Impact of Plant Growth Promoting Rhizobacteria on Crop Production

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Abstract: Rhizospheric soils of crop plants have more flora and fauna due to availability of more organic compound, macronutrient and micronutrient. Rhizobacteria that exert beneficial effects on plant growth and development are referred to as Plant Growth Promoting Rhizobacteria (PGPR). Plant growth promoting rhizobacteria is a group of free living soil bacteria, which have ability to promote growth and yield of crop plant by direct and indirect mechanism. PGPR is generally two type, one is colonies inside plant cells that called intracellular PGPR (iPGPR) and other colonies out side plant in rhizosphere that called extracellular PGPR (ePGPR). This review generally focused on direct and indirect mechanism of PGPR. Direct mechanism of plant growth promotion may involve the synthesis of substances by the bacterium or facilitation of the uptake of nutrients from the environment. The indirect mechanism of plant growth occurs when PGPR lessen or prevent the deleterious effects of plant pathogens on plants by production of inhibitory substances or by increasing the natural resistance of the host. The search for PGPR and investigation of their mode of action are increasing at a rapid use as commercial biofertilizers. The mode of action and practical application of PGPR in crop production are the major focus of this review.

Key words: PGPR, rhizosphere, IAA, phosphate solubilization, growth, yield

INTRODUCTION

Bacteria able to colonize plant root systems and promote plant growth are referred to as Plant Growth Promoting Rhizobacteria (PGPR) (Kloepper and Schroth, 1978). PGPR can affect plant growth either indirectly or directly; indirect promotion of plant growth occurs when PGPR lessen or prevent the deleterious effects of one or more phytopathogenic organisms; while direct promotion of plant growth by PGPR involves either providing plants with a compound synthesized by the bacterium or facilitating the uptake of certain nutrients from the environment (Glick, 1995). Thus, in the broadest sense, PGPR include the N2-fixing rhizobacteria that colonize the rhizosphere, providing N to plants, including the rhizobia of the well-characterized legume-rhizobia symbiosis. Regardless of the mechanisms of plant growth promotion, PGPR must colonize the rhizosphere around the roots, the rhizoplane

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PGPR and Their Hosts: Rhizospheric and Endophytic Region

For PGPR to have a beneficial effect on plant growth via an enhancement of the nutrient status of their host, there obviously needs to be an intimate relationship between the PGPR and the host plant. However, the degree of intimacy between the PGPR and the host plant can vary depending on where and how the PGPR colonizes the host plant. Relationships between PGPR and their hosts can be categorized into two levels of complexity: (1) Rhizospheric and (2) Endophytic.

Rhizospheric Region

The rhizosphere can be defined as any volume of soil specifically influenced by plant roots and/or in association with roots and hairs and plant-produced material (Andrade et al., 1997; Mahafee and Kloepper, 1997; Bringham et al., 2001). This space includes soil bound by plant roots, often extending a few mm from the root surface (Bringham et al., 2001) and can include the plant root epidermal layer (Mahafee and Kloepper, 1997). Plant exudates in the rhizosphere, such as amino acids and sugars, provide a rich source of energy and nutrients for bacteria, resulting in bacterial populations greater in this area than outside the rhizosphere. Extracellular PGPR (ePGPR) which is existing in the rhizosphere. ePGPR increase plant growth through a variety of mechanisms; these include genera such as Bacillus, Pseudomonas, Burkholderia, Erwinia, Caulobacter, Serratia, Arthrobacter, Micrococcus, Flavobacterium, Chromobacterium, Agrobacterium, Hyphomicrobiun and free-living nitrogen-fixing bacteria (Azotobacter and Azospirillum) (Foster et al., 1983; Prithiviraj et al., 2003; Gray and Smith, 2005). Most rhizosphere organisms occur within 50 mm of root surface and populations within 10 mm of root surface may reach 1.2×10^9 cells cmK^-3 or 10^5-10^12 microbial cells g K^-1 soil. Despite large numbers of bacteria in the rhizosphere, only 7-15% of the total root surface is generally occupied by microbial cells (Foster et al., 1983; Pinton et al., 2001; Gray and Smith, 2005).

Endophytic Region

Rhizobacteria that establish inside plant roots, forming more intimate associations, are endophytes. To aid in this conceptualization, simple terms have been adopted: intracellular PGPR-(iPGPR) bacteria residing inside plant cells, producing nodules and being localized inside those specialized structures. These include a wide range of soil bacteria forming less formal associations than the rhizobia-legume symbiosis; endophytes may stimulate plant growth, directly or indirectly and include the rhizobia. Soil bacteria in the genera Rhizobium,
Bradyrhizobium, Sinorhizobium, Azorhizobium, Mesorhizobium and Alorhizobium, belonging to the family Rhizobiaceae, invade plant root systems and form root nodules (Martinez-Romero and Wang, 2000). Collectively they are often referred to as rhizobia. These iPGPR are mostly Gram-negative and rod-shaped, with a lower proportion being Gram-positive rods, cocci and pleomorphic forms. The primary mechanism by which rhizobia increase plant growth is N₂-fixation.

Root Colonization by PGPR

Successful colonization and persistence in the plant rhizosphere are required for PGPR to exert their beneficial effect on plants (Elliott and Lynch, 1984). Rhizosphere colonization is also considered to be a crucial step in the application of microorganisms for beneficial purposes such as biofertilization, phytostimulation, bicontrol and phytoremediation (Lugtenberg et al., 2001). Root colonization, which is a complex process, is under the influence of various parameters such as bacterial traits, root exudates, biotic and abiotic factors (Benizri et al., 2001). The method chosen for studying the traits associated with root colonization depends on the objective and different approaches and techniques have been used to quantify and identify inoculated strains on the host plant (Lugtenberg et al., 2001). The major rhizobacterial genera include free living and symbiotic bacterial species belonging to Acetobacter, Arthrobacter, Azospirillum, Azotobacter, Bacillus, flavobacter, Pseudomonas, Proteus, Rhizobium, Serratia, Xanthomonas and other (Glick, 1995).

MODE OF ACTION OF PGPR AS BIOFERTILIZERS

PGPR inoculant currently commercialized as novel solution for plant growth enhancements through direct, indirect mechanism and combination of mode of action.

The direct mechanisms of plant growth promotion may involve the synthesis of substances by the bacterium or facilitation of the uptake of nutrients from the environment (Glick et al., 1999). The direct growth promoting mechanisms are as follows (1) Biological nitrogen fixation (2) Increasing the availability of nutrients in the rhizosphere (solubilization of phosphorus, facilitated absorption of iron by production of siderophores) and (3) inducing of phytohormones production such as auxins, cytokinins, gibberellins (Kloepper et al., 1989; Glick, 1995; Glick et al., 1999; Vessev, 2003; Patten and Glick, 2002). The indirect mechanism of plant growth occurs when PGPR lessen or prevent the deleterious effects of plant pathogens on plants by production of inhibitory substances or by increasing the natural resistance of the host (Handelsman and Stabb, 1996; Nehl et al., 1996; Carteiaux et al., 2003). The indirect mechanisms of plant growth promotion by PGPR include (1) antibiotic production (2) depletioin of iron from the rhizosphere (3) synthesis of antifungal metabolites (4) production of fungal cell wall lysing enzymes (5) competition for sites on roots and (6) induced systemic resistance (Weller and Cook, 1986; Durne et al., 1993; Kloepper et al., 1988; Liu et al., 1995; Glick et al., 1999).

Direct Mechanism

Biological Nitrogen Fixation

Symbiotic Nitrogen Fixation

Legume and their rhizobia are often introduced to agricultural ecosystems to improve soil fertility and farming systems flexibility (Brockwell and Bottomley, 1995; Sessitsch et al., 2002). Nitrogen is known to be an essential nutrient for plant growth and development. Intensive farming practices that achieve high yield require chemical fertilizers, which are not
costly but may also create environmental problems. The extensive use of chemical fertilizers in agriculture is currently under debate due to environmental concern and fear for consumer health. Consequently, there has recently been growing level of interest in environmentally and friendly sustainable agricultural practices and organic farming system (Ribgy and Caceres, 2001; Lee and Song, 2007). Increasing and extending the role of biofertilizers such as rhizobium would reduce the need for chemical fertilizers and decrease adverse environmental effects. Therefore, in the development and implementations of sustainable agriculture techniques, biofertilization is great importance in alleviating environmental pollution and the deterioration of nature (Elkoca et al., 2008).

*Rhizobium* symbiosis with legumes species is of special importance, producing 50% of 175 million tons of total biological nitrogen fixation annually worldwide (Sarioglu et al., 1993). Chickpea and *Rhizobium leguminosarum* subsp. *ciceri* association annually produce up to 176 kg N ha⁻¹ depending on cultivar, bacterial strain and environmental factors (Rupela and Saxena, 1987; Beck et al., 1991, Yadav et al., 2010). However, Rhizobium species producing nodules in chickpea are specific only to this species and thus inoculation with effective strains is advised in soils with no or weak bacterial presence (Rupela and Saxena, 1987).

Nitrogen is one of the most common nutrients required for plant growth and productivity as it forms an integral part of proteins, nucleic acids and other essential biomolecules (Boekman, 1997). More than 80% of nitrogen is present in the atmosphere, but is unavailable to plants. It needs to be converted into ammonia, a form available to plants and other eukaryotes. Biological nitrogen fixation involves the conversion of nitrogen to ammonia by microorganisms using a complex enzyme system identified as nitrogenase (Kim and Rees, 1994). Biological nitrogen fixation fixes about 60% of the earth’s available nitrogen and represents an economically beneficial and environmentally sound alternative to chemical fertilizers (Ladiha and Kundu, 1997). Plant growth-promoting rhizobacteria that fix nitrogen in non-leguminous plants are diazotrophs that form a non-obligate interaction with the host (Olick et al., 1999). The nitrogen fixation in chickpea is performed by two species of genus *Mesorhizobium*, *M. ciceri* (Nour et al., 1994) and *M. mediterraneum* (Nour et al., 1995). The symbiosis between chickpea and its specific rhizobia has been recently studied in several countries-Tunisia (Aoutani et al., 2001), Morocco (Maatallah et al., 2002), Canada (Kyei-Boahen et al., 2002), Turkey (Igen et al., 2002) and Portugal (Laranjo et al., 2001, 2002) because of the promising agricultural usefulness of this crop as a grain legume for human and animal nutrition and because of the interesting extreme host specificity of its rhizobia. The most studied and longest exploited FGPR are the rhizobia (including the *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Rhizobium* and *Sinorhizobium*) for their ability to fix N₂ in their legume hosts. The root nodules bacteria in the *α-Proteobacteria* are contained in five families: Rhizobiaceae, Phyllobacteriaceae, Bradyrhizobiaceae, Hyphomicrobiaceae and Methylobacteriaceae as defined by their 16S rDNA sequence analysis (Sawada et al., 2003). Commercial rhizobia inoculants for use on legume crops were first introduced in the 1890s (Fred et al., 1932).

symbioses expanded rapidly in the 1970s and 1980s and their ability to produce nodules on sea buckthorn (Hippophae rhamnoides) (Oremus, 1980) solidified a new line of dynamic research. Jarvis et al. (1997) described the genus *Mesorhizobium* (rhizobia phylogenetically intermediate between the genera *Bradyrhizobium* and *Rhizobium*) to include root nodule bacteria that had considerable phenotypic and genotypic differences to the other root nodule bacteria genera. In case of lentil, seed treatment with *Rhizobium leguminosarum*, increased seedling height, root nodules mass and shoot biomass. Similarly, nodulation was found to be improved in peanut by an array of *Rhizobium* species (Dey et al., 2004). Similarly data were reported by Yanni (1992), the response of lentil, chickpea and pea upon with *Rhizobium*.

**Non-Symbiotic Nitrogen Fixation**

*Nodobacter* species (*Azotobacter chroococcum* and *Azotobacter vinelandii*) and *Azospirillum* species (Mirza et al., 2001) are free living, heterotrophic diazotrophs that fix nitrogen in non leguminous plant such as wheat, rice and others crops. Yield of rice in field trials increased significantly 20% with applications of *Azotobacter* (Yanni and El-Fattah, 1999). One of the best studied diazotrophs for nitrogen fixation is *Azospirillum* sp. isolated from nitrogen-poor soils by Beijerinck in 1925 (Holguin et al., 1999). Members of this bacterial genus are capable of fixing atmospheric nitrogen and of promoting plant growth. A mixed inoculum of *Staphylococcus* and *Azospirillum* promoted the nitrogen fixing activity of *Azospirillum* (Holguin and Bashan, 1997). Combined inoculation of *A. brasilense* with *Pseudomonas striata* significantly increased grain yield, nitrogen and phosphorus uptake of sorghum (Alagawadi and Gaur, 1992). Oliveira et al. (1997) demonstrated that co-inoculation of clover with a mixture of *A. brasilense* Sp7 and *Rhizobium* sp. resulted in increased acetylene reduction, nodulation and shoot dry weight of plants. Endophytic bacteria that colonize the interiors of plant tissues such as roots, stem and leaves and are able to fix nitrogen are also found to be beneficial for plant growth (James et al., 1997). Some experiments have involved the colonization of para-nodules on associations involving wheat and various diazotrophs (Chen et al., 1993; Gantar and Elhai, 1999; Tehan et al., 1991; Youssef et al., 1998), *Azorhizobium caulinodans* and rice (Christiansen-Weniger, 1996), *Azotobacter nigricans* and rape (Koval’skaya et al., 2001) and *Azospirillum* sp. and maize (Christiansen-Weniger and Vanderleyden, 1994).

**Increasing the Availability of Nutrients in the Rhizosphere**

There is ample evidence that the mode of action of many PGPR is by increasing the availability of nutrients for the plant in the rhizosphere (Glick, 1995; Vessey, 2003). The method by which these increases take place involve solubilization of unavailable forms of nutrients, siderophore production and ammonia production which helps facilitate the transport of certain nutrients.

**Solubilization of Phosphorus**

Phosphorus is second only to nitrogen in mineral nutrients most commonly limiting the growth of terrestrial plants. Ironically, soils may have large reserves of total P, but the amounts available to plants is usually a tiny proportion of this total (Stevenson and Cole, 1999). Indian soils are normally deficient in available phosphorus even though the bound component may be sufficient abundant (Johri et al., 2003). Therefore, the use of PSM (phosphate solubilizing microorganism) is very common. However, immobilization of added
Fig. 1. Phosphate solubilizing (a) bacteria _Pseudomonas aeruginosa_ strain BHUPSB01 (accession number GU124822) and (b) _Burkholderia cepacia_ strain BHUPSB03 (accession number GU124830) strain showing halo zone around bacterial colony on Pikovskaya agar media.

Phosphorus in soils is a serious problem (Gaind et al., 2000). The low availability of P to plants is because the vast majority of soil P is found in insoluble forms and plants can only absorb P in two soluble forms, the monobasic (H₂PO₄⁻) and the diabasic (HPO₄²⁻) ions. _In vitro_ phosphate solubilizing bacteria _Pseudomonas aeruginosa_ strain BHUPSB01 (accession number GU124822), _P. aeruginosa_ strain BHUPSB02 (GU124826) and _Pseudomonas putida_ strain BHUPSB04 (accession number GU124834), _Burkholderia cepacia_ BHUPSB03 (GU124830), _Paenibacillus polymyxa_ BHUPSB16 (GU124833), _P. polymyxa_ BHUPSB17 (GU124838) and _Bacillus subtilis_ BHUPSB13 (GU124812 showed halo zone around bacterial colony on Pikovskaya agar media (Gaur, 1990). This halo zone showed to solubilization of tricalcium phosphate in soluble form due to production of organic acid (Fig. 1a, b).

The solubilization of P in the rhizosphere is the most common mode of action implicated in PGPR that increase nutrient availability to host plants (Richardson, 2001). Examples of recently studied associations include _Azotobacter chroococcum_ and wheat (Kumar and Narula, 1999), _Bacillus circulans_ and _Cladosporium herbarum_ and wheat (Singh and Kapoor, 1999), _Bacillus_ sp. and five crop species (Pal, 1998), _Enterobacter agglomerans_ and tomato (Kim and McDonald, 1998), _Pseudomonas chlororaphis_ and _P. putida_ and soybean (Cattelan et al., 1999), _Rhizobium_ sp. and _Bradyrhizobium japonicum_ and radish (Antoun et al., 1998) and _Rhizobium leguminosarum_ bv. _Phaseoli_ and maize (Chabot et al., 1998). Phosphate-solubilizing bacteria are common in rhizospheres (e.g., Nautiyal et al., 2000; Vazquez et al., 2000). However, the ability to solubilize P by no means indicates that a rhizospheric bacterium will constitute a PGPR. For example, Cattelan et al. (1999) found only two of five rhizospheric isolates positive for P solubilization actually had a positive effect on soybean seedling growth. Likewise, not all P-solubilizing PGPR increase plant growth by increasing P availability to the hosts. For example, Freitas et al. (1997) found a number of P-solubilizing _Bacillus_ sp. isolates and a _Xanthomonas maltophilia_ isolate from canola (_Brassica napus_ L) rhizosphere which had positive effects on plant growth, but no effects on P content of the host plants.
Phosphate solubilizing bacteria are also known to increase phosphorus uptake resulting in better growth and higher yield of crop plants (Alagawadi and Gaur, 1988; Gaur et al., 2004; Verma et al., 2010). These microorganisms are bacteria and fungi that inhabit the rhizosphere (Azcon et al., 1976; Bowen and Rovira, 1999). Most soil bacteria can solubilize insoluble phosphates, particularly active are those that belong to the genera *Pseudomonas*, *Enterobacter* and *Bacillus* as well as some soil fungi, *Penicillium* and *Aspergillus* (Domey and Lipmann, 1988; Pargiri and Bezbearah, 1990; Rao, 1992; Rokade and Patil, 1993; Whitlaw, 2000; Yadav et al., 2010). Some researchers prefer to use fungal P-solubilizers arguing that bacterial strains can lose their ability to solubilize P after several cycles of in vitro culture (Whitlaw, 2000), but this point is quite controversial.

**Facilitated Absorption of Iron by Production of Siderophores**

Siderophores are low-molecular weight iron-binding molecules that are synthesized by many microorganisms under low-iron conditions (Neilands, 1981). Microbial siderophores may stimulate plant growth directly by increasing the availability of iron in the soil surrounding the roots (Klopper et al., 1980). Marschner and Römheld (1994) reported that plants may also utilize siderophores synthesized by microorganisms colonizing the rhizosphere, this would be a source of soluble iron for the host plant. Plants such as sorghum, oats, peanut, cotton, cucumber and sunflower demonstrated the ability to use radiolabelled microbial siderophores as a sole source of iron (Crowley et al., 1988; Bar-Ness et al., 1991; Clute et al., 1984; Jurkevitch et al., 1986; Wang et al., 1993). Growth of cucumber in the presence of microbial siderophores resulted in increased plant biomass and chlorophyll content (Isman and, 1998). Uptake of microbial siderophores by plants has been attributed to microorganisms living.

Iron is an essential nutrient of plants, but it is relatively insoluble in soil solutions. Plant roots prefer to absorb iron as the more reduced ferrous (Fe$^{2+}$) ion, but the ferric (Fe$^{3+}$) ion is more common in well aerated soil although it is easily precipitated in iron-oxide forms (Salisbury and Ross, 1992). However, there is a controversy as the significance of bacterial Fe$^{3+}$ siderophore uptake to the iron nutrition of plants. While some believe that there contribution of these siderophores to the overall iron requirements of plants is small (Glick, 1995), other suggest an important role (Dujsiff et al., 1994), even a vital role, especially in calcareous soils (Mossalha et al., 2000). Bar-Ness et al. (1992), who had earlier supported the concept of bacterial siderophore uptake by plants (Bar-Ness et al., 1991), concluded that two bacterial siderophores (pseudobactin and ferrioxamine B) were inefficient as iron sources for plants and that rhizospheric siderophore-producing bacteria can be in competition with the plant for iron. In fact, the vast majority of research on microbial siderophores in the rhizosphere is associated with their biocontrol activities due to their competitive effects with plant pathogens (Huffman et al., 1994).

**Production of Phytohormones**

One of the direct mechanisms by which PGPR promote plant growth is by production of plant growth regulators or phytohormones (Glick, 1995). Frankenberger and Arshad (1995) have discussed in detail the role of auxins, cytokinins, gibberellins, ethylene and Abscisic Acids (ABA) which, when applied to plants, help in increasing plant yield and growth. Microbial production of individual phytohormones such as auxins and cytokinins has been reviewed by various authors over the last 20 years (Pilet et al., 1979; Hartmann et al., 1983; Fallik et al., 1988; Barbieri and Galli, 1993; Patten and Glick, 1996, 2002).
Auxins

The production of an active substance by the fungi Rhizopus stolonifer and Absidia ramosa was identified to be auxin by Thimmann (1935), following induction of curvature in Avena as demonstrated by Nielsen (Frankenberger and Arshad, 1995). Various authors have identified the production of indole-3-acetic acid by microorganisms in the presence of the precursor tryptophan or peptone. Some of the plant responses to auxin are as follows: (1) cell enlargement (2) cell division (3) root initiation (4) root growth inhibition (5) increased growth rate (6) phototropism (7) geotropism and (8) apical dominance (Frankenberger and Arshad, 1995). Eighty percent of microorganisms isolated from the rhizosphere of various crops have the ability to produce auxins as secondary metabolites (Kampert et al., 1975; Loper and Scroth, 1986). Bacteria belonging to the genera Azospirillum, Pseudomonas, Xanthomonas and Rhizobium as well as Alcaligenes faecalis, Enterobacter cloacae, Acetobacter diazotrophicus and Bradyrhizobium japonicum have been shown to produce auxins which help in stimulating plant growth (Patten and Glick, 1996). Various metabolic pathways such as (1) indole-3-acetamide pathway (2) indole-3-pyruvic acid pathway (3) tryptophan side chain pathway (4) tryptamine pathway and (5) indole-3-acetonitrile pathway are involved in the production of IAA. Phytopathogens such as Agrobacterium tumefaciens, A. rhizogenes and P. syringae pv. savastanoi synthesize IAA via the indole-3-acetamide pathway (Liu et al., 1982; Offringa et al., 1986). Synthesis of IAA by Rhizobium sp. in the presence and absence of tryptophan has also been demonstrated (Kittel et al., 1989; Verma et al., 2010). Bent et al. (2001) reported that the production of indole compounds by three different strains, Paenibacillus polymyxa L6, P. polymyxa Pw-2 and Pseudomonas fluorescens M20 increased in concentration with increasing concentrations of tryptophan (0-200 mg mL\(^{-1}\)) at different times. Reports by Askar et al. (2002) showed that PGPR strains produced 24.6 μg mL\(^{-1}\) of auxins in the presence of the precursor L-tryptophan in the medium, which was 184-fold more than that without L-tryptophan. Example of phytohormones producing bacteria under in vitro condition (Table 1). The isolates of Bacillus, Pseudomonas and Azotobacter produced IAA, whereas only 85.7% of Rhizobium was able to produce IAA. Production of ammonia was commonly detected in the isolates of Bacillus (95.0%) followed by Pseudomonas (94.2%), Rhizobium (74.2%) and Azotobacter (45.0%) (Joseph et al., 2007). Higher level of IAA production by Pseudomonas was recorded by other workers (Xie et al., 1996). Ahmad et al. (2005) has reported that bacterial isolates were tested for the production of indole acetic acid (IAA) in a medium with 0, 1, 2 and 5 mg mL\(^{-1}\) of tryptophan. Production of IAA in fluorescent Pseudomonas isolates increased with an increase in tryptophan concentration from 1 to 5 mg mL\(^{-1}\) in the majority of isolates. IAA production in Azotobacter isolates has been reported by other researchers (Gonzalez Lopez and Vela, 1981; Nieto and Frankenberger, 1989; Khalid et al., 2001). IAA production has reported in Azospirillum sp. under in vitro condition (Dobbelaere et al., 2001; Lambrecht et al., 2000) (Table 1).

Other Phytohormones

Production of other phytohormones by biofertilizing-PGPR has been identified, but not nearly to the same extent as bacteria which produce IAA. Cytokinins are a class of phytohormones which are known to promote cell divisions, cell enlargement and tissue expansion in certain plant parts (Salisbury, 1994). Researchers have recently begun to identify cytokinin production by PGPR. Gibberellins (gibberellic acid, GA) are a class of phytohormones most commonly associated with modifying plant morphology by the extension of plant tissue, particularly stem tissue (Salisbury, 1994). Evidence of GA production by PGPR is rare, however Gutierrez-Manero et al. (2001) provide evidence that
four different forms of GA are produced by Bacillus pumilus and Bacillus licheniformis (Table 1). Inoculation of alder (Alnus glutinosa) with these PGPR could effectively reverse a chemically induced inhibition of stem growth. Although this is not strong evidence of GA production being a common method of growth promotion by PGPR, it does suggest that it may have a role and indicates that more research is this area is warranted. Ethylene is the only gaseous phytohormone. It is also known as the ‘wounding hormone’ because its production in the plant can be induced by physical or chemical perturbation of plant tissues (Salisbury, 1994). Among its myriad of effects on plant growth and development, ethylene production can cause an inhibition of root growth. Glick et al. (1998) put forward the theory that the mode of action of some PGPR was the production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an enzyme which could cleave ACC, the immediate precursor to ethylene in the biosynthetic pathway for ethylene in plants. They submitted that ACC deaminase activity would decrease ethylene production in the roots of host plants and result in root lengthening. Subsequently, Glick’s research program has provided numerous empirical studies with wild-type and genetically modified PGPR to support their theory (Holguin and Glick, 2001; Li et al., 2000; Mayak et al., 1999; Saleh and Glick, 2001; Shah et al., 1998; Wang et al., 2000). In some cases, the growth promotion effects of ACC deaminase-producing PGPR appear to be best expressed in stressful situations such as flooded (Griechko and Glick, 2001) or heavy metal-contaminated soils (Burd et al., 1998).

### The Indirect Mechanism

The indirect mechanism of plant growth occurs when PGPR lessen or prevent the deleterious effects of plant pathogens on plants by production of inhibitory substances or
Table 2: Biological control by PGPR against certain diseases, pathogens and insects in different crops

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<tr>
<th>Crop</th>
<th>Disease/pathogen/insect</th>
<th>PGPR</th>
<th>References</th>
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<tr>
<td>Barley</td>
<td>Powdery mildew</td>
<td><em>B. subtilis</em></td>
<td>Schodeck et al. (1980)</td>
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<td><em>Sclerotium rolfsii</em></td>
<td><em>Pseudomonas cepacia</em></td>
<td>Fridlender et al. (1993)</td>
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<td>Carnation</td>
<td><em>Fusarium</em> wilt</td>
<td><em>Pseudomonas sp.</em> (WCS 417)</td>
<td>Van Peer et al. (1991)</td>
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<td>Cotton</td>
<td>Damping off</td>
<td><em>Pseudomonas fluorescens</em></td>
<td>Howell and Stipanovic (1979, 1980)</td>
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<td><em>Methylobacterium incognita</em></td>
<td><em>B. subtilis</em></td>
<td>Sikora (1998)</td>
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<td><em>Helicoverpa armigera</em></td>
<td><em>Pseudomonas cepacia</em></td>
<td>Fridlender et al. (1993)</td>
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<td><em>M.arenaria</em></td>
<td><em>Pseudomonas gledioli</em></td>
<td>Quingwen et al. (1998)</td>
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<td>Cucumber</td>
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<td><em>Pseudomonas putida</em> (89B-27),</td>
<td>Kloepper et al. (1993)</td>
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<td>Bacterial wilt</td>
<td><em>Sorotinia marcescens</em> (90-166)</td>
<td>Kloepper et al. (1993)</td>
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<td><em>Pseudomonas putida</em> (89B-27),</td>
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<td>Cucumber</td>
<td>Bacterial angular leaf spot</td>
<td><em>P. putida</em> (89B-27), <em>Flavonoma oryzihabitan</em></td>
<td>Kloepper et al. (1993)</td>
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<td><em>INR-5, S. marcescens</em> (90-166), <em>Bacillus pumilus</em> (INR-7)</td>
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<td>Cucumber mosaic virus</td>
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<td>Cucumber</td>
<td>Striped Cucumber beetle</td>
<td><em>P. putida</em> (89B-27), <em>Flavonoma oryzihabitan</em> (INR-5)</td>
<td>Kwach et al. (1997)</td>
</tr>
<tr>
<td>Green</td>
<td><em>Aspergillus sp.</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Sindhu et al. (1999)</td>
</tr>
<tr>
<td>gram</td>
<td><em>Curvularia sp.</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Sindhu et al. (1999)</td>
</tr>
<tr>
<td></td>
<td><em>Fusarium oxysporum</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Sindhu et al. (1999)</td>
</tr>
<tr>
<td></td>
<td><em>Rhizococenia solani</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Sindhu et al. (1999)</td>
</tr>
<tr>
<td>Mung bean</td>
<td>Root rot. Root knot</td>
<td><em>P. aeruginosa, B. subtilis</em></td>
<td>Siddiqui et al. (2001 a, b)</td>
</tr>
<tr>
<td>Rice</td>
<td>Rice sheath blight</td>
<td><em>Streptomycyes sp.</em> and <em>Bacillus cereus</em> in combination with <em>P. fluorescens</em> and <em>Burkholderia</em></td>
<td>Sung and Chung (1997)</td>
</tr>
<tr>
<td>Rice</td>
<td>Rice sheath blight</td>
<td><em>Combination of P. fluorescens</em> strain F1 and Fp7</td>
<td>Nandakumar (1998)</td>
</tr>
<tr>
<td>Rice</td>
<td><em>Rhizococenia solani</em></td>
<td><em>P. fluorescens Strains F1 and Fp7</em></td>
<td>Vidhyasekaran and Muthumilan (1999)</td>
</tr>
<tr>
<td>Blue mold</td>
<td><em>S. marcescens</em> 90-1 16, <em>B. pumilus</em> SE 34, <em>Ps. fluorescens</em> 89-8-6 1, <em>B. subtilis</em> T4, <em>B. pasteurii</em> C-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
<td>Tomato mottle virus</td>
<td><em>B. subtilis strain IN 937b</em></td>
<td>Murphy et al. (2000)</td>
</tr>
<tr>
<td>Wheat</td>
<td>Take till disease</td>
<td><em>Bacillus, Pseudomonas, Penicillium, Bacillus</em></td>
<td>Renwick et al. (1991)</td>
</tr>
<tr>
<td></td>
<td><em>B. lycopersici</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Pierson and Weller (1994)</td>
</tr>
<tr>
<td></td>
<td><em>Fusarium oxysporum</em></td>
<td><em>Pseudomonas sp.</em></td>
<td>Pierson and Weller (1994)</td>
</tr>
</tbody>
</table>

by increasing the natural resistance of the host. Control of phytopathogenic microorganisms by releasing siderophores, B-1,3-glucanase, chitinases, antibiotics, fluorescent pigment and cyanide (Scher and Baker, 1982; Veisard et al., 1989; Catellan et al., 1999; Pal et al., 2001).

Many rhizobacteria including fluorescent *Pseudomonas* secrete a variety of antifungal molecule under in vitro and in situ conditions (Cock et al., 1995). There are several reports in vitro antagonism of pathogenic fungi and field performance by bacteria recovered from the rhizosphere of plants in India (Johri et al., 1997). Some important plant disease controlling bacteria have been depicted in Table 2. *Pseudomonas aeruginosa* strain BHUPSBO1 (accession number GU124822), *P. aeruginosa* strain BHUPSBO2 (GU124826) and *Pseudomonas putida* strain BHUPSBO4 (accession number GU124834), *Burkholderia cepacia* BHUPSBO3 (GU124830), *Paenibacillus polymyxa* BHUPSBO16 (GU124833), *P. polymyxa* BHUPSBO7 (GU124838) and *Bacillus subtilis* BHUPSBO13 (GU124812 showed antagonistic against phytopathogenic fungi *Fusarium oxysporum* and *Rhizococenia solani* (Fig. 2, 3).

The rhizosphere and root zone of tea (Camellia sinensis) is a good habitat for PGPR strains represented by *Bacillus*, *Proteus* and *Pseudomonas*, inhibitory to phytopathogenic fungi in vitro, viz., *Fusarium oxysporum* f. sp. *lycopersici*, *Fusarium oxysporum* f. sp.
Fig. 2: Antagonistic activity of *Pseudomonas aeruginosa* strain BHUPSB01 (accession number GU124822) against *Fusarium oxysporum*

![Image](image1.png)

Fig. 3: Antagonistic activity of *Pseudomonas putida* strain BHUPSB04 (accession number GU124834) against *Rhizoctonia solani*

![Image](image2.png)

*cv. ciceri, F. udum, F. solani, F. moniliformae, F. semitectum, Fomes lamiensis and Ustulina zonata* (Kumar-Dileep and Bezbarah, 1996; Kumar and Bezbarah, 1997). Suppression of soil borne plant pathogens by siderophore producing pseudomonads was observed (Bakker et al., 1986, 1987; Loper, 1988) and the wild type strain was more effective in suppressing disease compared to non-siderophore-producing mutants. *Pseudomonas* sp. strains MRS23 and CRP55b showed varying diameters of inhibition zones of the four pathogenic fungi, *Aspergillus* sp. *F. oxysporum*, *P. aphanidermatum* and *R. solani* in the plating media (Kings B, PDA and NB) (Goel et al., 2002). *Pseudomonas* strains MRS23 and CRP55b inhibited the growth of pathogenic fungi, i.e., *Aspergillus* sp. *Fusarium oxysporum* f. sp. *ciceri* and *Rhizoctonia solani* under culture condition (Goel et al., 2002). Like this, several species of pseudomonas, viz. *P. fluorescens*, *P. putida*, *P. cepacia* *(Burkholderia cepacia)* and *P. aeruginosa* isolated from plant tissue or soil have been reported as potential biocontrol agents of several phytopathogenic fungi (Duffy et al., 1996; Goel et al., 2000). Saukia et al. (2003, 2004, 2005, 2009) reported that *Pseudomonas fluorescens* I-94 (PI-94) and
P. fluorescens (Pf4-92) strains that were isolated from rhizosphere soil of chickpea showed Induced Systemic Resistance (ISR) against fusarium wilt of chickpea and charcoal rot (Srivastava et al., 2001). Earlier studies indicated that shoot and root lengths were significantly increased in P. fluorescens treated chickpea plants and the reduction in disease severity was more pronounced when chemical inducers were applied with P. fluorescens (Saikia et al., 2003). Root rot disease in mung bean has controlled by Pseudomonas aeruginosa, Bacillus subtilis (Siddhichi et al., 2001) (Table 2).

Siderophore production is an important feature for the suppression of plant pathogens and promotion of plant growth. Fluorescent siderophore production was observed as a mechanism of biocounter of bacterial wilt disease in the fluorescent pseudomonads RBL 101 and RSI 125. Press et al. (2001) reported the catechol siderophore biosynthesis gene in Serratia marcescens 90-166 and associated with induced resistance in cucumber against anthracnose. Pseudomonads also produce two other siderophores, pyochelin and its precursor salicylic acid and pyochelin is thought to contribute to the protection of tomato plants from Pythium by Pseudomonas aeruginosa?NSK2 (Buyzens et al., 1996). Howell and Stipanovic (1979, 1980) has been reported damping off disease in cotton controlled by Pseudomonas fluorescens. Different environmental factors can also influence the quantity of siderophores produced (Duffy and Défago, 1999).

EFFECT OF PGPR ON PLANT GROWTH AND YIELDS

Table 3 lists many of the PGPR which have been implicated as helper bacteria in various legume-rhizobia symbioses and co-inoculation with other plant growth promoting rhizobacteria for enhanced crop production. There is evidence for a number of modes of action for PGPR stimulation of legume-rhizobia symbioses, but the most commonly implicated mode is phytohormone-induced (usually IAA) stimulations of root growth (e.g., Molla et al., 2001; Srinivasan et al., 1996; Vessey and Buss, 2002). In this way, the stimulation of nodulation is most commonly an indirect effect; the PGPR stimulates root growth, which provides more sites for infection and nodulation. However, this is not always the case. Cattelan et al. (1999) found that a number of putative PGPR had positive effects on shoot and/or root growth in soybean and were positive for production of IAA or ACC deaminase, but these putative PGPR had no positive effects on nodulation. In fact, Cattelan et al. (1999) found several rhizospheric isolates which stimulated aspects of the soybean-bradyrhizobia symbiosis and which had β-glucosamidase or cyanide production.

Phosphate-solubilizing Bacillus sp. stimulates plant growth through enhanced P nutrition (Elkoca et al., 2008; Whitelaw et al., 1997; Verma et al., 2010) and increasing the uptake of N, P, K and Fe (Biswas et al., 2000). Some PGPR strains, from a range of genera, enhance legume growth, nodulation and nitrogen fixation, root and shoot biomass, nodules dry matter, nitrogenase activity and grain yield in chickpea (Parmar and Dadarwal, 1999; Hamaoui et al., 2001; Sindhu et al., 2002a; Zaidi et al., 2003; Gull et al., 2004). Combined inoculation of Rhizobium with Pseudomonas striata or Bacillus and with Bacillus megaterium (Elkoca et al., 2008) have shown increased dry matter, grain yield and phosphorus uptake significantly over the uninoculated control in legumes. Interactions between these PGPR with Rhizobium may be antagonistic or synergistic and the beneficial effects of such interactions could be exploited for economic gain (Dubey, 1996; Glick, 1995). Many different N2-fixing bacteria, including symbionts, such as root nodulating Rhizobium sp. (Bohio et al., 1992) and different free-living rhizobacteria, such as Azospirillum, Azotobacter, Bacillus, Enterobacter, Pseudomonas, Serratia and Streptomyces (Kloepper
Table 3: Co-inoculation of Legumes with PGPR and Rhizobium

<table>
<thead>
<tr>
<th>Crop</th>
<th>Rhizobium</th>
<th>Co-inoculating PGPR</th>
<th>Plant responses to inoculation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td><em>R. meliloti</em></td>
<td><em>Pseudomonas</em></td>
<td>Upon co-inoculation, a significant increase in plant growth, nitrogenase activity, nodule total nodule weight and total plant nitrogen was reported</td>
<td>Knight and Langston-Unicfer (1988)</td>
</tr>
<tr>
<td>Bean</td>
<td><em>R. phaseoli</em></td>
<td><em>Pseudomonas putida</em></td>
<td>Inoculation with <em>P. putida</em> markedly increased nodulation compared to a <em>R. phaseoli</em> control. Also, 2-ketogluconic acid, a pH5Sphate-solubilizing compound, was detected in <em>P. putida</em></td>
<td>Grimes and Mount (1984)</td>
</tr>
<tr>
<td>Chickpea</td>
<td>Indigenous</td>
<td><em>A. brasilense</em></td>
<td>Inoculation with <em>A. brasilense</em> has the potential to prevent or at least diminish the effects caused by salinity stress in greenhouse experiments with chickpeas irrigated with saline water</td>
<td>Harououi et al. (2001)</td>
</tr>
<tr>
<td></td>
<td><em>Rhizobium</em></td>
<td></td>
<td><em>Mesorhizobium Pseudomonas</em> A significant increase in nodule weight and shoot biomass was observed when co-inoculated with <em>Mesorhizobium</em> and <em>Pseudomonas</em> in sterilized chilljar conditions. In pot experiment, co-inoculation significantly increased root and shoot biomass</td>
<td>Sindhu et al. (2002a, b)</td>
</tr>
<tr>
<td></td>
<td><em>Rhizobium</em></td>
<td><em>Pseudomonas, Bacillus</em></td>
<td>Upon co-inoculation, reduction in wilt incidence and an increase in nodulation were observed</td>
<td>Patmar and Dadarwal (1999)</td>
</tr>
<tr>
<td></td>
<td><em>Rhizobium</em></td>
<td><em>Pseudomonas, Bacillus</em></td>
<td>A significant increase in nodule weight, root and shoot biomass and total plant nitrogen were reported due to co-inoculations</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Rhizobium sp.</em></td>
<td><em>P. fluorescens</em></td>
<td>A significant increase in nodule weight, root and shoot biomass and total plant nitrogen were reported due to co-inoculation</td>
<td>Verma et al. (2010)</td>
</tr>
<tr>
<td>Chickpeas, <em>Rhizobium</em></td>
<td><em>A. brasilense</em></td>
<td></td>
<td>Inoculation with <em>A. brasilense</em> increased nodule dry weight, various plant growth parameters and seed yield of nodulated chickpeas in the field. In common bean, inoculation with <em>Rhizobium meliloti</em> and <em>R. tropici</em> increased seed yield while combined inoculation with <em>Rhizobium</em> and <em>A. brasilense</em> resulted in a further increase. Plants inoculated with <em>A. brasilense</em> alone did not differ in yield from the non-inoculated controls, despite a relative increase in shoot dry weight</td>
<td>Bhardwaj et al. (1996)</td>
</tr>
<tr>
<td>Clover</td>
<td><em>R. leguminosarum</em> sp. Strain</td>
<td>267 and <em>R. trifolii</em></td>
<td>Co-inoculation of clover plants significantly increased shoot weight and nodule weight in comparison with control plants infected only with <em>R. leguminosarum</em> brv. trifolii</td>
<td>Derylo and Skonupska (1993)</td>
</tr>
<tr>
<td>Common bean</td>
<td><em>R. phaseoli</em></td>
<td><em>Rhizobium</em></td>
<td><em>A. brasilense</em></td>
<td>Co-inoculation caused a marked increase in nodulation. Co-inoculation promoted root hair formation and an increase in secretion of the nod gene induced flavonoids resulting in greater numbers of nodules</td>
</tr>
<tr>
<td>Green gram</td>
<td><em>Bradyrhizobium Bacillus</em> sp. (Vigna)</td>
<td>15 and S24</td>
<td></td>
<td>Co-inoculants of the FGPR, <em>Bacillus</em> and <em>Bradyrhizobium</em> strains failed to show any conclusive influence on nodulation and ARA at 50 days of plant growth. <em>Bacillus</em> had a direct effect on shoot biomass development, N-content and grain yield of grain legume when co-inoculated with <em>Bradyrhizobium</em> strain S24 at 50 and 80 days of plant growth. Also, single inoculation of <em>Bacillus</em> isolates significantly increased grain yield over the non-inoculated control</td>
</tr>
<tr>
<td>Natural pasture</td>
<td><em>Indigenous</em></td>
<td><em>A. brasilense</em></td>
<td>Inoculation with <em>A. brasilense</em> showed a similar effect to that of phosphate fertilization.</td>
<td>Iriogob et al. (2000)</td>
</tr>
</tbody>
</table>
Table 3: Continued

<table>
<thead>
<tr>
<th>Crop</th>
<th>Rhizobium</th>
<th>Coinoculating Organism</th>
<th>Plant responses to inoculation</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Pea</td>
<td><em>B. leguminosarum</em></td>
<td><em>Pseudomonas</em></td>
<td>Numbers of nodules were greater in co-inoculated plants than with <em>B. leguminosarum</em> inoculation alone</td>
<td>Bolton et al. (1990)</td>
</tr>
<tr>
<td>Peas, Chick peas, Vetch</td>
<td><em>Rhizobium</em></td>
<td><em>A. brasilense</em></td>
<td>Co-inoculation significantly increased seed yield, but did not affect dry matter yield of garden peas and chickpeas. Vetch co-inoculation significantly increased N₂-fixation, nitrogen content and dry matter yield</td>
<td>Sarig et al. (1986)</td>
</tr>
<tr>
<td>Soybean</td>
<td><em>B. japonicum</em></td>
<td><em>S. lugenslactan</em></td>
<td>Nodulation, nitrogen fixation, protein and N yield were increased by co-inoculation</td>
<td>Dushti et al. (1998)</td>
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<td></td>
<td><em>2-68, S. protea mackulis 1-102</em></td>
<td><em>P. fluorescens</em></td>
<td>Co-inoculation increased colonization of <em>Bradyrhizobium japonicum</em> on soybean roots, node number and the acetylene reduction test</td>
<td>Chebotar et al. (2001)</td>
</tr>
<tr>
<td></td>
<td><em>B. japonicum</em></td>
<td><em>Azospirillum</em></td>
<td>Co-inoculation promoted nodulation, nitrogenase activity and plant growth</td>
<td>Intisayhas et al. (1983)</td>
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<td></td>
<td><em>B. japonicum</em></td>
<td><em>S. lugenslactan</em></td>
<td>Co-inoculation increased grain yield, grain protein</td>
<td>Folomenko et al. (1987)</td>
</tr>
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<td><em>2-68, S. protea mackulis 1-102</em></td>
<td><em>P. putida, P. fluorescens</em></td>
<td>Co-inoculation promoted significant increase in the weight and number of nodules. Several strains increased the dry weight of shoots and roots when inoculated with <em>B. japonicum</em>, but these effects did not correlate with changes in number and weight of nodules</td>
<td>Folomenko et al. (1987)</td>
</tr>
<tr>
<td>White clover</td>
<td><em>R. leguminosarum</em></td>
<td><em>A. brasilense</em></td>
<td>Nodulation, nitrogen fixation, protein and N yield were increased by co-inoculation</td>
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and Beauchamp, 1992; Hufle et al., 1994; Cakmakci et al., 1999), have already been described. When used as seed inoculants, some of these free-living N₂-fixing bacteria show beneficial effects on plant growth and hence they are called Plant Growth-Promoting Rhizobacteria (PGPR) (Davison, 1988). *Bacillus* species used as biofertilizers may have direct effects on plant growth through the synthesis of plant growth hormones (Amer and Utkhede, 2000). N₂-fixation and solubilization of phosphate (Sahin et al., 2004). Phosphate-solubilizing *Bacillus* sp. stimulates plant growth through enhanced P-nutrition (Whitelaw et al., 1997), increasing the uptake of N, P, potassium (K) and iron (Fe) (Biswas et al., 2000). Phosphorus biofertilizers could help increase the availability of phosphates accumulated in the soil and could enhance plant growth by increasing the efficiency of biological nitrogen fixation and the availability of Fe and zinc (Zn) through production of plant growth promoting substances (Kucey et al., 1989). Indeed, trials with *Bacillus* species have shown yield increases in many crops (Greengough and Batson, 1989; Ozuturk et al., 2003).

*Rhizobium* or *Bradyrhizobium* are also widely used in agriculture for crop improvement because of their ability to fix atmospheric nitrogen. Some PGPR strains, from a range of genera, enhance legume growth, nodule formation and nitrogen fixation when co-inoculated with rhizobia (Crimes and Mount, 1984; Petersen et al., 1996). Co-inoculation studies with PGPR and *Rhizobium/Bradyrhizobium* sp. have been shown to increase root and shoot biomass, nodules, dry matter, nitrogenase activity, N₂-fixation and grain yield in chickpea (Parmar and Dadarwal, 1999; Hamaoui et al., 2001; Sindhu et al., 2002a; Zaidi et al., 2003; Gull et al., 2004) and various legumes such as common bean (Crimes and Mount, 1984), green gram
(Sindhu et al., 1999) and soybean (Dash et al., 1998). Furthermore, combined inoculations with N,-fixing and P-solubilizing bacteria were more effective than single inoculation possibly by providing a more balanced nutrition for plants (Belimov et al., 1995). Dual inoculations increased yields in many crops compared to single inoculations with N,-fixing or P-solubilizing bacteria (Alagawadi and Gaur, 1992; Belimov et al., 1995; Verma et al., 2009).

Anjair et al. (2003) has been reported that Pseudomonas aeruginosa PNA1, an isolate from chickpea rhizosphere in India, protected pigeonpea and chickpea plants from fusarium wilt disease, which is caused by Fusarium oxysporum f.sp. ciceri and Fusarium udum. Inoculation with strain PNA1 significantly reduced the incidence of fusarium wilt in pigeonpea and chickpea on both susceptible and moderately tolerant genotypes. Valverde et al. (2006) has been reported effects of coinoculations with Pseudomonas jessenii PS06 (a phosphate-solubilizing bacteria) and Mesorhizobium ciceri C-2/2 strains enhanced the growth and seed yield of chickpea under greenhouse and field conditions. Co-inoculation studies with PGPR and Rhizobium/Bradyrhizobium sp. have been shown to increased root and shoot biomass, nodule dry matter, nitrogenase activity, N2-fixation and grain yield in chickpea (Sindhlu et al., 2002a, b; Zaidi et al., 2003; Gull et al., 2004; El-koca et al., 2008) and various legume such as green gram (Sindhu et al., 1999) and pigeonpea (Tilak et al., 2006). Mittal et al. (2008) has been reported the effect of six phosphate-solubilizing fungi (PSF, two strains of Aspergillus awamori and four of Penicillium citrinum) isolated from rhizosphere of various crops, was observed on the growth and seed production of chickpea plants (Cicer arrietinum L. cv. GP2) in pot experiments. Akhtar and Siddiqui (2009) has been reported that effects of Phosphate solubilizing microorganisms (Glomus intraradices, Pseudomonas putida, P. alcaligenes, P. aeruginosa (Pa28), A. awamori and Rhizobium sp. was observed on the growth, nodulation yield and root-rot disease complex of chickpea under field condition. Inoculation of Rhizobium sp. caused a greater increase in growth and yield than P. putida, P. aeruginosa or G. intraradices. Hamaoui et al. (2001) also reported that inoculation with PGPR significantly enhanced nodulation by native rhizobia in chickpea and faba bean. Favorable effects of inoculation with N2-fixing and P-solubilizing microorganisms and significant increase in nodulation and N2-fixation, N% and total plant nitrogen of legume crops have been reported by many workers (Manjunatha and Devi, 1990; Petersen et al., 1996; Khan et al., 1997; Sindhu et al., 2002a, b; Zaidi and Khan (2007) reported that the stimulatory effect of rhizotrophic microorganisms on growth, yield and nutrient uptake of chickpea was determined in a pot experiment using sterilised soil deficient in available phosphorus (P). Plant vigour, yield and nutrient uptake were significantly enhanced following inoculation with Mesorhizobium ciceri and the phosphate solubilising bacterium Serratia (T1) or phosphate solubilising fungus Penicillium (WP6). Akhtar and Siddiqui (2008) have been reported that Glomus intraradices, Pseudomonas alcaligenes and Bacillus pumilus: effective agents for the control of root-rot disease complex of chickpea (Cicer arrietinum L.). Sivaramaiah et al. (2007) reported that Rhizobacteria belonging to Bacillus sp. were isolated from the rhizosphere of chickpea (Cicer arrietinum). Two Bacillus strains CBS127 and CBS155 inhibited the growth of all the four pathogenic fungi (Alternaria sp., Fusarium oxysporum, Pythium aphanidermatum and Rhizoctonia solani) tested on nutrient agar medium plates in vitro. Ben-Romdhane et al. (2008) reported that selection of high nitrogen-fixing rhizobia (Mesorhizobium ciceri strain CMG 6 and Mesorhizobium ciceri strain CTM 225) nodulating chickpea (Cicer arrietinum L.) for semi-arid Tunisia. Siddiqui and Mahmood (2001b) have been reported the effects of rhizobacteria, i.e. Pseudomonas fluorescens, Azotobacter chroococcum and Azospirillum brasilense, alone and in combination with root symbionts; Rhizobium sp. and Glomus mossea, on the growth of chickpea, Cicer arrietinum and reproduction of Meloidogyne javanica were studied.
Rhizobium sp. with P. fluorescence was better for nodulation than the use of Rhizobium sp. alone or its use with A. brasilense. Root colonization by G. mosseae was better in the presence of P. fluorescens or A. chroococcum than the use of G. mosseae alone or its use with A. brasilense. P. fluorescens caused greater root colonization followed by A. chroococcum and A. brasilense. Verma et al. (2009) have reported that the maximum significant increase in nodule number, dry weight of nodule, root and shoot were recorded in co-inoculation of Mesorhizobium sp. and Pseudomonas fluorescens followed by co-inoculation of Mesorhizobium sp., Azotobacter chroococcum and Bacillus megaterium over uninoculated control in both year of field study while nitrogen and phosphorus content increase in nodules, grain and straw. Verma et al. (2010) have reported that application of Rhizobium sp. BHURC01 and plant growth promoting rhizobacteria on nodulation, plant biomass and yields of chickpea (Cicer arietinum L.).

The higher grain yield 37.26 and 23.64% and straw yield 27.95 and 21.70% in first and second year of field study, respectively was increased significantly in co-inoculation of Rhizobium sp. BHURC01 with P. fluorescens followed by B. megaterium and A. chroococcum over uninoculated control.

CONCLUSION

The rhizosphere of a plant is a zone of intense microbial activity. Rhizobacteria that exert beneficial effect on plant growth and development or refered to as plant growth promoting rhizobacteria (PGPR). PGPR can affect plant growth directly or indirectly. Indirect promotion of plant growth occurs when introduced PGPR lessense or prevents deterious effect of one and more phytopathogenic organisms in the rhizosphere. The direct promotion of plant growth by PGPR may include the production of plant growth regulators or facilitating the uptake of certain nutrient from the root environment. There is increasing evidence that rhizobia can promote the growth of non-legumes via direct and indirect mechanism. Further more, co-inoculation of legumes with rhizobia and PGPR is even more effective for improving nodulation and growth of legumes. Application of PGPR strains can provide an effective, economical and practical way of plant protection via disease suppression. PGPR strains mixture often show synergistic action in plant protection and growth promotion involving many mechanisms. Effective plant growth promoting rhizobacteria may be enhancing plant growth and grain yield in multiple crop production.

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