal plants is also being studied these days. The principal N_2-fixation mechanism, the symbiotic system, plays a critical role in enhancing the fertility and maximising production of low-N soils.

Biological N_2-fixed by the *Rhizobium*-legume symbiosis can also benefit cereals grown in intercrops or crops cycled with legumes. The grasses in many natural grassland systems utilise nitrogen fixed by their legume counterparts to meet their nitrogen needs, and the protein provided as a result of this connection improves the fodder quality for animal production (Paynel *et al*. 2001) [147]. Rhizobia as PGPR can contribute to growth promotion in non-legume species in addition to symbiotic N_2 fixation in legumes (Höflich *et al* 2000) [95]. Rhizobia naturally produce molecules that promote crop growth (auxins, abscisic acids, cytokinins, riboflavin, lumichrome, lipo-chitooligosaccharides and vitamins) to act as PGPR, and their colonisation and infection of cereal roots would be expected to increase vigour and grain yield (Matiru and Dakora 2004) [131]. *Rhizobium*'s other PGPR roles include phytohormone production (Arshad and Frankenberger 1998) [16], inorganic phosphorus solubilization (Chabot *et al*. 1996) [42], siderophore release (Plessner *et al*. 1993; Jadhav *et al*. 1994) [149, 98] and antagonism against plant pathogenic bacteria (Ehteshamul-Haque and Ghaffar 1993) [62].

PGPR and phosphorus solubilisation

Phosphorus (P) is one of the most important macronutrients for plant growth and development and insufficient P availability to crop plants is a global problem. P availability reduces crop output on 30-40% of the world's arable land (Vance, Uhde-Stone, & Allan 2003) [195]. PSBs (phosphate solubilizing bacteria) may play a key role in providing phosphate to plants in a more environmentally friendly and long-term manner. Mineral forms such as apatite, hydroxyapatite and oxyapatite, as well as organic forms such as inositol phosphate (soil phytate), phosphomonoesters, phosphodiesters and phosphotriesters, are found in soil. Phosphate-solubilizing bacteria (PSB) are one of the most essential bacterial physiological features in soil biogeochemical cycles (Jeffries, Gianinazzi, Perotto, Turnau, & Barea 2003) [99], as well as in plant growth promotion by PGPR.

Bacillus, *Rhizobium*, and *Pseudomonas* bacteria have been found to be the most effective phosphate solubilizing bacteria (Banerjee *et al*. 2010) [23]. The most common PSB bacteria include *Azotobacter*, *Bacillus*, *Beijerinckia*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Microbacterium*, *Pseudomonas*, *Rhizobium* and *Serratia* (Bhattacharyya & Jha, 2012) [30]. *Azotobacter chroococcum, Bacillus circulans, Cladosporium herbarum, BradyRhizobium japonicum, Enterobacter agglomerans, Pseudomonas chlororaphis, Pseudomonas putida* and *Rhizobium leguminosarum* are some examples of widely reported P-solubilizing microbial species intimately associated with a wide range of agricultural crops (Antoun, Beauchamp, Goussard, Chabot, & Lalande 1998; Cattelan, Hartel, & Fuhrmann 1999; Chabot, Beauchamp, Kloepper, & Antoun 1998) [14, 40, 43]. There have also been cases of phosphate solubilization by *Azotobacter*, a non-symbiotic nitrogen fixer (Kumar *et al*. 2001) [113]. *Rhizobium* (e.g., *Rhizobium*/Brady *Rhizobium*) phosphate-solubilizing activity is linked to the synthesis of 2-ketogluconic acid, implying that the organism's phosphate-solubilizing activity is solely attributable to its capacity to lower medium p^H (Halder and Chakrabarty 1993) [87]. The ability to dissolve phosphate also depends on the type of nitrogen source utilised in the media, with more solubilization in the presence of ammonium salts than in the presence of nitrate. This is thought to be due to protons being extruded to compensate for ammonium uptake, resulting in a lower extracellular p^H (Roos 1984) [158].

The action of low molecular weight organic acids generated by diverse soil bacteria typically results in the solubilization of inorganic phosphorus (Zaidi, Khan, Ahemad & Oves 2009) [206]. In contrast, organic phosphorus is mineralized through the production of a variety of phosphatases that catalyse the hydrolysis of phosphoric esters (Glick, 2012). Phosphate solubilization and mineralization can coexist in the same bacterial strain (Tao, Tian, Cai, & Xie 2008). Phosphorus solubilizing bacteria not only provide P to plants, but they also help them grow by increasing the efficiency of BNF and increasing the availability of other trace elements (Tao, Tian, Cai, & Xie 2008) such as iron, zinc. The possibility of enhancing P uptake of crops by inoculation with P-solubilizing strains of PGPR presents a promising approach towards recovering the reservoirs of insoluble phosphorus from the soil and thus minimizing the external application of phosphate fertilizers to the soil.

PGPR in phytoremediation

Plant and microbe interactions are used in green technology to improve contaminated soil. Phytoremediation is a cost-effective, ecologically friendly, solar-powered soil remediation method that depends on plants' ability to intercept, take up, accumulate, sequestrate, stabilise, or translocate pollutants. Abiotic and biotic factors such as soil pH, soil components, nutrient availability, plant selection and kind of contaminants all influence phytoremediation (Thijs *et al*. 2016) [184]. It has recently been discovered that the effectiveness rate of phytoremediation is significantly dependent on the plant microbiome (Hou *et al*. 2019) [101]. When PGPR are introduced to a contaminated site, they boost the ability of plants to store heavy metals, recycle nutrients, maintain soil structure, detoxify pollutants, and manage diseases and pests; PGPR also reduces metal toxicity by modifying their bioavailability in plants. Root exudates such as free amino acids, proteins, carbohydrates, alcohols, vitamins, and hormones, which are significant sources of sustenance for microbes, are provided by the plants (Tak *et al*. 2013) [189]. Researchers have described a biological application of PGPR for heavy metal phytoremediation and salt-impacted soil phytoremediation (Nakkeeran *et al*. 2006; Barea 2015; Le Mire *et al*. 2016) [141, 24, 122]. Plant-microbiome interactions are currently being explored as part of a metaorganism strategy to determine the most promising strategies to improve phytoremediation success rates.

The role of

a) Plant host selection.
b) Root exudates.
c) Investigation of single or microbial consortium *in situ*.
d) Molecular study of PGPR strains are all combined in the PGPR-based metaorganism approach (Thijs *et al*. 2016) [184].

PGPR for biocontrol

Through antibiosis, parasitism, competition for resources and space in the vicinity of plant roots, and/or activation of host defence responses, PGPR indirectly aids plant growth by suppressing harmful bacteria that restrict plant growth or root diseases (Podile and Kishore 2006) [150]. *Bacillus subtilis* strains are the most extensively utilised PGPR because of their disease-fighting and antibiotic-producing capacities (Kokalis-Burelle *et al*. 2006) [112]. *Fluorescent pseudomonads* are also known to reduce soil-borne fungal diseases by creating antifungal compounds and sequestering iron in the rhizosphere by releasing iron-chelating siderophores, making it unavailable to other species (Dwivedi and Johri 2003) [57].

Suppression of deleterious microorganisms by PGPR is mainly by parasitism, by competing for available nutrients, production of enzymes or toxins and inducing resistance by activating plant defence response against pathogens (Podile and Kishore 2006) [150]. *Fluorescent pseudomonads* attach themselves to plant roots and absorb available nutrients, reducing the nutrients available for disease growth (Walsh *et al*. 2001) [201]. For pathogen eradication, PGPR competes for resources with native rhizosphere microorganisms. Siderophore synthesis by PGPR sequesters the majority of available Fe 3+ in the rhizosphere, forcing pathogens to becoming iron-deficient and is hence a key contributor to pathogen suppression (O'Sullivan and O'Gara 1992) [140]. The PGPR synthesises hydrolytic enzymes, enhances nutrient competition, regulates the level of the plant hormone ethylene via the ACC-deaminase enzyme and creates siderophores to protect the rhizosphere from plant diseases (Kumari *et al*. 2016; Anand *et al*. 2016) [114, 12]. There are numerous examples of PGPR being used to effectively control soil-borne illnesses (Haas and Defago 2005) [86].

PGPR and biotic stress tolerance

Drought, salinity, high and low temperatures, heavy metal toxicity, and nutrient deficiency are all examples of extreme environmental conditions that can cause significant annual reductions in overall crop production, yield and quality worldwide as climate change risks arise (Acquaah 2009; Awasthi *et al*. 2014; Shrivastava and Kumar 2015) [3, 17, 170]. Living organisms, such as bacteria, viruses, fungi, insects and nematodes, cause biotic stress in plants (Hamid *et al*. 2021) [88]. The accumulation of specific solutes, such as proline, sugars, polyamines, betaines, polyhydric alcohols and other amino acids, results in PGPR-mediated plant osmolytes homeostasis, which plays a key role in maintaining turgor-driven cellular swelling to withstand osmotic stress caused by drought and high soil salinity (Vurukonda *et al*. 2016) [200]. PGPR releases osmolytes that function in tandem with those produced by plants to improve plant growth and development and so maintain plant health (Sandhya *et al*. 2010; Vardharajula *et al*. 2011) [160, 196]. Another study found that using a combination of PGPR, compost, and mineral fertiliser resulted in increased amounts of soluble sugar and proline, which improved wheat's capacity to retain membrane stability, chlorophyll content and water potential under stress (Kanwal *et al*. 2017) [103].

PGPR in seed priming

Soaking seeds in bacterial solution activates physiological processes in the seed, preventing plumule and radicle development until the seeds are exposed to temperature and oxygen after being sowed (Anita *et al*. 2013) [13]. Even before sowing, PGPR continue to replicate in the seed and proliferate in the spermosphere (Taylor and Harman 1990) [183]. Seed biopriming is being studied because it allows endophytic bacteria to enter the sidewalls while avoiding the harmful effects of high temperatures. The use of a biopriming treatment may help to promote faster and more even germination, as well as improved plant growth (Moeinzadeh *et al*. 2010) [133]. In crops such as carrot (Jensen *et al*. 2004) [100], sweet corn (Callan, Mathre and Miller 1990, 1991) [37] and tomato (Callan, Mathre and Miller 1990, 1991) [37], biopriming using rhizospheric bacteria has been documented (Harman and Taylor 1988; Legro and Satter 1995; Warren and Bennett 1999) [89, 119, 202]. When it comes to the efficacy and survivability of biological agents, priming has been shown to be advantageous and to improve plant growth and yield (Harman, Taylor and Stasz 1989; Callan, Mathre and Miller 1990, 1991; Warren and Bennett 1999) [90, 37, 202].

Seed priming with PGPR results in better germination and seedling establishment (Anita *et al*. 2013) [13]. When combined with bacterial coating, bio-osmopriming can considerably improve the uniformity of germination and plant growth features. When uniform germination and superior stand establishment choices are taken into account, biopriming is the preferred strategy. Biopriming has been practised and explained in a variety of ways by various researchers (Callan, Mathre and Miller 1991; Bennett, Mead, and Whipps 2009; Moeinzadeh *et al*. 2010) [36, 27, 133]. There are many methods for explaining biopriming, which differ in the temperature and length of time the seeds are soaked (Gholami, Shahsavani and Nezarat 2009; Abuamsha, Salman, and Ehlers 2011) [71, 2]. Some of the researchers have also surface disinfected the seeds before soaking into the bacterial suspension (Sharifi, Khavazi and Gholipouri 2011; Firuzsalari, Mirshekari and Khochebagh 2012) [167, 65]. Biopriming of *Abies hickelii* and *A. religiosa* with *Pseudomonas fluorescens* alongside hydropriming has shown a rise within the germination percentage up to 91.45% in *A. hickelii* and 68% during *A. religiosa* (Rodriguez *et al*. 2015). Alwathnani *et al*. (2012) [10] demonstrated the antagonistic effect of *Trichoderma harzianum* and *Trichoderma viride* against *Fusarium oxysporum* as inhibition of radial growth of pathogen. Bio priming with *Pseudomonas flourescens* improved flooding tolerance in Sandal (*Santalum album*) seedlings. (Chitra *et al*. 2021) [46]

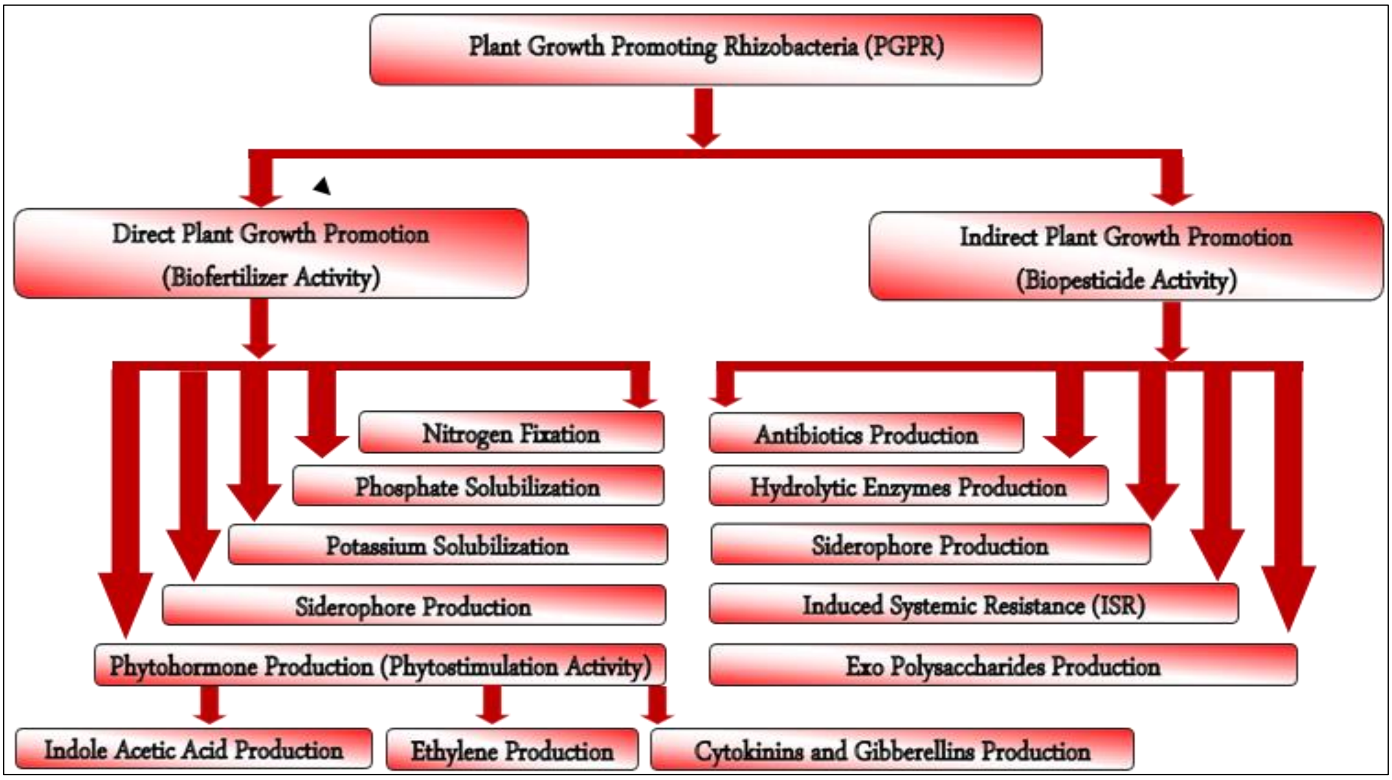

Fig 1: Mode of action of Plant Growth Promoting Rhizobacteria (Gupta *et al*. 2015) [81]

Conclusion

Recently, studies on PGPR have attained more significant and scientific attention. PGPR plays an essential role in helping plants to establish and grow in nutrient deficient conditions. Considering the good impact of PGPR in terms of biofertilization, biocontrol, and bioremediation, all of which exert a positive influence on crop productivity and ecosystem functioning, encouragement should be given to its implementation in agriculture. Several PGPR stains are being commercialized for various crops in agriculture and these are widely used. By exploiting the PGPR from forest ecosystem, it is possible to develop microbiome and these can be well utilized for plantations trees and also for agriculture crops, since forest is a source of diversified microbes, flora and fauna, which can be well exploited for the natural sources.

References

1. Abd-Alla MH, Elenany AE, Ramadan T, Zohri EM, Nafady IM. Nodulation and nitrogen fixation of some wild legumes from differing habitats in Egypt. European Journal of Biological Research. 2017;7(1):9-21.
2. Abuamsha R, Salman M, Ehlers RU. Effect of seed priming with *Serratia plymuthica* and *Pseudomonas chlororaphis* to control *Leptosphaeria maculans* in different oilseed rape cultivars. European journal of plant pathology. 2011;130(3):287-295.
3. Acquaah G. Principles of plant genetics and breeding. John Wiley & Sons, 2009.
4. Adesemoye AO, Torbert H, Kloepper JW. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial ecology. 2009;58(4):921-929.
5. Aditya B, Ghosh A, Chattopadhyay D. Co-inoculation effects of Nitogen fixing and Phosphate solublising microorganisms on teak (*Tectona grandis*) and Indian redwood (*Chukrasia tubularis*). Journal of Biological Sciences. 2009;1:23-32.
6. Ahemad M, Kibret M. Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. Journal of King saud University-science 2014;26(1):1-20.
7. Ahmad F, Ahmad I, Khan MS. Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol. Res. 2008;163:173-181.
8. Akhtar SS, Amby DB, Hegelund JN, Fimognari L, Grobkinsky DK, Westergaard JC, *et al*. *Bacillus*

licheniformis FMCH001 increases water use efficiency via growth stimulation in both normal and drought conditions. Frontiers in plant science. 2020;11:297.

9. Alvarez MI, Sueldo RJ, Barassi CA. Effect of *Azospirillum* on coleoptile growth in wheat seedlings under water stress. Cereal Research Communications, 1996, 101-107.
10. Alwathnani HA, Perveen K. Biological control of fusarium wilt of tomato by antagonist fungi and cyanobacteria. African Journal of Biotechnology. 2012;11(5):1100-1105.
11. Amara U, Khalid R, Hayat R. Soil bacteria and phytohormones for sustainable crop production. In Bacterial metabolites in sustainable agroecosystem. Springer, Cham., 2015, 87-103.
12. Anand K, Kumari B, Mallick MA. Phosphate solubilizing microbes: an effective and alternative approach as biofertilizers. J Pharm Pharm Sci. 2016;8(2):37.
13. Anita VÉGH, Palkovics L. First occurence of fire blight on apricot (*Prunus armeniaca*) in Hungary. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 2013;41(2):440-443.
14. Antoun H, Beauchamp CJ, Goussard N, Chabot R, Lalande R. Potential of *Rhizobium* and Brady *Rhizobium* species as plant growth promoting rhizobacteria on non-legumes: effect on radishes (*Raphanus sativus* L.). In Molecular microbial ecology of the soil. Springer, Dordrecht, 1998, 57-67.
15. Arkhipova TN, Prinsen E, Veselov SU, Martinenko EV, Melentiev AI, Kudoyarova GR. Cytokinin producing bacteria enhance plant growth in drying soil. Plant Soil. 2007;292:305-315.
16. Arshad M, Frankenberger WT Jr. Plant growth regulating substances in the rhizosphere: Microbial production and functions. Adv Agron. 1998;62:146-151.
17. Awasthi R, Kaushal N, Vadez V, Turner NC, Berger J, Siddique KH, *et al*. Individual and combined effects of transient drought and heat stress on carbon assimilation and seed filling in chickpea. Functional Plant Biology. 2014;41(11):1148-1167.
18. Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, *et al*. Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Frontiers in plant science. 2018;9:14-73.
19. Bagyalakshmi TA, Ramesh V, Arivudainambi USE, Rajendran A. A novel endophytic fungus *Pestalotiopsis* sp. inhibiting *Pinus canariensis* with antibacterial and antifungal potential. International Journal of Advanced Life Sciences. 2012;1:1-7.
20. Bajracharya AM. Plant growth promoting rhizobacteria (PGPR): Biofertiliser and Biocontrol agent-Review article. Journal of Balkumari College. 2019;8:42-45.
21. Ballhorn DJ, Elias JD, Balkan MA, Fordyce RF, Kennedy PG. Colonization by nitrogen-fixing Frankia bacteria causes short-term increases in herbivore susceptibility in red alder (*Alnus rubra*) seedlings. Oecologia. 2017;184(2):497-506.
22. Banerjee MR, Yesmin L, Vessey JK, Rai M. Plant-growth-promoting rhizobacteria as biofertilizers and biopesticides. Handbook of microbial biofertilizers. Food Products Press, New York, 2006, 137-181.
23. Banerjee S, Palit R, Sengupta C, Standing D. Stress induced phosphate solubilization by '*Arthrobacter*' Sp. And '*Bacillus*' sp. isolated from tomato rhizosphere. Australian Journal of crop science. 2010;4(6):378-383.
24. Barea JM. Future challenges and perspectives for applying microbial biotechnology in sustainable agriculture based on a better understanding of plant-microbiome interactions. Journal of soil science and plant nutrition. 2015;15(2):261-282.
25. Barriuso J, Pereyra MT, Lucas García JÁ, Megías M, Gutierrez Mañer FJ, Ramos B. Screening for putative PGPR to improve establishment of the symbiosis *Lactarius deliciosus-Pinus* sp. Microb Ecol. 2005;50:82-89.
26. Bending GD, Poole EJ, Whipps JM, Read DJ. Characterisation of bacteria from *Pinus sylvestris-Suillus luteus* mycorrhizas and their effects on root-fungus interactions and plant growth. FEMS Microbiol. Ecol. 2002;39:219-227.
27. Bennett AJ, Mead A, Whipps JM. Performance of carrot and onion seed primed with beneficial microorganisms in glasshouse and field trials. Biological Control. 2009;51(3):417-426.
28. Bent E, Tuzun S, Chanway CP, Enebak S. Alterations in plant growth and in root hormone levels of lodgepole pines inoculated with rhizobacteria. Can J Microbiol. 2001;47:793-800.
29. Bent E, Breuil C, Enebak S, Chanway CP. Surface colonization of lodgepole pine (*Pinus contorta* var. latifolia [Dougl. Engelm.]) roots by *Pseudomonas fluorescens* and Paeni*Bacillus* polymyxa under gnotobiotic conditions. Plant and Soil. 2002;241(2):187-196.
30. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. World Journal of Microbiology and Biotechnology. 2012;28(4):1327-1350.
31. Bishnoi U. PGPR interaction: an ecofriendly approach promoting the sustainable agriculture system. Advances in botanical research. 2015;75:81-113.
32. Bresson J, Vasseur F, Dauzat M, Labadie M, Varoquaux F, Touraine B, *et al*. Interact to survive: *Phyllobacterium* brassicacearum improves Arabidopsis tolerance to severe water deficit and growth recovery. PLoS One. 2014;9(9):e107-607.
33. Brunetta JMFC, Alfenas AC, Mafia RG, Gomes MG, Binoti DB, Fonseca EP. Avaliação da especificidade de rizobactérias isoladas de diferentes espécies de *Pinus* sp. R Árvore. 2007;31:1027-1033.
34. Bulgarelli D, Garrido-Oter R, Munch PC, Weiman A, Droge J, Pan Y, *et al*. Structure and function of the bacterial root microbiota in wild and domesticated barley. Cell Host Microbe. 2015;17:392-403. Doi: 10.1016/j.chom. 2015.01.011
35. Çakmakçı, Ramazan, Mosber Goltay, Milton Ada, Alatürk Fırat, Ali Baboo. The Effect of Auxin and Auxin-Producing Bacteria on the Growth, Essential Oil Yield, and Composition in Medicinal and Aromatic Plants. Current Microbiology, 2020, 77. 10.1007/s00284-020-01917-4.
36. Callan NW, Mathre DE, Miller JB. Field performance of sweet corn seed bio-primed and coated with *Pseudomonas fluorescens* AB254. Hort. Science. 1991;26(9):1163-1165.
37. Callan NW, Mathre D, Miller JB. Bio-priming seed

treatment for biological control of *Pythium ultimum* preemergence damping-off in sh-2 sweet corn. Plant Disease. 1990;74:368-372.

38. Cardoso EJBN, De Figueiredo Vasconcellos RL, Ribeiro CM, Miyauchi MYH. PGPR in coniferous trees. In Bacteria in Agrobiology: Crop Ecosystems. Springer, Berlin, Heidelberg, 2011, 345-359.
39. Cassán F, Perrig D, Sgroy V, Masciarelli O, Penna C, Luna V. *Azospirillum* brasilense Az39 and Brady *Rhizobium japonicum* E109, inoculated singly or in combination, promote seed germination and early seedling growth in corn (*Zea mays* L.) and soybean (*Glycine max* L.). European Journal of Soil Biology. 2009;45:28-35.
40. Cattelan AJ, Hartel PG, Fuhrmann JJ. Screening for plant growth-promoting rhizobacteria to promote early soybean growth. Soil Science Society of America Journal. 1999;63(6):1670-1680.
41. Celloto VR, Oliveira AJB, Gonçalves JE, Watanabe CSF, Matioli G, Gonçalves RAC. Biosynthesis of indole-3-acetic acid by new *Klebsiella oxytoca* free and immobilized cells on inorganic matrices. Sci World J, 2012, 1-7.
42. Chabot R, Antoun H, Cescas MP. Growth promotion of maize and lettuce by phosphate solubilizing *Rhizobium leguminosarum* biovar phaseoli. Plant Soil. 1996;184:311-321.
43. Chabot R, Beauchamp CJ, Kloepper JW, Antoun H. Effect of phosphorus on root colonization and growth promotion of maize by bioluminescent mutants of phosphate-solubilizing *Rhizobium leguminosarum* biovar phaseoli. Soil Biology and Biochemistry. 1998;30(12):1615-1618.
44. Chaparro JM, Badri DV, Vivanco JM. Rhizosphere microbiome assemblage is affected by plant development. The ISME journal. 2014;8(4):790-803.
45. Chew K, Georgics. Hackett, Indianapolis, 2002, 152.
46. Chitra P, Jijeesh CM. Biopriming of seeds with plant growth promoting bacteria *Pseudomonas* fluorescens for better germination and seedling vigour of the East Indian sandalwood. New Forests, 2021, 1-13.
47. Cordero I, Balaguer L, Rincón A, Pueyo JJ. Inoculation of tomato plants with selected PGPR represents a feasible alternative to chemical fertilization under salt stress. Journal of Plant Nutrition and Soil Science. 2018;181(5):694-703.
48. Crannell WK, Tanaka Y, Myrold DD. Calcium and pH interaction on root nodulation of nursery-grown red alder (*Alnus rubra* Bong.) seedlings by Frankia. Soil Biology and Biochemistry. 1994;26:607-614.
49. Damayanti TA, Pardede H, Mubarik NR. Utilization of root-colonizing bacteria to protect hot-pepper against Tobacco Mosaic Tobamovirus. HAYATI Journal of Biosciences. 2007;14(3):105-109.
50. Deka H, Deka S, Baruah CK. Plant growth promoting rhizobacteria for value addition: mechanism of action. In Plant-Growth Promoting Rhizobacteria (PGPR) and Medicinal Plants. Springer, Cham., 2015, 305-321.
51. Delshadi S, Ebrahimi M, Shirmohammadi E. Influence of plant-growth-promoting bacteria on germination, Growth and nutrients? uptake of *Onobrychis sativa* L. under drought stress. Journal of Plant Interactions. 2017;12:200-208. https://doi.org/10.1080/17429145.2017.13 16527.
52. Dey RKKP, Pal KK, Bhatt DM, Chauhan SM. Growth promotion and yield enhancement of peanut (*Arachis hypogaea* L.) by application of plant growth-promoting rhizobacteria. Microbiological research. 2004;159(4):371-394.
53. Diagne N, Arumugam K, Ngom M, Nambiar-Veetil M, Franche C, Narayanan KK, *et al*. Use of Frankia and actinorhizal plants for degraded lands reclamation. BioMed Research International, 2013, 948-258.
54. Dobbelaere S, Vanderleyden J, Okon Y. Plant growth-promoting effects of diazotrophs in the rhizosphere. Critical reviews in plant sciences. 2003;22(2):107-149.
55. Dodd IC, Zinovkina NY, Safronova VI, Belimov AA. Rhizobacterial mediation of plant hormone status. Annals of Applied Biology. 2010;157(3):361-379.
56. Dubeikovsky AN, Mordukhova EA, Kochetkov VV, Polikarpova FY, Boronin AM. Growth promotion of blackcurrant softwood cuttings by recombinant strain *Pseudomonas fluorescent* BSP53a synthesizing an increased amount of indole-3-acetic acid. Soil Biol. Biochem. 1993;25:1277-1282.
57. Dwivedi D, Johri BN. Antifungals from fluorescent pseudomonads: biosynthesis and regulation. Current Science, 2003, 1693-1703.
58. Egamberdieva D. Alleviation of salt stress by plant growth regulators and IAA producing bacteria in wheat. Acta Physiol. Plant. 2009;31:861-864. Doi: 10.1007/s11738-009-0297-0
59. Egamberdieva D, Davranov K, Wirth S, Hashem A, Abd_Allah EF. Impact of soil salinity on the plant-growth-promoting and biological control abilities of root associated bacteria. Saudi Journal of Biological Sciences. 2017;24(7):1601-1608.
60. Egamberdieva D, Jabborova D, Hashem A. *Pseudomonas* induces salinity tolerance in cotton (*Gossypium hirsutum*) and resistance to Fusarium root rot through the modulation of indole-3-acetic acid. Saudi journal of biological sciences. 2015;22(6):773-779.
61. Egamberdieva D, Shrivastava S, Varma A. (Eds.). Plant-growth-promoting rhizobacteria (PGPR) and medicinal plants. Cham: Springer International Publishing, 2015.
62. Ehteshamul-Haque S, Ghaffar A. Use of Rhizobia in the control of root diseases of sun flower, okra, soybean and mungbean. J Phytopathol. 1993;138:157-163.
63. Enebak SA, Wei G, Kloepper JW. Effects of plant growth-promoting rhizobacteria on loblolly and slash pine seedlings. Forest Sci. 1998;44:139-144.
64. Fernando WD, Nakkeeran S, Siddiqui ZA. Plant growth promoting rhizobacteria formulations and its scope in commercialization for the management of pests and diseases. In PGPR: Biocontrol and biofertilization. Springer, Dordrecht, 2005, 257-296.
65. Firuzsalari SM, Mirshekari B, Khochebagh SB. Effect of seed inoculation with bio-fertilizer on germination and early growth of corn. Int Res J App Basic Sci. 2012;3:1097-102.
66. Fixation and Biotechnology. Journal of Biotechnology, 91, 143-e153.
67. Frey-Klett P, Churina JL, Pierrat JC, Garbaye J. Dose effect in the dual inoculation of an ectomycorrhizal fungus and a mycorrhiza helper bacterium in two forest nurseries. Soil Biol. Biochem. 1999;31:1555-1562.
68. Gamit DA, Tank SK. Effect of siderophore producing microorganism on plant growth of Cajanus cajan (*Pigeon*

pea). International Journal of Pure and Applied Microbiology. 2014;4(1):20-27.

69. Garcia JAL, Domenech J, Santamaría C, Camacho M, Daza A, Mañero FJG. Growth of forest plants (pine and holm-oak) inoculated with rhizobacteria: relationship with microbial community structure and biological activity of its rhizosphere. Environ Exp Bot. 2004;52:239-251.
70. Germida JJ, Walley FL. Plant growth promoting rhizobacteria alter rooting patterns and arbuscular mycorrhizal fungi colonization of field grown spring wheat. Biol Fertil Soils. 1996;23:113-120.
71. Gholami A, Shahsavani S, Nezarat S. The effect of plant growth promoting rhizobacteria (PGPR) on germination, seedling growth and yield of maize. World Academy of Science, Engineering and Technology. 2009;49:19-24.
72. Giron D, Glevarec G. Cytokinin-induced phenotypes in plant-insect interactions: learning from the bacterial world. Journal of Chemical Ecology. 2014;40(7):826-835.
73. Glick BR, Jacobson CB, Schwarze MMK, Pasternak JJ. 1-Aminocyclopropae-1-carboxylic acid deaminase play a role on plant growth by *Pseudomonas* putida GR12-2. In: Ryder MH, Stephens PM, Bowen GD (eds) Improving plant productivity with rhizosphere bacteria. CSIRO, Adelaide, 1994, 150-152.
74. Glick BR. Phytoremediation: synergistic use of plants and bacteria to clean up the environment. Biotechnology advances. 2003;21(5):383-393.
75. Glick BR, Pasternak JJ. Plant growth promoting bacteria. Molecular biology-principles and applications of recombinant DNA, 2003, 436-54.
76. Glick BR, Karaturovic DM, Newell PC. A novel procedure for rapid isolation of plant growth promoting *Pseudomonas*. Canadian Journal of Microbiology. 1995;41:533-e536.
77. Goteti PK, Leo DAE, Desai S, Ahmed SMH. Prospective zinc solubilising bacteria for enhanced nutrient uptake and growth promotion in Maize (*Zea mays* L.). International Journal of Microbiology, 2013, 1-7.
78. Gouda S, Kerry RG, Das G, Paramithiotis S, Shin HS, Patra JK. Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiological Research. 2018;206:131-140.
79. Govindasamy V, Senthilkumar M, Magheshwaran V, Kumar U, Bose P, Sharma V, *et al*. *Bacillus* and *Paeni bacillus* spp.: potential PGPR for sustainable agriculture. In Plant growth and health promoting bacteria. Springer, Berlin, Heidelberg, 2010, 333-364.
80. Guang-Can TAO, Shu-Jun TIAN, Miao-Ying CAI, Guang-Hui XIE. Phosphate-solubilizing and-mineralizing abilities of bacteria isolated from soils. Pedosphere. 2008;18(4):515-523.
81. Gupta G, Parihar SS, Ahirwar NK, Snehi SK, Singh V. Plant growth promoting rhizobacteria (PGPR): current and future prospects for development of sustainable agriculture. J Microb. Biochem. Technol. 2015;7:096-102.
82. Gupta S, Dikshit AK. Biopesticides: An ecofriendly approach for pest control. Journal of Biopesticides. 2010;3:186-188.
83. Gutierrez Manero FJ, Acero N, Lucas JA, Probanza A. The influence of native rhizobacteria on European alder (*Alnus glutinosa* (L) Gaertn.). II Characterisation and biological assays of metabolites from growth promoting and growth inhibiting bacteria. Plant Soil. 1996;182:67-74.
84. Gutierrez Manero FJ, Ramos B, Probanza A, Mehouachi J, Tadeo FR, Talon M. Plant growth promoting rhizobacteria *Bacillus pumilus* and *Bacillus* licheniformis produce high amount of physiologically active gibberellins. Physiol. Plant. 2001;111:206-211.
85. Hellriegel H, Wilfarth H. Untersuchungen uber die Stickstoffnahrung der Gramineen und Leguminosen Beilageheft zu der Z des Vereins Rubenzucker-Industrie Deutschen Reichs, 1888, 234.
86. Haas D, Défago G. Biological control of soil-borne pathogens by fluorescent pseudomonads. Nature reviews microbiology. 2005;3(4):307-319.
87. Halder AK, Chakrabarty PK. Solubilization of inorganic phosphate by. Folia Microbiologica, Prague. 1993;38:325-o30.
88. Hamid B, Zaman M, Farooq S, Fatima S, Sayyed RZ, Baba ZA, *et al*. Bacterial Plant Biostimulants: A Sustainable Way towards Improving Growth, Productivity and Health of Crops. Sustainability. 2021;13(5):28-56.
89. Harman GE, Taylor AG. Improved seedling performance by integration of biological control agents at favorable pH levels with solid matrix priming. Phytopathology. 1988;78(5):520-525.
90. Harman GE, Taylor AG, Stasz TE. Combining effective strains of *Trichoderma harzianum* and solid matrix priming to improve biological seed treatments. Plant Disease. 1989;73(8):631-637.
91. Hayat R, Ahmed I, Sheirdil RA. An overview of plant growth promoting rhizobacteria (PGPR) for sustainable agriculture. Crop production for agricultural improvement, 2012, 557-579.
92. Hayat R, Ali S, Amara U, Khalid R, Ahmed I. Soil beneficial bacteria and their role in plant growth promotion: a review. Annals of microbiology. 2010;60(4):579-598.
93. Haymer D. Genetics and insect pest management in agriculture. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2015. https://doi.org/10.1079/ PAVSNNR201510049.
94. Henson BJ, Watson LE, Barnum SR. The evolutionary history of nitrogen fixation, as assessed by nif D. Journal of molecular evolution. 2004;58(4):390-399.
95. Höflich G, Tauschke M, Kühn G, Rogasik J. Influence of agricultural crops and fertilization on microbial activity and microorganisms in the rhizosphere. Journal of agronomy and crop science. 2000;184(1):49-54.
96. Hou J, Liu W, Wu L, Ge Y, Hu P, Li Z, *et al*. *Rhodococcus* sp. NSX2 modulates the phytoremediation efficiency of a trace metal-contaminated soil by reshaping the rhizosphere microbiome. Applied Soil Ecology. 2019;133:62-69.
97. Ijaz M, Tahir M, Shahid M, Ul-Allah S, Sattar A, Sher A, *et al*. Combined application of biochar and PGPR consortia for sustainable production of wheat under semiarid conditions with a reduced dose of synthetic fertilizer. Brazilian Journal of Microbiology. 2019;50(2):449-458.
98. Jadhav RS, Thaker NV, Desai A. Involvement of the siderophore of cowpea *Rhizobium* in the iron nutrition of the peanut. World J Microbiol Biotechnol. 1994;10:360-

361.
99. Jeffries P, Gianinazzi S, Perotto S, Turnau K, Barea JM. The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. Biology and fertility of soils. 2003;37(1):1-16.
100. Jensen B, Knudsen IM, Madsen M, Jensen DF. Biopriming of infected carrot seed with an antagonist, Clonostachys rosea, selected for control of seedborne *Alternaria* spp. Phytopathology. 2004;94(6):551-560.
101. Kandoliya UK, Vakharia DN. Molecular characterization of *Pseudomonas* fluorescens inhibiting the chickpea wilt pathogen *in vitro*. International Journal of Plant Protection. 2013;6(2):241-246.
102. Kang SM, Khan AL, Hamayun M, Shinwari ZK, Kim YH, Joo GJ, *et al*. Acinetobacter calcoaceticus ameliorated plant growth and influenced gibberellins and functional biochemicals. Pak. J Bot. 2012;44(1):365-372.
103. Kanwal F, Kramer J, Asch SM, Chayanupatkul M, Cao Y, El-Serag HB. Risk of hepatocellular cancer in HCV patients treated with direct-acting antiviral agents. Gastroenterology. 2017;153(4):996-1005.
104. Kashyap BK, Solanki MK, Pandey AK, Prabha S, Kumar P, Kumari B. *Bacillus* as plant growth promoting rhizobacteria (PGPR): A promising green agriculture technology. In Plant health under biotic stress. Springer, Singapore, 2019, 219-236.
105. Kennedy IR, Choudhury ATMA, Kecskés ML. Non-symbiotic bacterial diazotrophs in crop-farming systems: can their potential for plant growth promotion be better exploited? Soil Biology and Biochemistry. 2004;36(8):1229-1244.
106. Khare E, Arora NK. Effect of indole-3-acetic acid (IAA) produced by *Pseudomonas* aeruginosa in suppression of charcoal rot disease of chickpea. Current Microbiology. 2010;61:64-68.
107. Kim J, Rees DC. Nitrogenase and biological nitrogen fixation. Biochemistry. 1994;33(2):389-397.
108. Kloepper JW, Leong J, Teintze M, Schroth MN. Enhanced plant growth by siderophores produced by plant growth-promoting rhizobacteria. Nature. 1980;286(5776):885-886.
109. Kloepper JW, Wei G, Tuzun S. Rhizosphere Population Dynamics and Internal Colonization of Cucumber by Plant Growth-Promoting Rhizobacteria which Induce Systemic Resistance to Colletotrichum Orbiculare. In Biological control of plant diseases. Springer, Boston, MA, 1992, 185-191.
110. Kloepper JW. Plant growth promoting rhizobacteria as biological agents. In: Soil microbial ecology: application in agricultural and environmental management. Sd by Meeting FB. Jr. Marcel Dekker Inc., NY, USA, 1992, 255-274.
111. Kloepper JW, Schroth MN. Plant growth promoting rhizobacteria on radishes. IV International Conference on Plant Pathogenic Bacteria. Angers France. 1978;2:879-882.
112. Kokalis-Burelle N, Kloepper JW, Reddy MS. Plant growth-promoting rhizobacteria as transplant amendments and their effects on indigenous rhizosphere microorganisms. Applied Soil Ecology. 2006;31(1-2):91-100.
113. Kumar V, Singh KP. Enriching vermicompost by nitrogen fixing and phosphate solubilizing bacteria. Bioresource Technology. 2001;76(2):173-175.
114. Kumari S, Deori M, Elancheran R, Kotoky J, Devi R. *In vitro* and *in vivo* antioxidant, anti-hyperlipidemic properties and chemical characterization of *Centella asiatica* (L.) extract. Frontiers in pharmacology. 2016;7:400.
115. Kunikowska A, Byczkowska A, Kaz´mierczak A. Kinetin induces cell death in root cortex cells of *Vicia faba* ssp. minor seedlings. Protoplasma, 2012. Doi: 10.1007/s00709-012-0466-7
116. Laranjo M, Alexandre A, Oliveira S. Legume growth-promoting rhizobia: An overview on the Meso *Rhizobium* genus. Microbiological Research. 2014;169(1):2-17.
117. Le Mire G, Nguyen M, Fassotte B, Du Jardin P, Verheggen F, Delaplace P, *et al*. Implementing biostimulants and biocontrol strategies in the agroecological management of cultivated ecosystems. Biotechnologie, Agronomie, Société et Environnement, 2016.
118. Lebeis SL. The potential for give and take in plant-microbiome relationships. Frontiers in plant science. 2014;5:287.
119. Legro B, Satter H, Bradford K, Hartz T. Biological control of Pythium through seed coating and seed priming with Trichoderma. In Monterey Proceedings of the 4th National Symposium on Stand Establishment of Horticultural Crops, Monterey, California, 1995, 23-57.
120. Lehr NA, Schrey SD, Hampp R, Tarkka MT. Root inoculation with a forest soil streptomycete leads to locally and systemically increased resistance against phytopathogens in Norway spruce. New Phytol. 2008;177:965-976.
121. Li Z, Song C, Yi Y, Kuipers OP. Characterization of plant growth -promoting rhizobacteria from perennial ryegrass and genome mining of novel antimicrobial gene clusters. BMC Genomics. 2020;21:157. https://doi.org/10.1186/s12864 -020 -6563 -7.
122. Lindemann SR, Bernstein HC, Song HS, Fredrickson JK, Fields MW, Shou W, *et al*., Engineering microbial consortia for controllable outputs. ISME J. 2016;10:2077-2084. https://doi.org/10.1038/ismej.2016.26.
123. Liu L, Kloepper JW, Tuzun S. Induction of systemic resistance in cucumber by plant growth promoting rhizobacteria: duration of protection and effect of host resistance on protection and root colonization. Phytopathology. 1995;85:1064-1068.
124. Lucas-Garcia J, Probanza A, Ramos B, Barriuso J, Gutierrez-Mañero F. Effects of inoculation with plant growth rhizobacteria (PGPRs) and Sino *Rhizobium fredii* on biological nitrogen fixation, nodulation and growth of *Glycine max* cv. Osumi. Plant and Soil. 2004;267:143-153.
125. Lucy M, Reed E, Glick BR. Applications of free-living plant growth-promoting rhizobacteria. Antonie van leeuwenhoek. 2004;86(1):1-25.
126. Ma X, Chen H, Ceder G. Electrochemical properties of monoclinic NaMnO2. Journal of The Electrochemical Society. 2011;158(12):A1307.
127. Maheshwari DK, Dheeman S, Agarwal M. Phytohormone-producing PGPR for sustainable agriculture. In Bacterial metabolites in sustainable agroecosystem. Springer, Cham., 2015, 159-182.
128. Mahmood A, Turgay OC, Farooq M, Hayat R. Seed biopriming with plant growth promoting rhizobacteria: A

review. FEMS microbiology ecology. 2016;92(8):fiw-112.

129. Mamta RP, Pathania V, Gulati A, Singhd B, Bhanwra RK, Tewari R. Stimulatory effect of phosphate-solubilizing bacteria on plant growth, stevioside and rebaudioside-A contents of Stevia rebaudiana Bertoni. Applied Soil Ecology. 2010;46:222-229.
130. Martínez-Viveros O, Jorquera MA, Crowley DE, Gajardo GMLM, Mora ML. Mechanisms and practical considerations involved in plant growth promotion by rhizobacteria. Journal of soil science and plant nutrition. 2010;10(3):293-319.
131. Matiru VN, Dakora FD. Potential use of rhizobial bacteria as promoters of plant growth for increased yield in landraces of African cereal crops. African Journal of Biotechnology. 2004;3(1):1-7.
132. Mishra J, Fatima T, Arora NK. Role of secondary metabolites from plant growth-promoting rhizobacteria in combating salinity stress. In Plant microbiome: Stress response. Springer, Singapore, 2018, 127-163.
133. Moeinzadeh A, Sharif-Zadeh F, Ahmadzadeh M, Tajabadi F. Biopriming of Sunflower (*Helianthus annuus* L.) Seed with '*Pseudomonas* fluorescens' for Improvement of Seed Invigoration and Seedling Growth. Australian Journal of Crop Science. 2010;4(7):564-570.
134. Morgado González A, Espinosa Victoria D, Gómez Merino FC. Efficiency of plant growth promoting rhizobacteria (PGPR) in sugarcane. Terra Latinoamericana. 2015;33(4):321-330.
135. Nakkeeran S, Kavitha K, Chandrasekar G, Renukadevi P, Fernando WGD. Induction of plant defence compounds by *Pseudomonas* chlororaphis PA23 and *Bacillus* subtilis BSCBE4 in controlling damping-off of hot pepper caused by Pythium aphanidermatum. Biocontrol Science and Technology. 2006;16(4):403-416.
136. Narasimhan K, Basheer C, Bajic VB, Swarup S. Enhancement of plant-microbe interactions using a rhizosphere metabolomics-driven polychlorinated biphenyls 1 [w]. Plant Physiology. 2003;132:146-153. https://doi.org/10.1104/pp.102.016295.populations.
137. Naseem H, Bano A. Role of plant growth-promoting rhizobacteria and their exopolysaccharide in drought tolerance of maize. Journal of Plant Interactions. 2014;9(1):689-701.
138. Naz I, Bano A, Ul-Hassan T. Isolation of phytohormones producing plant growth promoting rhizobacteria from weeds growing in Khewra salt range, Pakistan and their implication in providing salt tolerance to *Glycine max* L. African Journal of Biotechnology, 2009, 8(21).
139. Oleńska E, Małek W, Wójcik M, Swiecicka I, Thijs S, Vangronsveld J. Beneficial features of plant growth-promoting rhizobacteria for improving plant growth and health in challenging conditions: A methodical review. Science of the Total Environment, 2020, 140-682.
140. O'sullivan DJ, O'Gara F. Traits of fluorescent *Pseudomonas* spp. involved in suppression of plant root pathogens. Microbiological reviews. 1992;56(4):662-676.
141. Oteino N, Lally RD, Kiwanuka S, Lloyd A, Ryan D, Germaine KJ, *et al*. Plant growth promotion induced by phosphate solubilizing endophytic *Pseudomonas* isolates. Frontiers in Microbiology. 2015;6:745.
142. Pandya ND, Desai PV. Screening and characterization of GA3 producing *Pseudomonas monteilii* and its impact on plant growth promotion. International Journal of Current Microbiology and Applied Sciences. 2014;3(5):110-115.
143. Parmar P, Sindhu SS. Potassium solubilization by rhizosphere bacteria: Influence of nutritional and environmental conditions. Journal of Microbiology Research. 2013;3(1):25-31.
144. Patten CL, Glick BR. Bacterial biosynthesis of indole-3-acetic acid. Can J Microbiol. 1996;42:207-220.
145. Patten CL, Glick BR. Role of *Pseudomonas* putida indoleacetic acid in development of the host plant root system. Applied and environmental microbiology. 2002;68(8):3795-3801.
146. Paul EA, Clark FE. Soil microbiology and biochemistry. Academic Press, London, 1996.
147. Paynel F, Murray PJ, Cliquet JB. Root exudates: a pathway for short-term N transfer from clover and ryegrass. Plant and soil. 2001;229(2):235-243.
148. Penrose DM, Moffatt BA, Glick BR. Determination of 1-aminocycopropane-1-carboxylic acid (ACC) to assess the effects of ACC deaminase-containing bacteria on roots of canola seedlings. Canadian Journal of Microbiology. 2001;47(1):77-80.
149. Plessner O, Klapach T, Guerinot ML. Siderophore utilization by Brady *Rhizobium japonicum*. Appl. Environ Microbiol. 1993;59:1688-1690.
150. Podile AR, Kishore GK. Plant growth-promoting rhizobacteria. In: Gnanamanickam SS (ed) Plant-Associated Bacteria. Springer, Netherlands, 2006, 195-230.
151. Prajapati K, Modi HA. Growth promoting effect of potassium solubilizing *Enterobacter hormaechei* (KSB-8) on Cucumber (*Cucumis sativus*) under hydroponic conditions. International Journal of Advanced Research in Biological Sciences. 2016;3(5):168-173.
152. Raza W, Ling N, Yang L, Huang Q, Shen Q. Response of tomato wilt pathogen *Ralstonia solanacearum* to the volatile organic compounds produced by a biocontrol strain *Bacillus* amyloliquefaciens SQR-9. Sci. Rep. 2016a;6:248-56.
153. Raza W, Yousaf S, Rajer FU. Plant growth promoting activity of volatile organic compounds produced by Bio-control strains. Sci. Lett. 2016b;4(1):40-43.
154. Reetha S, Bhuvaneswari G, Thamizhiniyan P, Mycin TR. Isolation of indole acetic acid (IAA) producing rhizobacteria of *Pseudomonas fluorescens* and *Bacillus subtilis* and enhance growth of onion (*Allim cepa*. L). International Journal of Current Microbiology and Applied Sciences. 2014;3(2):568-574.
155. Revillas JJ, Rodelas B, Pozo C, Martínez-Toledo MV, González-López J. Production of B-group vitamins by two *Azotobacter* strains with phenolic compounds as sole carbon source under diazotrophic and adiazotrophic conditions. Journal of applied microbiology. 2000;89(3):486-493.
156. Richardson AE. Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Functional Plant Biology. 2001;28(9):897-906.
157. Rincón A, Valladares F, Gimeno TE, Pueyo JJ. Water stress responses of two Mediterranean tree species influenced by native soil microorganisms and inoculation with a plant growth promoting rhizobacterium. Tree Physiol. 2008;28:1693-1701.
158. Roos W, Luckner M. Relationships between proton extrusion and fluxes of ammonium ions and organic acids in *Penicillium cyclopium*. Microbiology.

1984;130(4):1007-1014.

159. Russo A, Vettori L, Felici C, Fiaschi G, Morini S, Toffanin A. Enhanced micropropagation response and biocontrol effect of *Azospirillum brasilense* Sp245 on *Prunus cerasifera* L. clone Mr. S 2/5 plants. Journal of Biotechnology. 2008;134(3-4):312-319.
160. Sandhya VSKZ, Ali SZ, Grover M, Reddy G, Venkateswarlu B. Effect of plant growth promoting *Pseudomonas* spp. on compatible solutes, antioxidant status and plant growth of maize under drought stress. Plant Growth Regulation. 2010;62(1):21-30.
161. Santi C, Bogusz D, Franche C. Biological nitrogen fixation in non-legume plants. Annals of Botany. 2013;111(5):743-767.
162. Saravanakumar D, Ciavorella A, Spadaro D, Garibaldi A, Gullino ML. *Metschnikowia pulcherrima* strain MACH1 outcompetes *Botrytis cinerea*, *Alternaria alternata* and *Penicillium expansum* in apples through iron depletion. Postharvest Biology and Technology. 2008;49(1):121-128.
163. Schoebitz M, Osman J, Ciampi L. Effect of immobilized *Serratia* sp. by spray-drying technology on plant growth and phosphate uptake. Chilean Journal of Agricultural & Animal Sciences. 2013;29:111-119.
164. Schrey SD, Schellhammer M, Ecke M, Hampp R, Tarkka MT. Mycorrhiza helper bacterium *Streptomyces* AcH 505 induces differential gene expression in the ectomycorrhizal fungus *Amanita muscaria*. New Phytol. 2005;168:205-216.
165. Sgroy V, Cassán F, Masciarelli O, Florencia M, Papa D, Lagares A, *et al*. Isolation and characterization of endophytic plant growth-promoting (PGPB) or stress homeostasis-regulating (PSHB) bacteria associated to the halophyte *Prosopis strombulifera*. Appl. Microbiol Biotechnol. 2009;85(2):371-381.
166. Shariatmadari Z, Riahi H, Seyed Hashtroudi M, Ghassempour A, Aghashariatmadary Z. Plant growth promoting cyanobacteria and their distribution in terrestrial habitats of Iran. Soil Science & Plant Nutrition. 2013;59(4):535-547.
167. Sharifi RS, Khavazi K, Gholipouri A. Effect of seed priming with plant growth promoting Rhizobacteria (PGPR) on dry matter accumulation and yield of maize (*Zea mays* L.) hybrids. International Research Journal of Biochemistry and Bioinformatics. 2011;1(3):076-083.
168. Sharma K, Mitra D, Uniyal N, Chauhan A, Sarkar P. Study on plant hormone (indole-3-acetic acid) producing level and other plant growth promotion ability (PGPA) by *Asparagus racemosus* (L.) rhizobacteria. J Chem Pharm Res. 2016;8:995-1002.
169. Sharma SN, Maheshwari A. Expression patterns of DNA repair genes associated with priming small and large chickpea (*Cicer arietinum*) seeds. Seed Science and Technology. 2015;43(2):250-261.
170. Shrivastava P, Kumar R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi journal of biological sciences. 2015;22(2):123-131.
171. Singh N, Kumar S, Bajpai VK, Dubei RC, Maheshwari DK, Kang SC. Biological control of *Macrophomina phaseolina* by chemotactic fluorescent *Pseudomonas aeruginosa* PN1 and its plant growth promotory activity in chir-pine. Crop Prot. 2010;29:1142-1147
172. Singh N, Pandey P, Dubey RC, Maheshwari DK. Biological control of root rot fungus *Macrophomina phaseolina* and growth enhancement of *Pinus roxburghii* (Sarg.) by rhizosphere competent *Bacillus subtilis* BN1. World J Microbiol Biotechnol. 2008;24:1669-1679.
173. Smith DL, Subramanian S, Lamont JR, Bywater-Ekegard M. Signaling in the phytomicrobiome: breadth and potential. Front. Plant Sci. 2015b;6:709. Doi: 10.3389/fpls.2015.00709
174. Spaepen S, Versées W, Gocke D, Pohl M, Steyaert J, Vanderleyden J. Characterization of phenylpyruvate decarboxylase, involved in auxin production of *Azospirillum brasilense*. Journal of Bacteriology. 2007;189(21):7626-7633.
175. Štajner D, Mimica-Dukić N, Gasić O. Adaptability to drought in sugar beet cultivars. Biologia Plantarum. 1995;37(1):107.
176. Steenhoudt O, Vanderleyden J. *Azospirillum*, a free-living nitrogen-fixing bacterium closely associated with grasses: Genetics, biochemical and ecological aspects. FEMS Microbiology Reviews. 2000;24:487-506.
177. Sumner ME. Crop responses to *Azospirillum* inoculation. Adv Soil Sci. 1990;12:153-168.
178. Sunithakumari K, Devi SNP, Vasandha S. Zinc solubilizing bacterial isolates from the agricultural fields of Coimbatore, Tamil Nadu, India. Current Science. 2016;110:196-205.
179. Swarnalakshmi K, Yadav V, Tyagi D, Dhar DW, Kannepalli A, Kumar S. Significance of plant growth promoting rhizobacteria in grain legumes: Growth promotion and crop production. Plants. 2020;9(11):15-96.
180. Taiz L, Zeiger E. Plant Physiology. 5th Edition, Sinauer Associates Inc., Sunderland, 2010, 782.
181. Tak HI, Ahmad F, Babalola OO. Advances in the application of plant growth-promoting rhizobacteria in phytoremediation of heavy metals. Reviews of Environmental Contamination and Toxicology. 2013;223:33-52.
182. Tank N, Saraf M. Salinity-resistant plant growth promoting rhizobacteria ameliorates sodium chloride stress on tomato plants. Journal of Plant Interactions. 2010;5(1):51-58.
183. Taylor AG, Harman GE. Concepts and technologies of selected seed treatments. Annual review of phytopathology. 1990;28(1):321-339.
184. Thijs S, Sillen W, Rineau F, *et al*. Towards an enhanced understanding of plantmicrobiome interactions to improve phytoremediation: Engineering the metaorganism. Frontiers in Microbiology. 2016;7:1-15. https://doi.org/10.3389/fmicb.2016.00341.
185. Thijs S, Sillen W, Rineau F, Weyens N, Vangronsveld J. Towards an enhanced understanding of plant-microbiome interactions to improve phytoremediation: engineering the metaorganism. Frontiers in Microbiology. 2016;7:341.
186. Thijs S, Vangronsveld J. Rhizoremediation, in: Lugtenberg B. (Eds), Principles of Plant-Microbe Interactions. Springer, Cham., 2015. https://doi.org/10.1007/978 - 3 -319 -08575 -3_29.
187. Tien TM, Gaskins MH, Hubbell DH. Plant growth substances produced by *Azospirillum* brasilense and their effect on the growth of pearl millet (*Pennisetum americanum* L.). Applied and Environmental Microbiology. 1979;37:1016-e1024.

188. Turan M, Ekinci M, Yildirim E, GneȘ A, Karagz K, Kotan R, *et al*. Plant growth-promoting rhizobacteria improved growth, nutrient and hormone content of cabbage (*Brassica oleracea*) seedlings. Turk. J Agric. For. 2014;38:327-333. Doi: 10.3906/tar-1308-62
189. Turner TR, James EK, Poole PS. The plant microbiome. Genome biology. 2013;14(6):1-10.
190. Umesha S, Singh PK, Singh RP. Microbial biotechnology and sustainable agriculture, in: Singh RL, Monda S. (Eds.), Biotechnology for sustainable agriculture. Woodhead Publishing, Sawston, 2018, 185-205. https://doi.org/10.1016/B978-0-12-812160-3.00006-4.
191. Vacheron J, Desbrosses G, Bouffaud ML, Touraine B, Moënne-Loccoz Y, Muller D, *et al.* Plant growth-promoting rhizobacteria and root system functioning. Frontiers of Plant Science. 2013;4:356.
192. Vaid S, Kumar B, Sharma A, Shukla A, Srivastava P. Effect of Zn solubilizing bacteria on growth promotion and Zn nutrition of rice. Journal of Soil Science and Plant Nutrition. 2014;14:889-910.
193. Van Loon LC, Bakker PAHM, Pieterse CMJ. Systemic resistance induced by rhizosphere bacteria. Annu Rev Phytopathol. 1998;36:453-483.
194. Van Loon LC. Plant responses to plant growth-promoting rhizobacteria. In New perspectives and approaches in plant growth-promoting Rhizobacteria research. Springer, Dordrecht, 2007, 243-254.
195. Vance CP, Uhde-Stone C, Allan DL. Phosphorus acquisition and use: critical adaptations by plants for securing a non-renewable resource. New Phytologist. 2003;157(3):423-447.
196. Vardharajula S, Zulfikar Ali S, Grover M, Reddy G, Bandi V. Drought-tolerant plant growth promoting *Bacillus* spp.: Effect on growth, osmolytes and antioxidant status of maize under drought stress. Journal of Plant Interactions. 2011;6(1):1-14.
197. Vargas R, Detto M, Baldocchi DD, Allen MF. Multiscale analysis of temporal variability of soil CO_2 production as influenced by weather and vegetation. Global Change Biology. 2010;16(5):1589-1605.
198. Vasconcellos RLF, Cardoso EJBN. Rhizospheric streptomycetes as potential biocontrol agents of *Fusarium* and *Armillaria* pine rot and as PGPR for Pinus taeda. Bio Control. 2009;54:807-816.
199. Vejan P, Abdullah R, Khadiran T, Ismail S, Nasrulhaq Boyce A. Role of plant growth promoting rhizobacteria in agricultural sustainability A review. Molecules. 2016;21(5):573.
200. Vurukonda SSKP, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. Microbiological research. 2016;184:13-24.
201. Walsh UF, Morrissey JP, O'Gara F. *Pseudomonas* for biocontrol of phytopathogens: from functional genomics to commercial exploitation. Current Opinion in Biotechnology. 2001;12(3):289-295.
202. Warren JE, Bennett MA. Bio-osmopriming tomato (*Lycopersicon esculentum* Mill.) seeds for improved stand establishment. Seed science and technology. 1999;27(2):489-499.
203. Young JPW, Mutch LA, Ashford DA, Zézé A, Mutch KE. The molecular evolution of host specificity in the *Rhizobium*-legume symbiosis. In 'Genes in the Environment'. The Fifteenth Special Symposium of the British Ecological Society, Oxford, UK, Blackwell Publishing, 2001 Sep, 245-257.
204. Zahran HH. Rhizobia from wild legumes: diversity, taxonomy, ecology, nitrogen, 2001.
205. Zahran HH. Rhizobia from wild legumes: diversity, taxonomy, ecology, nitrogen fixation and biotechnology. Journal of biotechnology. 2001;91(2-3):143-153.
206. Zaidi A, Khan M, Ahemad M, Oves M. Plant growth promotion by phosphate solubilizing bacteria. Acta microbiologica et immunologica Hungarica. 2009;56(3):263-284.
207. Zehnder G, Kloepper J, Yao C, Wei G. Induction of systemic resistance against cucumber beetles (Coleoptera: Chrysomelidae) by plant growth-promoting rhizobacteria. J Econ Entomol. 1997;90:391-396.
208. Zhang Y, Gao X, Shen Z, Zhu C, Jiao Z, Li R, Shen Q. Pre-colonization of PGPR triggers rhizosphere microbiota succession associated with crop yield enhancement. Plant and Soil. 2019;439(1):553-567.
209. Zulueta-Rodríguez R, Hernández-Montiel LG, Murillo-Amador B, Rueda-Puente EO, Capistrán LL, Troyo-Diéguez E, *et al*. Effect of hydropriming and biopriming on seed germination and growth of two Mexican fir tree species in danger of extinction. Forests. 2015;6(9):3109-3122.