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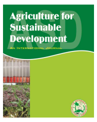

DSOE A PLANT GROWTH PROMOTING RHIZOBACTERIA ENHANCE GROWTH AND NUTRIENT UPTAKE OF CROPS

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ABSTRACT

A thin layer of soil surrounding the plant root where majority of soil organism's predominance resides and roots influenced soil health as well as quality called as rhizosphere. This surrounding zone of plant roots in soil extended up to 1 mm wide, but has no distinct edge. Soil organisms reside in the rhizosphere derived energy, carbohydrates and other essential nutrients by utilizing the compounds and materials released from plant roots. The majority of microorganisms present in the rhizosphere are thought to have no direct consequence on plant growth and vigor. Rhizosphere soil include both beneficial as well as deleterious microorganism. Beneficial microorganisms have been exploited to great success the use of inoculants of nitrogen fixing bacteria, P-solubilizing microorganisms to limit the need for costly fertilizers in legume and cereal crops. Plant growth promoting rhizobacteria (PGPR) are bacteria that living in the rhizosphere which colonize plant roots and promote plant growth, yield and/or reduce disease or insect damage. The plant growth promoting effects of PGPR are mainly derived from morphological and physiological changes of the inoculated plant roots and their functions, and the enhancement of nutrient uptake. This review paper discusses about the effect of composite PGPR on crop growth, nutrient uptake and yield of different agricultural crops.

Keywords:

Crops
Growth,
Nutrient uptake,
PGPR,
Rhizosphere

INTRODUCTION

Plant growth promoting rhizobacteria (PGPR) a heterogeneous group of bacteria that are living in the rhizosphere soil, at root surfaces and in association with roots, which improve the plant and soil health directly or indirectly. The term PGPR first used by Kloepper and Schroth (1978). PGPR promote plant growth by producing growth regulators that excite the activity of other beneficial microorganisms, stimulate the plant directly, aid in nodulation, or indirectly stimulate nodulation. However, they also accelerate mineralization and uptake of certain nutrients e.g. Fe, P, Mn, Zn and Cu etc., Tinker (1984). PGPR alter the solubility of mineral nutrient by releasing organic acids and creating acidity via CO_2 (respiration). The rhizosphere is a favorable habitat for acid producing bacteria (Rouatt and Katznelson, 1961). Production of organic acid was the major mechanism of action by which insoluble phosphate compound were converted to more soluble forms. An activity of the PGPR in the rhizosphere affects rooting patterns and the supply of available nutrients to plants, thereby modifying the quality and quantity of root exudates. In last few decades a large array of bacteria including species of *Azospirillum*, *Azotobacter*, *Pseudomonas*, *Enterobacter*, *Arthrobacter*, *Burkholderia* and *Bacillus* have reported to enhance plant growth (Kloepper *et al.*, 1989; Parewa and Yadav, 2014; Maurya *et al.*, 2014; Meena *et al.*, 2014a; 2014b; Meena *et al.*, 2013). In recent years, the use of PGPR to plant growth has increased dramatically in various part of the world. Beneficial rhizobacteria have potential as part of an overall management system to reduce the use of fertilizer and provide a sustainable agriculture.

Importance of PGPR

Beneficial effects of PGPR result from one or several of these mechanisms. Importances of PGPR in natural and managed ecosystems are listed below.

Indigenous soil microorganisms in the soil habitat play key roles in ecosystem functioning through controlling nutrient cycling reactions essential for maintaining soil fertility and also contributing to the genesis and maintenance of soil structure (Kirk *et al.*, 2004; Wani *et al.*, 2008; Khan *et al.*, 2009). Microbial activity in the rhizosphere soil affects the rooting patterns and supply of available nutrients to

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plants, in a manner that modify the quality and quantity of root exudates (Gryndler, 2000).

PGPR play an important role in biological activities, such as the biological control of plant pathogens, nutrient cycling and seedling/plant growth through the production of various substances (Persello-Cartieaux *et al.,* 2003; Zahir *et al.,* 2004).

Solubilization of inorganic phosphate/mineralization of organic phosphate by PSB or other nutrients (Singal *et al.,* 1994; Jeon *et al.,* 2003; Aslantas *et al.,* 2007). PGPR are able to provide sufficient iron in iron-limited soils (Wang *et al.,* 1993) and or other important mineral, e.g. Availability of P to the plant (Singh and Singh, 1993). PGPR accelerate mineralization and uptake of certain nutrients (Fe, P, Mn, Zn and Cu) (Tinker, 1984). Nutrient transfer from dead to living plants may occur. It increases crop yield by 10-30% besides reducing the input cost for crop production.

Rhizosphere microorganisms produced biologically active substances (eg. amino acids, plant hormones, vitamins, other organic compounds and volatile substances) that stimulate the growth rates of AMF (Barea, 2000).

PGPR produces compounds that increase root cell permeability, thereby increasing the rates of root exudation and stimulates the growth of arbuscular mycorrhizal fungi (AMF) hyphae in the rhizosphere. Composite PGPR enhances growth, yield attributes and yield of wheat crop (Parewa and Yadav, 2014)

Factors affecting PGRP activities

It has been reported that activities of plant growth promoting rhizobacteria are greatly influenced by soil type or cultural practices such as fertilizer application (Gryndler *et al.,* 2001). Chanway and Holl (1992) reported that response of PGPR in correspondence to certain geographical areas. Similarly, Nowak (1998) found that inoculation benefits of certain strain varied with plant species, cultivar and growth conditions. The use of PGPR to augment crop productivity has been limited largely due to the variability and inconsistency of results observed under laboratory, greenhouse and field trials. Soil is an unpredictable environment and an intended result is sometimes difficult to achieve. Climatic variations has also a large impact on the effectiveness of PGPR but sometimes unfavorable growth conditions in the field are to be expected as a normal functioning of agriculture (Zaidi *et al.,* 2009). Soil type, nutrient, organic matter, and moisture content also affect PGPR functions (Burr *et al.,* 1978)

Mechanisms of PGPR:

There are several way by which plant growth promoting rhizobacteria may affect plant growth directly by atmospheric nitrogen fixation, production of plant growth regulators, production of siderophores that solubilize and sequester iron, solubilization of minerals such as phosphorus that enhance plant growth at various stages of development. Growth promotion can also occur indirectly when PGPR function as biocontrol agents of soil-borne plant pathogens and weeds, production of antibiotics e.g. *Karalicin*, *Oomycin*, *Azomyicin* or by reducing the negative effect of deleterious rhizobacteria. However, the major function of PGPR is through the suppression of plant pathogens by releasing antibiotics, cyanide, and enzymes (Kloepper, 1993). (Figures 1 and 2).

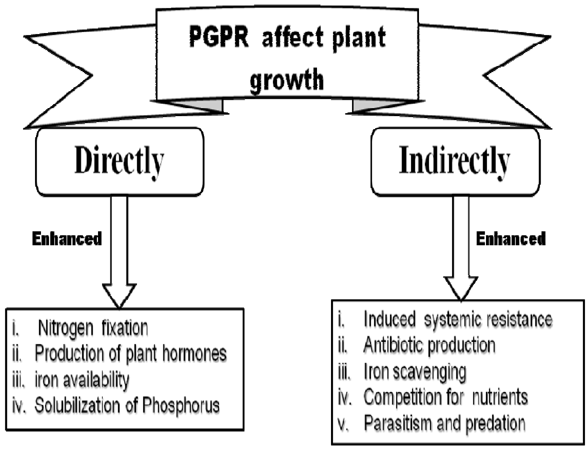

Figure1. Plant growth promoting rhizobacteria affect plant growth directly and indirectly

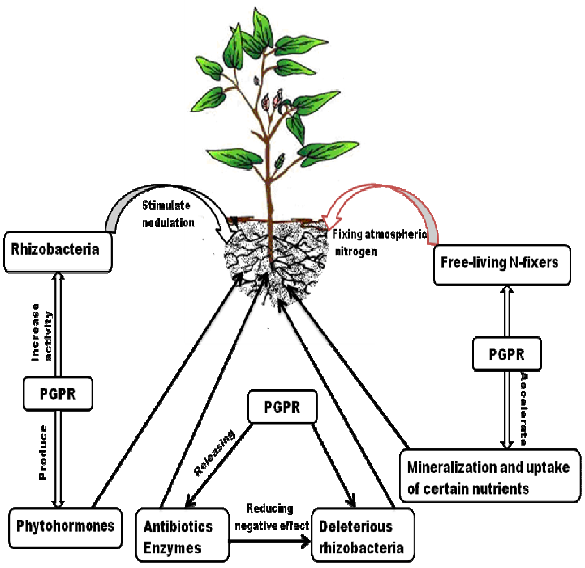

Figure2. Possible indirect and direct pathways PGPR may influence plant growth

The exact mechanisms by which PGPR promote plant growth are not fully understood, but the direct mechanisms of plant growth promotion may include (i) Symbiotic nitrogen fixation and asymbiotic nitrogen fixation (Boddey and Dobereiner, 1995). (ii) Solubilization of inorganic phosphate and mineralization of organic phosphate and/or other nutrients (iii) The ability to produce plant growth regulators like Auxin, cytokinins, gibberellic acid, abscisic acid (ABA) and ethylene (Arshad and Frankenberger, 1993; Glick, 1995; Patten and Glick, 2002). Indirect growth promotion occurs when PGPR promote plant growth in restricting conditions (Glick *et al.*, 1999). This can happen directly by producing antagonistic substances, or indirectly by inducing resistance to pathogens (Glick, 1995). The indirect mechanism of plant growth promotion include (i) antagonism against phytopathogens by production of siderophores (Scher and Baker, 1982), antibiotics (Shanahan *et al.,* 1992) and cyanide (Flaishman *et al.,* 1996), (ii) Induced systemic resistance (Liu *et al.,* 1995; 1996), (iii) Competition for nutrients, therefore PGPR can affect plant growth by one or more of these mechanisms and also use different abilities for growth promotion at various times during life cycle of the plant (Glick *et al*., 1999).

Effect of PGPR on plant growth, yield and nutrient uptake

Plant growth-promoting rhizobacteria (PGPR) have the ability to increase germination, seedling emergence, growth, vigour, establishment and therefore yield of various cereals and non-cereals crops (Van *et al.,* 2000; Grichko and Glick, 2001; Gravel *et al.,* 2007) by enhancing the availability of nitrogen (Riggs *et al.,* 2001; Anjum *et al.,* 2007), iron (Masalha *et al*., 2000) and phosphorous (Villegas and Fortin, 2002) to agricultural crops.

Crops and PGPR

Cereal crops

Enhanced mineral uptake in inoculated cereal plant was proposed as a possible mechanism of PGPR. Kundu and Gaur (1980a) reported that greater yield of wheat and nutrients uptake were observed when seeds were treated with single or mixed cultures of bacteria as compared to uninoculated treatment. Similarly, the synergistic effects of N_2 fixer and phosphate solubilizing microorganisms on plant vigor, nutrient uptake, and yields of various crops have been reported (Rai and Gaur, 1988). The major element involved was suggested to be N in the form of nitrate in wheat, sorghum and corn plants (Lin *et al.,* 1983 and Kucey, 1988) or ammonium in rice plants (Murty and Ladha, 1988). Other elements such as P, K and secondary elements were also suggested to play a key role in this plant bacterium interaction. PGPR inoculation has been shown to improve mineral uptake in several cereal species (Morgenstern and Okon, 1987; Bashan *et al.,* 2000) and to enhance proton efflux from roots of wheat seedlings. Proton efflux, the excretion of H^+ from the roots is one of the important mechanisms of ion uptake. Several studies indicate that PGPR may act as natural elicitors for improving the growth and yield of wheat.

Seed inoculation with *Glomus mosseae* and *G. fasciculatum* in the presence of *Azospirillum brasilense* produced significantly higher dry matter production and grain yield of barley than their corresponding controls (Rao *et al.*, 1986). Gaur and Alagawadi (1987) recorded significant increase in root nitrogenase activity, dry matter and seed yield of rice and sorghum due to combined inoculation of *Azospirillum sp*., *Pseudomonas striata* and *Bacillus polymyxa* as compared to individual inoculation. Combined inoculation of *Azospirillum brasilense* and *Pseudomonas strica* or *Bacillus polymyxa* significantly increased grain and dry matter yields of sorghum and; N and P uptake as compared with single inoculation of individual organisms (Alagawadi and Gaur, 1992). Belimov *et al.* (1995) observed that the mixed cultures of *Azospirillum lipoferum* 137, *Arthrobacter mysorens* 7 and *Agrobacterium radiobacter* 10 produced a significantly positive grain yield and also improved in root uptake of N and P of barley. Zahir *et al.* (1996) conducted a field experiment to study the effect of *Azotobacter* inoculation and inorganic fertilizer on growth and yield of wheat and the result showed that seed inoculation with various *Azotobacter* culture significantly increased the grain and straw yield, number of tillers compared to the non-inoculated control. Yanni and El-Fattah (1999) revealed that a biofertilizer containing two *Cyanobacteria Azospirillum* sp. and *Azotobacter* sp. along with a third of the recommended amount of urea fertilizer produced greater rice grain yield than any single component of biofertilizer and/or nitrogen fertilizer. Inoculation of wheat and maize with *Azotobacter* and *Azospirillum* increased plant growth, nutrient uptake and yield were also reported by (Dobbelaere *et al.*, 2001; Tilak *et al.,* 1982).

Ribaudo *et al.* (1998) reported that inoculation of maize plant with *Azospirillum* increased dry weight of shoot and root. Significant increase was found in the dry matter and yield of wheat with co-inoculation of *Aspergillus niger* and *Penicillium citrinum,* and *G. constrictum* (Omar, 1998). Corn seed inoculation with *Herbaspirillum seropediacae* along with nitrogen increased grain yield in greenhouse experiments by 49–82% as compare to without fertilizer (16%). This indicated that the inoculums improved nitrogen assimilation by the plant (Riggs *et al.,* 2001).

P-solubilizing microorganisms (PSM) alone or in combination produced maximum grain and biological yield, tillers per m2 and P content in wheat seed. Similarly, Zaidi and khan (2005) revealed that the yield contributing parameters, dry matter accumulation, grain yields, P uptake as well as nutrient content in wheat increased significantly with mixed inoculums of *Azotobacter chroococcum* + *Pseudomonas striata* + *Glomus fasciculatum*.

Khan and Zaidi (2007) concluded that the triple inoculation of *Azotobacter chroococcum* with *Bacillus* spp. and *Glomus fasciculatum* significantly increased the dry matter, grain yield, nutrient uptake and protein in wheat grains over the control. Single and dual inoculation of *Rhizobium* and phosphorus solubilizing bacteria with chemical fertilizer (P_2O_5) increased significantly root and shoot weight, plant height, spike length, grain yield, seed P content, leaf protein and leaf sugar content in wheat crop over control (Afzal and Bano, 2008). Similarly, Prasanna *et al.* (2008) opined that the *Azotobacter* + Blue Green Algae treatment gave the highest values of chlorophyll in leaves of wheat crop.

Rather and Sharma (2009) conducted field trail and found maximum nutrient content in wheat and their uptake was due to 100% RDF + Vermicompost + Zn + *Azotobacter* and minimum with control. Askary *et al.* (2009) revealed the co-inoculation of wheat seeds with *Azotobacter* and *Azospiriilum* had positive effects on seed weight and grain yields as compared to non inoculation plant. Likewise, Yazdani *et al.* (2009) showed that combined application of PSM and PGPR along with fertilizer (NPK) improved ear weight, row number, biological yield and harvest index and grain number/row and ultimately increased grain yield of maize compare to control/conventional fertilizer application. Furthermore, co-inoculation of PSM and PGPR reduced P application by 50 % without affecting corn grain yield.

Table 1. Responses of composite Plant Growth Promoting Rhizobacteria on cereals, pulses and oilseed crops

Crop	Bacteria	Response	Reference
Zea mays	*Azospirillum brasilense*	Improved mineral uptake	Lin *et al.*, 1983
Hordeum vulgare	*Glomus* sp. and *Azospirillum brasilense*	Produced maximum dry matter and grain yield	Rao *et al.*, 1986
Triticum aestivum	*Azotobacter* sp.	Increased the grain and straw yield, number of tillers	Zahir *et al.*, 1996
Oryza sativa	*Anabaena* and *Nostoc Azospirillum* sp	Produced greater grain yield	Yanni and El-Fattah, 1999
Triticum aestivum	*Azotobacter* and *Azospirillum*	Increased plant growth, nutrient uptake and yield	Tilak *et al.*, 1982
Sorghum bicolor	*A. brasilense*, *P. strica* or *B. polymyxa*	Increased grain and dry matter yields and NP uptake	Alagawadi and Gaur, 1992
Cicer arietinum	*Rhizobium*, *Pseudomonas striata*,	Increased dry matter, grain yield and P uptake	Elkoca *et al.*, 2008
Cicer arietinum	*Rhizobium*, *Pseudomonas*	Enhanced s growth, nodulation and nitrogen fixation	Parmar and Dadarwal, 1999
Cajanus cajan	*Rhizobium*, *Azotobacter chroococcum*,	Enhanced growth, nodulation, nitrogen fixation	Tilak *et al.*, 2006
Glycine max	*Bradyrhizobium*, *Pseudomonas striata*	Enhanced biological nitrogen fixation	Dubey, 1996
Glycine max	*Bradyrhizobium*, *P. fluorescens*	Enhanced nodulation	Nishijima *et al.*, 1988
Vigna mungo	*Rhizobium phosphobacteria*	Increased growth and yield	Selvakumar *et al.* , 2009
Vigna radiate	*A. chroococcum*, *G. fasciculatum*	Enhanced root infection, increased N and P uptake	Zaidi *et al.* , 2004
Arachis hypogaea	*Rhizobia*, *Azospirillum*, phosphobacteria	Increased pod yield	Balamurugan and Gunasekaran, 1996
Triticum aestivum	*Azotobacter and PSM*	Increased yield	Kundu and Gaur, 1980a
Helianthus annuus	*Azotobacter chroococcum*, *P. glaucum*	Enhanced growth and yield	Gururaj and Mallikarjunaiah, 1995
Helianthus annuus	*Azospirillum* and *Bacillus polymyxa*	Increased plant dry weight	Gehan and Abo-Baker, 2010
Helianthus annuus	*Bacillus* M-13	Increased yield, oil and protein content	Ekin, 2010
Arachis hypogaea	*fluorescent pseudomonads*	Enhanced yield and inhibited fungal pathogens	Dey *et al.*, 2004
Brassica nigra	PSM, *Azotobacter* sp.	Seed and stover yield	Khafi *et al.*, 2001
Brassica nigra	*Azotobacter*, *Azospirillum*	Increased seed yield	Chauhan *et al.*, 1995

Reddy and Singh (2011) showed that inoculation of P-solubilizing bacteria along with rock phosphate significantly increased yield, nutrient uptake and available P of wheat and maize plants as compared to the control. Agamy *et al.* (2012) conducted a field experiment to study the effect of biofertilizer, FYM and different dose of inorganic fertilizer singly or in combination on growth, yield, anatomical structure and physiological analysis of wheat plant and found that the application of biofertilizer and/or FYM in combination with NPK significantly increased all growth and yield attributes. Leaf pigments, total carbohydrates and crude protein in leaves, total carbohydrates and crude protein in grains were also found significantly higher by the combined application of biofertilizer + FMY + 50% NPK as compared to control or 100% NPK alone.

Namvar and Khandan (2013) studied the effect of mineral nitrogen fertilizer and biofertilizer inoculation on grain yield, yield components and protein content of wheat and concluded that the higher rates of nitrogen fertilizer and biofertilizer (*Azotobacter* and *Azospirillum* sp.) inoculation increased all growth and yield attributes and grain protein content. Application of 150 kg N/ha was significantly at par with 200 kg N/ha in the most of the studied traits. The result indicated that the moderate N rate (150 kg N/ha) can be beneficial to improve growth, development and total yield of inoculated wheat. Sharma *et al.* (2013) conducted a field experiment at Jabalpur to study the effect of integrated nutrient management on soil fertility as well as yield and mineral nutrition of wheat in a Vertisol. The results revealed that recommended dose of NPK + FYM along with 5 kg Zn/ha and PSB + *Azotobactor* significantly increased grain yield, protein content, nutrient uptake and physico-chemical properties of soil over the 100% NPK treatment.

Table 2. Response of composite PGPR on Horticultural crops

Crop	Bacteria	Response	Reference
Solanum tuberosum	*Bacillus polymyxa* and *Pseudomonas striata*	Increased the yield and P uptake	Kundu and Gaur, 1980
Allium cepa	*Azospirillum* and VAM	Increased TSS, sulphur content and yield	Ragland *et al.*, 1989
Lycopersicon esculentum	*Azospirillum* sp. and *Azotobacter chroococcmn*	Increased the plant height, root length and fruit yield	Subbiah, 1990
Musa paradisiaca	*Azospirillum, Azotobacter*	Enhanced the plant height, number of leaves and girth	Wange and Patil, 1994
Brassica oleracea	*Azospirillum* sp.	Improving the growth and yield	Kalyani *et al.*, 1996
Solanum tuberosum	*Azospirillum*, phosphobacteria and VAM	Increased yield	Thamizh and Nanjan, 1998
Raphanus sativus	Bradyrhizobia *japonicum*	Increased the dry matter yield	Antoun *et al.*, 1998
Lycopersicon esculentum	*Azospirillum* sp.	Increased growth, fruit yield and TSS	Sendur *et al.*, 1998
Piper nigrum	*Trichoderma sp.* and VAM	Produced robust disease-free rooted black pepper cuttings	Sarma, 2000
Piper nigrum	*P. fluorescens*	Enhanced nutrient uptake	Paul *et al.*, 2001
Zingiber officinale	*T. harzianum* and *Pseudomonas fluorescens*	Promoted growth of ginger suppressed soil-borne fungal	Jisha *et al.* (2002
Piper nigrum	Rhizobacteria and *T. harzianum*	Enhance growth	Anandaraj and Sarma (2003
Piper nigrum	*P. fluorescens* and *Trichoderma harzinaum*	Enhanced height, number of leaves, roots leaf area	Thankamani *et al.*, 2005
Piper nigrum	*P. fluorescens*	Enhanced nutrient uptake	Diby *et al.*, 2005
Rubus ideus	*Bacillus* sp.	Increased crop yield	Orhan *et al.*, 2006
Lycopersicon esculentum	*Bacillus simplex, Bacillus cereus*	Increased root length, shoots fresh and dry weight	Hassen and Labuschagne, 2010
Malus domestica	*Agrobacterium rubi, B. subtilis,*	Increased the No. of leaf, leaf area, annual shoots of plant	Karakur and Aslantas, 2010
Fragaria ananassa	*Bacillus and Pseudomonas*	*Increased the fruit yield, growth and*	*Esitken et al.*, 2010
Lycopersicon esculentum	*Pseudomonas-Azotobacter-Azosprillum*-AMF	Increased K uptake	Ordookhani *et al.* 2010
Cucurbita pepo	*P. putida, B. lentus, Azotobacter, Azospirillum*	Produced higher oil, seed and fruit yield	Habibi *et al.*, 2011
Brassica oleracea	PGPR Isolates MK5, MK7 and MK9	Increased No. of no wrapper leaves, curd diameter	Kaushal *et al.*, 2011
Curcuma Longa	*A. lipoferum T. viridae B. megaterium*	Improved plant growth and yield	Sumathi *et al.*, 2011
Momordica charantia	*Azospirillum, PSB* and *Bacillus subtilis*	Enhanced growth, yield, quality, root length and	Kumar *et al.*, 2012

Singh *et al.* (2013) carried out a field experiment at Gujarat to study the effect of bio-inoculant on wheat under dryland condition and revealed that seed inoculation with *Azotobacter*-8 significantly increased the growth and yield attributes of wheat. The seed bacterization with *Azotobacter*-8) along with 60 kg N/ha (Urea) and 40 kg N/ha (FYM) was most responsive treatment in respect of 23 and 36% increase in shoot fresh and dry weight, 26 and 38% increase in root fresh and dry weight, 39% increase in test weight of seed and 27% increase in yield as compared to control. The result clearly indicated that there was a saving of 20 kg N/ha, when *Azotobacter*-8) culture was used along with 60 kg N/ha (Urea) and 40 kg N/ha (FYM).

Parewa and Yadav (2014) conducted a field experiment at BHU, Varanasi to study the response of fertility levels, FYM and bio-inoculants on yield attributes, yield and quality of wheat during 2009-10 and 2010-11. The seed bacterization with the composite PGPR including (*Azotobactor chroococum* W5 + *Azospirillum brasilence* Cd + *Pseudomonas fluoirescens* BHU PSB06 + *Bacillus megaterium* BHU PSB14) + *Glomus fasciculatum* (Soil application) significantly increased the growth and yield attributes, yield of the wheat crop as compared to uninoculated control and other treatments.

Pulse crops

Pulse crops are an important source of protein in Indian diet. But the cultivation of pulse crops is taken mainly in poor and marginal lands resulting in low productivity. Besides this, minimal application of chemical fertilizers and cultivation as rainfed crops could be attributed to the poor yield or productivity of pulse crops in India. Since legume crops could fix atmospheric nitrogen by root nodulation *Rhizobium* sp. the augmentation of symbiotic nitrogen fixing bacteria along with phosphate solubilizing bacteria (PSB) will result in increased biomass production and economic yield of many legume crops. Hence, the application of combination of PGPR bacteria consisting of symbiotic nitrogen fixing bacteria, P- solubilizers and biocontrol agents to legume crops would result not only in increased yield but also reduced incidence of important diseases like root rot and wilt diseases in these crops. A number of researches have been conducted in the above view in various crops and found that application of composite PGPR to these legume crops resulted positively.

Nishijima *et al.* (1988) found that combined inoculation of *Bradyrhizobium* + *Pseudomonas fluorescens* enhanced root nodulation in soybean plant. Dubey (1996) reported that combined inoculation of *Bradyrhizobium* and *Pseudomonas* enhanced biological nitrogen fixation in soybean. Moreover, Shabayey *et al.* (1996) revealed that combined inoculation of *B. japonicum*, *P. fluorescens* and *G. mosseae* significantly increased the yield of soybean crop. Such results are due to a higher P uptake promoted by the PGPR and AMF. Some PGPR strain enhanced legumes growth, nodulation and nitrogen fixation, root and shoot biomass, nodule dry weight, grain yield in chickpea (Parmar and Dadarwal, 1999) and pigeonpea (Tilak *et al.,* 2006). Chickpea seed inoculated with phosphate solubilizing bacteria along with Mussoorie rock phosphate increased the yield attributes and grain yield (Kulkarni *et al.,* 2000). Dual inoculation of plant growth promoting rhizobacteria augmented yields in black gram (Tanwar *et al.,* 2002). Co-inoculation with PGPR, *Rhizobium* and *Bradyrhizobium* sp. shown to increase root and shoot biomass, nodule dry weight, N_2- fixation and grain yield of chickpea (Gull *et al.,* 2004), common bean and green gram (Sindhu *et al.,* 1999).

Zaidi *et al.* (2004) reported that the dual inoculation of free living N_2 fixer *Azotobacter chroococcum* and *G. fasciculatum* enhanced root infection, stimulated plant growth and increased N and P uptake by Greengram. Wani *et al.* (2007) conducted an experiment to find out the synergistic effect of the inoculation with nitrogen fixing and phosphate solubilizing rhizobacteria on chickpea. The result showed that the yield, dry matter, N and P uptake and nodulation was maximum in the treatment that received combination of *Mesorhizobium ciceri* RC4 + *Azotobacter chroococcum* A10 + *Bacillus* spp. PSB9 as seed inoculation than in the treatment that received that single strain or 100% RDF. Similarly, Rokhzadi *et al.* (2008) reported that the combined inoculation of four soil rhizospheric microorganisms (*Azospirillum-Azotobacter- Mesorhizobium- Pseudomonas*) increased pods number per plant, grain yield, biomass and protein content in seed of soybean as compared with single inoculant and uninoculated control. Combined inoculation of *Rhizobium* with *Pseudomonas striata* or/and with *Bacillus megaterium* increased dry matter, grain yield and P uptake significantly over the uninoculated control in legumes (Elkoca *et al.,* 2008; Selvakumar *et al.,* 2009)

Yadav *et al.* (2010) carried out an experiment at BHU Varanasi in plant growth chamber to investigate the effect of different strain of PGPR on the growth of chickpea plant. Isolates of PGPR induced production of plant hormones, phosphate solubilization and ammonia production to enhanced plant growth. Most of isolates resulted in a significant increase in shoot length, root length and dry matter production of shoot and root of chickpea seedlings and suggested that PGPR isolates viz. *Pseudomonas aeruginosa* strain BHUPSB02, *Pseudomonas putida* strain BHUPSB04 and *Bacillus subtilis* strain BHUPSB13 may be used as biofertilizers to enhance the growth and productivity of chickpea. *Singh et al.* (1993) conducted a field experiment at BHU, to study the response of phosphorus and bio-inoculants on yield and yield attributes, nutrient uptake and economics of pigeonpea and revealed that dual seed inoculation with PSB + PGPR (*Bacillus polymyxa-Rhizobium-Pseudomonas florencenses*) produced the highest yield and yield attributes, nutrient uptake, gross returns, net return and B: C ratio, significantly increased over PGPR (*Rhizobium-Pseudomonas florencenses),* PSB (*Bacillus polymyxa*) and control.

A study was conducted to evaluate the performance of three rhizosphere competent of microbial strains, viz., *Pseudomonas fluorescens* OKC, *Trichoderma asperellum* T42 and *Rhizobium* sp. RH4, individually and in combination in bioprimed seeds of chickpea and Rajma. The result demonstrated that bioprimed seeds in combined treatment showed significant higher germination percentage and better plant growth in both the crops compared to non-bioprimed control plants or individual application (Yadav *et al.,* 2013).

Konthoujam *et al.* (2013) conducted a field experiment at Manipur to study the effect of inorganic, biological and organic manures on nodulation, yield of soybean and soil properties. The results revealed that integration of 75% RDF with VC@ 1 t/ha and PSB produced significantly increased growth and yield attributes, oil and protein content of seed.

Oilseed crops

In the semi-arid tropics, the production levels of oilseed crops are hampered due to foliar and soil borne diseases incited by fungal pathogens. Present management of these oilseed crops diseases using chemical fungicides has environment related concerns. More over the labeled fungicides are very expensive and can't affordable by small and marginal farmers. Use of indigenous plant growth-promoting rhizobacteria (PGPR) as a viable alternative to increase the production level.

Balasubramanian and Palaniappan (1994) reported that seed inoculation with PSM along with FYM had beneficial effect on groundnut. Gururaj and Mallikarjunaiah (1995) found synergistic effects in sunflower with the triple inoculation of *Azotobacter chroococcum-Penicillium glaucum-Glomus fasciculatum*. Seed inoculation of mustard with Azotobacter or Azospirillum significantly increased seed yield (Chauhan *et al.,* 1995).

Desirable effects of combined inoculation with plant growth promoting rhizobacteria (PGPR) on growth parameters, grain yield and nutrient uptake by soybean plants have been reported by many researchers (Abdalla and Omar, 2001). Khafi *et al.* (2001) reported the maximum seed and stover yield of mustard crop received with the treatment involving 50% RDF along with PSM + *Azotobacter* culture. Patil *et al.* (2004) revealed that the combined inoculations of three beneficial organism's viz., *Rhizobium-Azospirillum*-PSB was more superior over both single and dual inoculations with respect to plant growth, yield of soybean and nutrient uptake. Dey *et al.* (2004) observed that plant growth-promoting *Fluorescent pseudomonades* significantly enhanced pod yield, haulm yield, nodule dry weight, root length, as well as inhibited fungal pathogens like *A. niger* and *Sclerotium rolfsii*, causing collar and stem rot respectively, of groundnut over the control. In mustard the seed and oil yield response and nutrient uptake was increased following seed inoculation with *B.* megaterium-*A. Chroococcum* and combined application of FYM@10 t/ha, + 75% RDF under field conditions (Chand, 2007).

A field experiment was conducted to evaluate the performance of groundnut under alluvial soils of eastern India with different kind of inoculants such as no inoculants, *Rhizobium, Bacillius polymyxa* and different levels of cobalt. The higher yield and nutrient uptake was observed with inoculation of *Rhizobium* and *Bacillus polymyxa* (Basu and Bhadoria, 2008).

Spices crops

Spice crops contribute a major portion in agricultural exports in Indian economy. Various spice crops are grown in different agroclima1tic zones in India. Continuous chemical fertilization only to these crops resulted in increased pest and disease incidence, micronutrient deficiencies along with poor soil fertility. As the awareness on organic cultivation of these crops increased manifold in the recent years, PGPR would offer solutions to the above mentioned problems. Application of N-fixers, P-solubilizers along with the biocontrol agents for many economically important pests and diseases resulted in increased productivity, reduced input costs and improvement in the quality of the products. The spices crops such as black paper, cardamom, ginger, nutmeg, clove, fenugreek, cumin, coriander and fennel are cultivated in Haryana, Punjab, Uttar Pradesh, Bihar, Madhya Pradesh, Andhra Pradesh and Tamil Nadu; and predominantly in the states of Rajasthan and Gujarat. Major production constraints of spices crop are low fertility of soils, poor germination, poor input management, slow initial growth, competition from weeds and high susceptibility to diseases, insect- pest and frost (Agarwal *et al.,* 2001). The plant growth promoting rhizobacteria (PGPR) are reported to alleviate in biotic and abiotic stress of several crops.

Since spice crops are cultivated in intensive cropping manner, PGPR organisms were studied mainly in relation to their disease control or resistance mechanism and growth promotion by the production of plant growth regulators in spice crops. Thankamani *et al.* (2005) studied that the effect of *P. fluorescens* (IISR-6) and *T. harzinaum* (P-26) on growth of black pepper in the nursery and result indicated that height, number of leaves, leaf area, number of roots, biomass production and uptake of N, P, K, Mg, Fe and Mn were increased with combined application of *P. fluorescens* (IISR-6) and *T. harzianum* (P-26). Sharma (2000) reported that the combined application of *Trichoderma* sp. and VAM produced robust disease-free rooted black pepper cuttings in the nursery. Similarly, Anandaraj and Sarma (2003) found that the significantly enhance growth of black pepper plants in the nursery due to application of rhizobacteria and *T. harzianum.* Jisha *et al.* (2002) found *T. harzianum* and *P. fluorescens* (IISR-6) promoted growth and vigour of black pepper, ginger and cardamom and suppressed soil-borne fungal pathogens in field conditions. Sumathi *et al.* (2011) studied the effect of application of bio-inoculants in turmeric crop at nursery conditions and found that combined application of bio-inoculants to turmeric crop resulted in improved plant growth and yield in terms of number of leaves, intercalary shoots and plant height compared to individual application of various bio-inoculants.

Vegetables

Vegetables are rich source of vitamins, proteins, carbohydrates and minerals, which constitute an important component in human nutrition. Besides the nutritional value of vegetables, increased interest is being bestowed on the functional and therapeutic benefits of vegetables in human health. Vegetables production requires heavy fertilization and irrigation resulted in reduced soil fertility due to lower application of organic manures. Productivity as well as quality of vegetables could be improved by application of PGPR inoculants there by reducing of chemical fertilizers and pesticides application significantly.

Potato yield and P uptake increased by seed inoculation with *Bacillus polymyxa* and *Pseudomonas striata* as single and mixed inoculants as reported by Kundu and Gaur (1980). Subbiah (1990) reported that *Azospirillum* inoculated tomato plants in black clay soil recorded the higher yield over the control and besides saving 50% RDN also improved the NUE. Similarly, Terry *et al.* (1996) revealed that application of both *Azospirillum brasilense* and *Azotobacter chroococcmn* along with 30 kg N increased the plant height, root length, fruit yield, fresh and dry weight of aerial parts in tomato and saving of 45 kg/ha N fertilizer. Moreover, Kalyani *et al.* (1996) studied the interaction of *Azospirillum* and fertilizer nitrogen on cauliflower and reported that soil inoculation of *Azospirillum* coupled with less nitrogen (80 kg/ha) had beneficial effect in improving the growth and yield, besides saving of RDN up to 50%.

Ragland *et al.* (1989) studied the effect of biofertilizers on quality parameters of onion and the result revealed that application of $3/4^{th}$ RDF of NP with *Azospirillum* and VAM increased total soluble solids (TSS), sulphur content and yield compared to control. Similarly, Thamizh and Nanjan (1998) stated that the combined application of *Azospirillum*, phosphor-bacteria and VAM with 75% RDF was recorded maximum yield which was 21% higher than uninoculated control in potato. Application of organic manure such as FYM, VC and *Azospirillum* along with RDF showed maximum growth and fruit yield and also total soluble solids, ascorbic acid and lycopene content in tomato reported by Sendur *et al.* (1998).

Nanthakumar and Veeraghavathatham (1999) resulted that combined application of FYM, *Azospirillum*, PSB with 75% RDF of NP increased yield and yield components in brinjal. Similarly, Gaikwad (1999) reported that dry matter, N and P uptake; and yield of brinjal significantly increases due to inoculation of PSMs along with single superphosphate or rock phosphate. Habibi *et al.* (2011) concluded that application of biofertilizers with 50% chemical and organic fertilizers reduced the need for C and produced higher oil, seed and fruit yield of pumpkin.

Ordookhani *et al.* (2010) revealed that the combined application of *Pseudomonas-Azotobacter-Azosprillum*-AMF enhanced maximum potassium uptake by shoot and nutrient contents in the fruit tomato as compared to the other treatment. Kaushal *et al.* (2011) opined the combined use of PGPR with N and P fertilizers significantly increase number of no wrapper leaves, curd diameter, curd depth and curd weight of cauliflower and induced IAA production and P-solubilization. Kumar *et al.* (2012) conducted a field trial to determine the effect of plant growth promoting rhizobacteria (PGPR) on growth and yield of bitter gourd and revealed that the inoculation of PGPR enhanced growth, yield, quality, root length and dry root weight of bitter gourd.

Fruit crops

Plant growth promoting rhizobacteria effects the fruit crops growth and nutrient uptake in numbers of ways. Jeeva (1987) reported that total soluble solids (TSS), total sugar and sugar to acid ratios were positively influenced by the inoculation of *Azospirillum* to banana crop over uninoculated control. Combined application of *Azospirillum*, *Azotobacter* and inorganic nitrogen fertilizer enhanced the plant height, number of leaves and girth in banana compared to un-inoculated control (Wange and Patil, 1994). Similar findings were reported by Orhan *et al.* (2006) under organic growing conditions that yield, cane length, number of cluster per cane and number of berries per cane of raspberry increased by root inoculation of *Bacillus* M-3 and *Bacillus* M-3 + *Bacillus* OSU-142. However, Several studies showed that PGPR can stimulate growth and increase yield of apple (Amarente *et al.*, 2002; Karlidag *et al.*, 2007; Pirlak *et al.*, 2007), mulberry (Sudhakar *et al.*, 2000), apricot (Esitken *et al.*, 2003), sweet cherry (Esitken *et al.*, 2006; Akca and Ercisli, 2010), kiwi (Erturk *et al.*, 2010) and banana (Kavino *et al.*, 2010).

Use of indigenous soil microorganisms increased the leaf number, area as well as number of annual shoots of plant, their diameter and also increased the concentration of P and Zn in the leaves of apple (Karakur and Aslantas, 2010). Mia, *et al.* (2010) resulted that PGPR inoculation along with reduce dose of N fertilizer improved root and shoot growth, photosynthetic rate and also increased the Ca uptake in banana. Esitken *et al.* (2010) revealed the effects of PGPR on yield, growth and nutrient contents of organically grown strawberry; and suggested that both root inoculation of *Bacillus* M3 and spraying of *Pseudomonas* BA-8 or *Bacillus* OSU-142 have potential to increase the fruit yield, growth and P, Fe, Cu and Zn content of the strawberry plant.

Medicinal plants

The World Health Organization (2008) has estimated that about 80% of global populations rely on traditional medicines, mostly plant drugs, for their primary health care needs. Moreover, modern medicines contain about 25% of drugs derived from plants. Medicinal plants are very important in modern civilization in order to obtain natural active substances known as secondary metabolites. An introduction of PGPR and AMF is known to increase the growth of many plant species including medicinal plants. The leaves of Begonia malabarica are used for the treatment of respiratory tract infections, diarrhoea, blood cancer, and skin diseases (Kiritkar and Basu, 1975).

Earanna (2001) reported that combined inoculation with *Glomus fasciculatum-Bacillus coagulans-Trichoderma harzianum* improved the yield of *Phyllanthus amarus* while *Glomus fasciculatum-Bacillus coagulans* inoculation showed the best for improving growth and yield of *Withania somnifera*. Selvaraj *et al.*, (2008) studied the effect of *Glomus mosseae* and some PGPR on the growth, biomass, nutrients and content of secondary metabolites of *Begonia malabarica* plant under green house conditions and revealed that *G. mosseae* along with PGPR enhanced the plant growth, biomass yield, nutrients and secondary metabolites of *B. malabarica*. Significant improvement in root length and dry matter content of mint were recorded by treating the root cutting of mint with bacterial solutions than control (Kaymak *et al.,* 2008). Similarly, Kumar *et al.* (2009) studied the effect of dual inoculation of *Azotobacter chroococcum-P. putida* on *Withania somnifera* and result showed that dual inoculation along with organic manure increased the root and seed yield, number of off shoots per plant and plant height as compared to control.

Hemashenpagam and Selvaraj (2011) conducted a green house nursery experiment to assess the interaction between AMF (*Glomus aggregatum*) and some PGPR in soil and their effect on growth, nutrition and content of secondary metabolites of *Solanum viarum* seedlings. The results revealed that maximum plant height, plant dry weight, P, Fe, Zn, Cu and Mn content and secondary metabolites, flavonoids, alkaloids and also enzyme activity namely acid phosphatase, alkaline phosphatase and dehydrogenase in the root zone soil were obtained in the triple inoculation with *G. aggregatum-B. coagulans-T. harzianum*. Similar trend was found by Sumithra and Selvaraj (2011) in *Sphaeranthes amaranthoides* medicinal plant.

Rajasekar and Elango (2011) opined that the PGPR in combination have the potential to increase the plant growth, root length and alkaloid content of *Withania somnifera*. Maximum plant height, number of branches, plant fresh and dry weights, oil percentage and yield in fresh herb and total carbohydrates in herb of rosemary were obtained with the application of compost at 8 ton/fed along with *Azotobacter Chroococcum-B. megaterium-B. circulanse* compared to other compost or biofertilizers (Abdullah *et al.,* 2012).

CONCLUSION

PGPR may enhance the plant growth and yield of the several crops. Inspite of them it can enhances the quality of the crop produce and thus overall improved yield without deteriorating the soil and environmental condition. Use of efficient soil and rhizo-microorganisms under soil-plant-environmental system its act as an eco-friendly, economic and sustainable productivity of agricultural system.

Table 3. Response of composite PGPR on Medicinal plants

Crop	Bacteria	Response	Reference
Phyllanthus amarus and *Withania somnifera*	*Glomus fasciculatum- Bacillus coagulans* or *Trichoderma harzianum*	Improved growth and yield	Earanna, 2001
Begonia malabarica	*Glomus mosseae + Bacillus coagulans+ Trichoderma viride*	Enhanced the plant growth, biomass yield, nutrients and secondary metabolites	Selvaraj *et al.,* 2008
Mentha piperita	*Bacillus megatorium*	Improved root length and dry matter content of root	Kaymak *et al.,* 2008
Withania somnifera	*Azotobacter chroococcum* and *Pseudomonas putida*	Increased the root yield, seed yield, number of off shoots per plant and plant height	Kumar *et al.,* 2009
Solanum viarum	*G. aggregatum + B. coagulans + T. harzianum.*	Increased plant height, plant dry weight, P, Fe, Zn, Cu and Mn content and secondary metabolites and enzyme activity	Hemashenpagam and Selvaraj, 2011
Sphaeranthes amaranthoides	*Glomus walkeri + Bacillus subtilis + Trichoderma viride*	Enhanced growth, biomass, nutrition and secondary metabolites	Sumithra and Selvaraj, 2011
Ocimum basilicum	*Pseudomonas + Azotobacter + Azosprillum*	Increased root fresh weight, N content and essential oil yield	Ordookhani *et al.,* 2011
Withania somnifera)	*Azospirillum, Azotobacter, Pseudomonas* and *Bacillus*	Increased plant height, root length and alkaloid content	Rajasekar and Elango, 2011
Rosmarinus officinalis	*Azotobacter Chroococcum + Bacillus megaterium +Bacillus circulanse*	Enhance dry weights, oil percentage and yield in fresh herb and total carbohydrates in herb	Abdullah *et al.,* 2012

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