Potential of PGPR in Agricultural Innovations

Haluk Caglar Kaymak

Contents

Abstract Plant growth promoting rhizobacteria (PGPR) are a group of free-living bacteria that colonize the rhizosphere and benefit the root growth in plants. Bacteria of diverse genera such as *Azospirillium*, *Bacillus*, *Burkholderia*, *Klebsiella*, *Pseudomonas*, etc., were identified as PGPR. These PGPR exert a direct effect on plant growth by inducing the production of phytohormones, supplying biologically fixed nitrogen, and increasing the phosphorous uptake by the solubilization of inorganic phosphates. These bacteria affect plant growth by indirect mechanisms that involve suppression of bacterial, fungal, viral, and nematode pathogens. A lot of study showed that inoculation with PGPR resulted in significant yield increases in different crops, rooting of hardwood and semi-hardwood cuttings, increased germination and enhanced emergence of seeds under different conditions, promoted nutrient uptake of roots, total biomass of the plants, increased seed weight, induced early flowering, etc. In this review, the importance of PGPR is discussed for

H.C. Kaymak
Faculty of Agriculture, Department of Horticulture, Atatürk University, 25240 Erzurum, Turkey
e-mail: hckaymak@atauni.edu.tr; hckaymak@yahoo.com

D.K. Maheshwari (ed.), *Plant Growth and Health Promoting Bacteria*,
Microbiology Monographs 18, DOI 10.1007/978-3-642-13612-2_3,

agricultural innovations with special references that utilises direct and indirect plant growth promotion.

1 Introduction

The rhizosphere, volume of soil surrounding roots influenced chemically, physically, and biologically by the plant root, is a highly favorable habitat for the reproduction of microorganisms, which exerts a potential impact on plant health and soil fertility (Sorensen 1997; Antoun and Prevost 2005; Podile and Kishore 2006). This environment is relatively rich in nutrients released by the plant roots, and its microbial communities are different from those that are not influenced by the roots (Alexander 1977; Burdman et al. 2000).

In the rhizosphere, very important and intensive interactions occur among the plant, soil, microorganisms, and soil microfauna (Antoun and Prevost 2005). These interactions can significantly influence plant growth and crop yields. In the rhizosphere, bacteria are the most abundant microorganisms. Rhizobacteria are rhizosphere-competent bacteria that aggressively colonize plant roots, could be free-living, parasitic, or saprophytic, and their diversity remains dynamic with a frequent shift in community structure and species abundance (Kunc and Macura 1988). These microbial communities are beneficial for plant growth, yield, and crop quality, and they have been called "plant growth promoting rhizobacteria (PGPR)" (Kloepper and Schroth 1978) including numerous strains of the genera *Acinetobacter*, *Aeromonas*, *Alcaligenes*, *Arthrobacter*, *Azospirillium*, *Azotobacter*, *Azoarcus*, *Bacillus*, *Beijerinckia*, *Burkholderia*, *Clostridium*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Gluconacetobacter*, *Klebsiella*, *Pseudomonas*, *Serratia*, *Rhizobium*, etc. (Burdman et al. 2000; Sudhakar et al. 2000; Hamaoui et al. 2001; Bertrand et al. 2001; Mirza et al. 2001; Bonaterra et al. 2003; Esitken et al. 2003a; Murphy et al. 2003; Raj et al. 2004; Joo et al. 2004; Esitken et al. 2006; Podile and Kishore 2006; Saleem et al. 2007).

PGPR can be divided into two groups according to their relationship with the plants: symbiotic bacteria and free-living rhizobacteria (Khan 2005). A lot of work have been done to study about the mechanisms and principles of the PGPR–plant relationship, which was widely accepted as the rhizosphere effect (Zhuang et al. 2007). Glick (1995) reported that PGPR function in three different ways: synthesizing particular compounds for the plants, facilitating the uptake of certain nutrients from the environment (Cakmakci et al. 2006; Garcia et al. 2004a, b; Siddiqui and Mahmood 2001), and preventing the plants from diseases (Guo et al. 2004; Jetiyanon and Kloepper 2002; Raj et al. 2003a, b).

In other words, these mentioned bacteria can directly cause plant growth, seed emergence, or improvement in crop yields by producing and secreting plant growth regulators such as auxins, gibberellins (GAs), and cytokinins. They elicit the root metabolic activities, supply biologically fixed nitrogen, and increase the phosphorous uptake by solubilization of inorganic phosphates (Burdman et al. 2000;

Podile and Kishore 2006). The near direct effect of PGPR is that these bacteria affect plant growth by indirect mechanisms that involve suppression of bacterial, fungal, viral, and nematode pathogens (Burdman et al. 2000; Kirankumar et al. 2008).

In this review, the importance of PGPR is discussed for agriculture innovations with special reference to their utilization in direct plant growth promotion such as seed emergence, secretion of plant growth regulators, and indirect plant growth promotion such as suppression of pest and disease.

2 Direct Plant Growth Promotion

PGPR influence direct growth promotion of plants by fixing atmospheric nitrogen, solubilizing insoluble phosphates, secreting hormones such as IAA, GAs, and Kinetins besides ACC deaminase production, which helps in regulation of ethylene.

2.1 Biological Nitrogen Fixation

Nitrogen is a well-known and essential key nutrient for plant growth and development. However, the global nitrogen cycle pollutes groundwater and increases the risk of chemical spills. The production of chemical fertilizers is a highly energy-intensive process using large amounts of fossil energy. High-input farming practices achieving high yields have created environmental problems and degradation in natural resources (Şahin et al. 2004). Thus, Figueiredo et al. (2008) reported that during the past couple of decades, the use of PGPR for sustainable and environment friendly agriculture has been increased tremendously in various parts of the world. Increasing and extending the role of bio-fertilizing with PGPR would reduce the need for chemical fertilizers and decrease their adverse environmental effects. Microorganisms are gaining importance in agriculture to promote the circulation of plant nutrients and reduce the need for chemical fertilizers (Şahin et al. 2004; Orhan et al. 2006).

Rhizosphere associated N-fixing bacteria have increasingly been used in nonlegume crop species such as sugar beet, sugar cane, rice, maize, and wheat (Döbereiner 1997; Hecht-Buchholz 1998; Şahin et al. 2004). For example, experiments with *Bacillus* species indicated yield increases in cereals (Belimov et al. 1995; Cakmakci et al. 2001; Öztürk et al. 2003) and maize (Pal 1998).

N-fixation is the first mechanism suggested to promote the growth of plants by *Azospirillum*. The majority of evidence collected during the last 3 decades concerning this mechanism has generated controversy (Bashan et al. 2004). At the same time, *Azospirillum* lead the list of PGPR assessed in worldwide experiments (Burdman et al. 2000; Dobbelaere et al. 2003; Vessey 2003; Lucy et al. 2004; Ramirez and Mellado 2005). *Pseudomonas* and *Bacillus* species (Alam et al. 2001; Cakmakci et al. 2001; Glick et al. 1994; Kokalis-Burelle et al. 2002), and the other PGPR and endophytic

bacteria, such as *Enterobacter*, *Klebsiella*, *Burkholderia*, and *Stenotrophomonas*, have been gaining attention in the recent years, because of their association with important crops and potential to enhance the plant growth (Chelius and Triplett 2000; Sturz et al. 2001; Verma et al. 2001; Dong et al. 2003; Ramirez and Mellado 2005).

Some greenhouse and field experiments have shown repeatedly that the transfer of nitrogen fixed by *Azospirillum* spp. to the plant is not enough (Bashan and Holguin 1997; Kennedy et al. 1997; Kennedy and Chellapillai 1998; Bashan et al. 2004). Yet other studies showed that the bacteria cannot fulfil all of the nitrogen requirements of the plants; nevertheless, it can contribute only significant amounts of nitrogen. For example, seed inoculation of chickpea with *Rhizobium*, N-fixing *Bacillus subtilis* (OSU-142) significantly increased N percentage compared with the control treatment and may substitute costly N fertilizers in chickpea production even in cold highland areas (Elkoca et al. 2008).

Similarly, N-fixing bacterial strains *Pseudomonas putida* RC06, *Paenibacillus polymyxa* RC05 and RC14, and *Bacillus* OSU-142 have great potential, and as formulations, they are used as biofertilizers for better yield and the quality of wheat, sugar beet, and spinach growth (Cakmakci et al. 2007; Cakmakci et al. 2006). The N-fixing *Bacillus* strains and *A. brasilense* sp246 have a potential on plant growth activity of spring wheat and barley cultivation in organic and low-N input agriculture (Öztürk et al. 2003; Canbolat et al. 2006). Inoculation with the *Rhizobium leguminosarum* E11 and *Azotobacter* sp. S8, strain E11 increased root dry weight, root length, and growth in cotton (Hafeez et al. 2004). Significant positive effects on growth, nodule number, and yield of soybean were obtained after inoculation with *Bradyrhizobium* spp strains S62 and S63 (Egamberdiyeva et al. 2004).

Furthermore, inoculation commonly and significantly reduced the required doses of nitrogen fertilization in numerous greenhouse and field experiments in a lot of plant species (Bashan and Levanony 1990; Bashan and Holguin 1997; Bashan et al. 2004).

The strain(s), soil types, climate, and the development of appropriate formulations as well as strategies of field experimentations should be considered for a successful application of PGPR when using as fertilizers.

2.2 Solubilization of Phosphates

Phosphorous (P), next to nitrogen, is one of the major and key nutrients limiting plant growth (Kumar and Narula 1999; Sundara et al. 2002; Podile and Kishore 2006). Even in phosphorous rich soil, most of the P is unavailable for the plants, as large amount of soil P is found in its insoluble form. Phosphate solubilizing bacteria (PSB) are common in the rhizosphere and can be used to overcome this problem (Vessey 2003).

PSB secretes organic acids and phosphatases that converts the insoluble phosphates into soluble monobasic and dibasic ions and may also solubilize inorganic phosphate and makes soil phosphorus, which otherwise remain fixed, available to

the plants (Kumar and Narula 1999; Whitelaw 2000; Gyaneshwar et al. 2002). In other words, phosphate solubilizing microorganisms convert insoluble phosphates into soluble forms through the process of acidification, chelation, exchange reactions, and production of gluconic acid (Rodriguez et al. 2004; Chung et al. 2005; Hameeda et al. 2008).

PSB are ubiquitous (Gyaneshwar et al. 2002), and *Bacillus*, *Enterobacter*, *Erwinia*, and *Pseudomonas* spp. are among the most potent strains (Podile and Kishore 2006). PSB is common in rhizospheres of crop plants, and few examples of beneficial association with phosphate solubilizing PGPR and plants include *B. megaterium* (M-3) and chickpea (Elkoca et al. 2008), *B. licheniformis* RC08 and *B. megaterium* RC07, and wheat and spinach (Cakmakci et al. 2007), *Enterobacter agglomerans* and tomato (Kim et al. 1998), *P. chlororaphis*, *P. putida*, and soybean (Cattelan et al. 1999), *Avena sativa* and PGPR strains isolated from the rhizosphere of forage (WenXing et al. 2008), *Serratia marcescens* EB 67, *Pseudomonas* sp. CDB 35, and maize (Hameeda et al. 2008).

In the controlled environment and in the field trials, single and dual N-fixing *B. subtilis* (OSU-142) and P-solubilizing *B. megaterium* (M-3) inoculations significantly increased all the parameters investigated in chickpea (plant height, shoot, root and nodule dry weight, N%, chlorophyll content, pod number, seed yield, total biomass yield, and seed protein content) compared with the control treatment, equal to or higher than N, P, and NP treatments (Elkoca et al. 2008).

In another research, Orhan et al. (2006) reported that plant growth promoting effects of two *Bacillus* strains OSU-142 (N-fixing) and M3 (N-fixing and phosphate solubilizing) were tested alone or in combinations of organically grown primocane fruiting raspberry (cv. Heritage) plants and a significant increase in yield (33.9 and 74.9%), cane length (13.6 and 15.0%), number of cluster per cane (25.4 and 28.7%), and number of berries per cane (25.1 and 36.0%) were observed when compared with that of the control.

Hameeda et al. (2008) reported that plant biomass increased with *Serratia marcescens* EB 67 and *Pseudomonas* sp CDB 35 under both glasshouse and field conditions. And also, seed treatment with EB 67 and CDB 35 increased the grain yield of field-grown maize by 85 and 64% compared with the uninoculated control.

Furthermore, four strains namely, *Arthrobacter aureofaciens*, *Phyllobacterium myrsinacearum*, *Rhodococcus erythropolis*, and *Delftia* sp. are being reported for the first time as PSB after confirming their capacity to solubilize considerable amount of tricalcium phosphate in the medium by secreting organic acids (Chen et al. 2006). Peix et al. (2001) notified that *Mesorhizobium mediterraneum* strain PECA21 was able to mobilize phosphorous efficiently in barley and chickpea when tricalcium phosphate was added to the soil. Also, treating with insoluble phosphates and inoculating with strain PECA21, the phosphorous content, dry matter, nitrogen, potassium, calcium, and magnesium content in both plants were significantly increased.

It was known that natural phosphate rocks have been identified as an alternative for P fertilizers. For example, there are almost 40 million tons of phosphatic rock deposits in India (Rodríguez and Fraga 1999), and this material should provide a

cheap source of phosphate fertilizer for crop production (Halder et al. 1990); especially, should be considered in organic production of horticulture and the other crops.

2.3 Plant Growth Regulators

Several stages of plant growth and development such as cell elongation, cell division, tissue differentiation, and apical dominance are controlled by the plant hormones, especially auxins and cytokinins. The biosynthesis and the underlying mechanism of auxins and cytokinins action are subjects of intense investigation. Auxins and cytokinins can be synthesized by both the plants and the microorganisms. Although the role of phytohormone biosynthesis by microorganisms is not fully explained, it is stated that direct mechanisms of plant growth by PGPR include production of plant hormones such as auxins, cytokinins, GAs, and lowering of plant ethylene levels (Glick 1995; Costacurta and Vanderleyden 1995; Lucy et al. 2004). A list of examples of plant growth stimulating phytohormones produced by PGPR is given in Table 1.

Auxin, indole-3-acetic acid (IAA), is a quantitatively important phytohormone produced by a member of PGPR, and treatment with auxin-producing rhizobacteria increased the plant growth (Vessey 2003; Erturk et al. 2008). On the one hand, most beneficial bacteria such as *Rhizobium*, *Bradyrhizobium*, and *Azospirillum* synthesize IAA via the Indole-3-pyruvic acid (IPyA) pathway (Manulis et al. 1991; Costacurta and Vanderleyden 1995; Patten and Glick 1996; Burdman et al. 2000). On the other hand, some pathogenic bacteria such as *Pseudomonas syringae*, *Agrobacterium tumefaciens*, and *Erwinia herbicola* synthesize IAA predominantly via the indole-3-acetamide (IAM) pathway (Dobbelaere et al. 2003).

The role of IAA in the observed plant growth promotion was obtained by attempting to mimic the effect of the bacterium for the root growth by the direct application of IAA on the roots. Inoculation with *Bacillus* RC23, *Paenibacillus polymyxa* RC05, *B. subtilis* OSU142, *Bacillus* RC03, *Comamonas acidovorans* RC41, *B. megaterium* RC01, and *B. simplex* RC19 with tea (*Camellia sinensis)* cuttings enhanced rooting percentages when compared with control because of IAA production of bacteria. Similarly, treatments of hardwood stem cuttings of kiwifruit cv. Hayward, stem cuttings of two rose selections (ERS 14, *Rosa canina*, and ERS 15, *Rosa dumalis*), sour cherry (*Prunus cerasus*) softwood and semi-hardwood cuttings and *Pistacia vera* cuttings with *Agrobacterium rubi* (A1, A16, and A18) and *Bacillus subtilis* OSU142 promoted rooting ratio and increased the numbers of lateral roots (Ercisli et al. 2000; Ercisli et al. 2003; Esitken et al. 2003b; Ercisli et al. 2004; Orhan et al. 2007).

In addition, *Azospirillum* is not only capable of nitrogen fixation but also codes for plant growth hormone auxins (Elmerich 1984). Strains of *Azospirillum* showed that production depended on the type of culture media and availability of tryptophan as a precursor. *A. brasilense* Cd produced the highest level of IAA among the

Table 1 Examples of plant growth stimulating phytohormones produced by PGPR

Phytohormones	PGPR	References
Gibberellin	*Acetobacter diazotropicus*	
	Herbospirillum seropedicae	Bastian et al. (1998)
	Bacillus lichenifirmis	
	Bacillus pumilus	Gutierrez-Manero et al. (2001)
	Bacillus cereus MJ-1	
	Bacillus macroides CJ-29	Joo et al. (2004)
	Bacillus pumilus CJ-69	
IAA	*Agrobacterium* sp.	
	Alcaligenes piechaudii	Barazani and Friedman (1999)
	Comamonas acidovorans	
	Azospirillum brasilense	Kaushik et al. (2000)
	Aeromonas veronii	
	Enterobacter cloacae	Mehnaz et al. (2001)
	Enterobacter sp.	Mirza et al. (2001)
	Comamonas acidovorans RC41	
	Paenibacillus polymyxa RC05	
	Bacillus RC23	Erturk et al. (2008)
	Bacillus simplex RC19	
	Bacillus RC03	
	Bacillus megaterium RC01	
Cytokinin	*Paenibacillus polymyxa*	Timmusk et al. (1999)
	Pseudomonas fluorescens	de Salamone et al. (2001)
		Bent et al. (2001)
ACC deaminase	*Pseudomonas putida*	Mayak et al. (1999)
	Pseudomonas cepacia	Cattelan et al. (1999)
	Enterobacter cloacae	Saleh and Glick (2001)
	Pseudomonas brassicacearum Am3	Belimov et al. (2007)
	Variovorax paradoxus 5C-2	Belimov et al. (2009)
	Pseudomonas putida Biovar B	Rodriguez et al. (2008)
	Pseudomonas putida N21	
	Pseudomonas aeruginosa N39	Zahir et al. (2009)
	Serratia proteamaculans M35	

Azospirillum strains tested (El-Khawas and Adachi 1999; Radwan 1998; Bashan et al. 2004).

The isolation and quantification of cytokinins in nonpathogenic soil bacteria in general and diazotrophic bacteria in particular has received a little attention. Cytokinins are a diverse group of labile compounds that are usually presented in small amounts in biological samples and are often difficult to identify and quantify (Dobbelaere et al. 2003).

Cytokinins are produced by bacteria such as *Azospirillum* and *Pseudomonas* spp. (Gaudin et al. 1994). Moreover, a few PGPR strains were reported to produce cytokinins, such as *Rhizobium leguminosarum*, *Paenibacillus polymyxa*, and *Pseudomonas fluorescens* (Noel et al. 1996; Timmusk et al. 1999; de Salamone et al. 2001; Bent et al. 2001; Vessey 2003). These studies sufficiently cloud the production of cytokinins, compared with IAA or GAs, in PGPR. Also, it appears that more

work is necessary before proving for the role of PGPR-produced cytokinins in plant growth promotion.

Also in the case of GAs, the bacterial genetic determinants have not been identified so far. Therefore, no mutants are available to demonstrate the role of this phytohormone in plant growth promotion (Dobbelaere et al. 2003). Also the evidence of GA production by PGPR is rare (Vessey 2003). On the other hand, PGPR such as *R. phaseoli*, *A. lipoferum*, *Azotospirillum brasilense*, *Acetobacter diazotropicus*, *Herbospirillum seropedicae*, *Bacillus licheniformis*, *B. pumilus*, *Bacillus cereus* MJ-1, *Bacillus macroides* CJ-29 were reported to produce GAs (Atzhorn et al. 1988; Bottini et al. 1989; Janzen et al. 1992; Bastian et al. 1998; Gutierrez-Manero et al. 2001; Joo et al. 2004 and Table 1). However, this is not a strong evidence of GA production in a common method of growth promotion by PGPR.

Nevertheless, in recent studies, Gutierrez-Manero et al. (2001) provide an evidence that four different forms of GAs are produced by *B. pumilus* and *Bacillus licheniformis*. Inoculation of alder (*Alnus glutinosa*) with these PGPR could effectively reverse a chemically induced inhibition of stem growth. In addition to this research, Joo et al. (2004) reported that the growth of red pepper plug seedlings was increased by *Bacillus cereus* MJ-1, *B. macroides* CJ-29, and *B. pumilus* CJ-69, though the number of leaves and stem diameter were not significantly changed. The greatest increase is in the height and the root fresh weight of the seedlings was by *B. pumilus*, which could increase the height by 12% and the root fresh weight by 20%.

In the last few years, a new mechanism of plant growth promotion involving ethylene has been proposed (Burdman et al. 2000). Showing that some soil bacteria contain 1-aminocyclopropane-1-carboxylate (ACC) deaminase (Klee et al. 1991) and 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 that 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 results in root lengthening. In some cases, the growth promotion effects of ACC deaminase-producing PGPR is the best expressed in stress conditions including drought (Zahir et al. 2008) and salt (Nadeem et al. 2007; Zahir et al. 2009) stress.

PGPR (containing ACC deaminase) boost plant growth particularly under stressed conditions by the regulation of accelerated ethylene production in response to a multitude of abiotic and biotic stresses such as salinity, drought, waterlogging, temperature, pathogenicity, and contaminants (Saleem et al. 2007). For example, under salinity stress, 1-aminocyclopropane-1-carboxylic acid-deaminase activity of *P. putida* (N21), *P. aeruginosa* (N39) and *Serratia proteamaculans* (M35) might have caused reduction in the synthesis of stress (salt)-induced inhibitory levels of ethylene (Zahir et al. 2009). Similarly, inoculation with *Variovorax paradoxus* 5C-2 improved growth, yield, and water-use efficiency of droughty peas (Belimov et al. 2009). It is reported that inoculation with *P. fluorescens* was found to be more effective in promoting root growth than that with *P. putida* as it caused up to 46% increase in root elongation and up to 94% increase in root weight of pea over the respective uninoculated drought stressed control (Arshad et al. 2008).

In addition to stress factors, recent studies indicated that canola plants inoculated with the *P. putida* strain HS-2 produced an increase in plant biomass (Rodriguez et al. 2008). The ACC-utilizing PGPR *Pseudomonas brassicacearum* strain Am3 increased in-vitro root elongation and root biomass of soil-grown tomato cv. Ailsa Craig at low bacterial concentrations but had negative effects on in-vitro root elongation at higher bacterial concentrations (Belimov et al. 2007).

2.4 Effects on Plant Growth

Since the last few decades, the response of agriculturally important crops to inoculation with PGPR was investigated in numerous field and greenhouse experiments carried out in various countries. On the basis of the given data, it was concluded that inoculation with PGPR resulted in significant yield increases in different crops, enhanced rooting of hardwood and semi-hardwood cuttings, seed germination and emergence under different conditions. In other words, they can affect plant growth and yield in a number of ways and enhancement of vegetative and reproductive growth is documented in a range of crops such as cereals or vegetables. Treatments with PGPR increase germination percentage, seedling vigor, emergence, plant stand, root and shoot growth, total biomass of the plants, seed weight, early flowering, grains, fodder and fruit yields, etc., (van Loon et al. 1998; Ramamoorthy et al. 2001). Applications of PGPR in relation to the plant growth in different subjects are described later with recent studies.

2.4.1 Yield and Yield Components

In crop production, there is a continuous demand of increasing crop productivity and quality. There are lot of agricultural practices applied for increasing the yield and the yield components. Recently, one of them is applications of PGPR for increasing yield and environment friendly crop production.

Floral and foliar applications of PGPR strains *Pseudomonas* BA-8 and *Bacillus* OSU-142 on apple trees significantly increased yield per trunk cross-section area (13.3–118.5%), fruit weight (4.2–7.5%), shoot length (20.8–30.1%), and shoot diameter (9.0–19.8%) in "Starkrimson" and yield per trunk cross-sectional area (TCSA; 14.9%) and fruit weight (6.5–8.7%) in "Granny Smith" compared with the control (Pırlak et al. 2007). Karlıdağ et al. (2007) reported similar results in apple. Thus, *Bacillus* M3 and/or OSU-142 and/or *Microbacterium* FS01 in combination have the potential to increase the yield and growth of apple trees.

In addition, Esitken et al. (2003a, 2005, 2006) and Orhan et al. (2006) reported that *Pseudomonas* BA-8, *Bacillus* OSU-142 and M3 increased the shoot length, crop yield and improved fruit quality of apricot, sweet cherry, and raspberry.

In another research, Cakmakci et al. (2006) suggested that in the greenhouse, inoculations with PGPR increased sugar beet root weight by 2.8–46.7% depending

on the species. Leaf, root, and sugar yield were increased by the bacterial inoculation by 15.5–20.8%, 12.3–16.1%, and 9.8–14.7%, respectively. Effective *Bacillus* species, such as OSU-142, RC07 and M-13, *Paenibacillus polymyxa* RC05, *P. putida* RC06, and *Rhodobacter capsulatus* RC04 may be used in organic and sustainable sugar beet agriculture.

The average weight of tomato fruit per plant treated with *Rhodopseudomonas* sp KL9 strain (82.7 g) was higher than those of others including the uninoculated control. The content of lycopene in the ripe tomato fruit increased by 48.3% with the application of *Rhodopseudomonas* sp. KL9, but *Rhodopseudomonas* sp BL6 did not show any effect on lycopene content although the lycopene content in the cells of *Rhodopseudomonas* sp BL6 were 1.12 mg/g (Lee et al. 2008a).

Dursun et al. (2008) reported that the highest rocket yield, average leaf weight, leaf length, leaf stem diameter, leaf area and root weight were obtained from *Pseudomonas* BA-7 applications when compared with *P. putidae* BA-8, *B. subtilis* OSU-142 and MFD-5, *B. megatorium* M3, *A. rubi* A-1, A-16, and A-18. The highest leaf number (8.23), leaf dry matter (6.70%), and root dry matter (11.85%) were determined in A-18, OSU-142 and MFD-5 applications, respectively, and especially *Burkholderia gladii* BA-7, *Pseudomonas* BA-8, and *Bacillus* OSU-142 have a great potential to increase the parameters of plant growth of rocket.

Although the examples of relations between the yield and PGPR applications can be increased, other recent studies such as de Freitas (2000), Herman et al. (2008), and Yıldırım et al. (2008) clearly demonstrated the potential of PGPR in increasing the plant growth and yield.

2.4.2 Seed Germination and Emergence

Sivritepe and Dourado (1995) reported that priming (osmoconditioning) is one of the physiological methods, which improves seed performance and provides faster and synchronized germination in vegetables. However, bio-priming with different genera, especially PGPR, have a great potential over other priming methods.

Nelson (2004) noted that PGPR were able to exert a beneficial effect upon plant growth such as increase in seed germination rate and percentage. Rodriguez et al. (2001) reported that using *Azospirillum* spp. gave better germination in both tomato and pepper seeds. Also, Vargas et al. (2001) mentioned that *Hafnia alvei* strain P3 increased germination by 36.5% when compared with the control in lettuce and inoculation of the soybean plants either with *Pseudomonas* strain PMZ2 or with *B. japonicum* increased seed emergence (Zaidi 2003). Similarly, Basavaraju et al. (2002) reported that inoculation of *Azotobacter chroococcum* strain C2 significantly increased the germination percentage in radish. The greenhouse inoculation experiment with pepper and maize pointed out that *Azotobacter* sp. strains 17 and 20 promoted pepper germination, while the *Azospirillum* strains 1 and 23 promoted maize germination (Reyes et al. 2008). Although studies were mentioned about the effect of bacterial strains on germination of different vegetable species that were conducted out under optimum conditions, Kaymak et al. (2009) suggested that bio-priming with *A. rubi* strain A16, *Burkholderia gladii* strain BA7, *P. putida* strain BA8,

B. subtilis strain BA142, *B. megaterium* strain M3 under saline stress could be useful to obtain higher seed germination percentage in radish.

Also, PGPR can be used under pathogenic factor. Thus, different isolates of plant growth-promoting rhizobacteria (i.e., *B. pumilus* (INR-7), *B. subtilis* (GBO-3), *B. subtilis* (IN937b), *B. pumilus* (SE-34), *Brevibacillus brevis* (IPC-11), *B. pumilus* (T-4), and *B. amyloliquefaciens* (IN937a)) were used for seed treatment to suppress the seedling diseases caused by fungi. Among them, isolates GBO3, IPC-11, and INR-7 increased seed germination and seedling vigour to the greatest extent (Lokesh et al. 2007). Alike, Begum et al. (2003) reported that PGPR, *B. pumilus* (SE-34), *B. pasteurii* (T4), *B. subtilis* (IN937-b), and *B. subtilis* (GBO3) strains reduced the incidence of seed mycoflora, which indirectly enhanced the seed germination percentage and vigour index of the seedlings in okra. In another recent study, de Araujo (2008) reported that the inoculation of seeds with *B. subtilis* is a promising technological alternative for seed treatment owing to the fact that inoculation with *B. subtilis*, formulated with oyster meal, increased emergence in cotton and soybean.

2.4.3 Rooting of Cuttings

There are many physiological and environmental factors that influence root formation, with exogenous treatments on cuttings being particularly important (Couvillon 1998). Growers have attempted to stimulate rooting by applying growth regulators, various chemical substances, etc. However, the use of chemicals can produce environmental problems and increase proportion costs. Ecological problems have raised interest in environmental friendly sustainable agricultural practices (Salantur et al. 2005). Therefore, use of PGPR can overcome such problems associated with environment (Kaymak et al. 2008).

Recent studies showed that bacteria in several genera (*Agrobacterium*, *Bacillus*, *Streptomyces*, *Pseudomonas*, and *Alcaligenes*) induce root formation and growth in stem cuttings (Bassil et al. 1991; Hatta et al. 1996; Rinallo et al. 1999). More recently, PGPR such as *A. rubi* (A1, A16 and A18), *B. subtilis* (OSU142), *Bacillus* (BA16, RC03, RC23), *B. gladii* (BA7), *P. putida* (BA8), *B. megatorium* (M3 and RC01), *Paenibacillus polymyxa* (RC05), *Comamonas acidovorans* RC41, and *B. simplex* RC19 were effectively used for both hardwood and semi-hardwood cuttings to obtain higher rooting percentages in sour cherry (Ercisli et al. 2000; Esitken et al. 2003b), kiwifruit (Ercisli et al. 2003), grapevine (Köse et al. 2003), rose (Ercisli et al. 2004), pistachio (Orhan et al. 2006), tea (*Camellia sinensis* var. *Sinensis*) (Erturk et al. 2008), and mint (*Mentha piperita* L.) (Fig. 1) (Kaymak et al. 2008).

2.4.4 Nutrient Uptake

Living plants require 16 essential elements to survive. Three of 16 elements (carbon, hydrogen, and oxygen) are supplied primarily from air and water. The remaining 13 are normally absorbed by plant roots. Each of these essential elements has at least one specially defined role in plant growth (Swaider et al. 1992; Decateau 2000).

Fig. 1 Effect of inoculation with PGPR (*Agrobacterium rubi* A16, *Burkholderia gladii* BA7, *Peseudomonas putida* BA8, *Bacillus subtilis* OSU142, and *Bacillus megatorium* M3) on root formation of mint cuttings

PGPR have been promised as a component in approaching for maintaining adequate plant nutrition and reducing the negative environmental effects of fertilizers. PGPR might increase nutrient uptake from soils, thus reducing the need for fertilizers and preventing the accumulation of nitrates and phosphates in agricultural soils (Yang et al. 2009). It is known that phosphorous and nitrogen is the major and key nutrients limiting plant growth and important macronutrient required for plant growth (Kumar and Narula 1999; Sundara et al. 2002; Podile and Kishore 2006).

Additionally, some PGPR promote root development (Mantelin and Touraine 2004) by the production of phytohormones such as indole acetic acid (Kloepper et al. 2007). Given that root tips and root surfaces are sites of nutrient uptake, it is likely that one mechanism by which PGPR lead to increased nutrient uptake is via stimulation of root development (Yang et al. 2009). It has also been suggested that PGPR increase uptake of mineral ions via stimulation of the proton pump ATPase (Mantelin and Touraine 2004), although experimental evidence for this is lacking (Yang et al. 2009).

Several studies can be given about the relations with PGPR and enhancement of nutrient uptake. For example, Naveed et al. (2008) notified that PGPR application significantly enhanced N, P, and K uptakes. The *Pseudomonas fluorescens* biotype G (N-3) was found to be the best in increasing the grain yield of maize and nutrient uptake. In addition, the inoculation process with *Azospirillum* and *Bacillus* spp. showed positive response in enhancing higher accumulation of nitrogen, phosphorus, and potassium in the plant tissues, enhanced root dry weight and top growth of the oil palm seedlings under field nursery conditions (Amir et al. 2005).

In other recent study, Dursun et al. (2008) reported that *Burkholderia gladii* BA-7, *P putidita* BA-8, *B. subtilis* OSU-142 and MFD-5, *B. megaterium* M3, *A. rubi* A-1, A-16, and A-18 applications increased mineral contents particularly N, K, P, Zn, Fe, Mn, Na, Ca, and Mg in rocket leaves when compared with the control.

In a study aimed at assessment of effects of foliar application of bacteria *Bacillus* OSU-142, *Burkholderia* OSU-7, and *Pseudomonas* BA-8 on yield and growth of apricot, it was stated that application of bacteria resulted in an increase of N, P, K, Ca, and Mg contents of leaves (Esitken et al. 2005). In a similar study, Esitken et al. (2003a) suggested that N, P, K, Ca, and Mg contents of leaves were higher on OSU 142-treated trees than on the untreated control and OSU 142 has the potential to increase the yield of apricot trees.

Therefore, PGPR contributed significantly to the reducing nutrient build up in the soil. Several studies are underway that will further define the utility of PGPR in nutrient management strategies aimed at reducing fertilizer application rates and nutrient runoff from agricultural sources (Yang et al. 2009; Kumar et al. 2009).

3 Indirect Plant Growth Promotion

Induced systemic resistance (ISR), antibiosis, competition for nutrients, parasitism, production of metabolites suppressive to deleterious rhizobacteria are some of the mechanism that indirectly benefit plant growth.

3.1 Induced Systemic Resistance

More recently, biological control has been considered as an alternative strategy to manage soil-borne plant diseases. Available literature revealed positive effects of specific strains of rhizobacteria on growth of many plant species in soils in which more or less defined pathogens cause substantial losses. For this reason, several rhizobacteria have extensively been used as biological agents to control many soil-borne plant pathogens (Jeun et al. 2004; Dell'Amico et al. 2005; Rajkumar et al. 2005).

A strain, *P. fluorescens* WCS417, active against *Fusarium oxysporum* f. sp. *dianthi* was tested on carnation and results showed that bacteria, while remaining confined to the plant root system, were still protective when the pathogen was slash-inoculated into the stem (Van Peer et al. 1991). This protective effect had to be plant-mediated because in this case the rhizobacteria and the pathogenic fungus were never found to contact each other on the plant (Van Loon and Bakker 2006). Several strains of PGPR, which applied to roots of cucumber, and the leaves were subsequently challenged inoculation with the anthracnose fungus *Colletotrichum orbiculare* (Gang et al. 1991). The phenomenon was called ISR. (Van Loon et al. 1998; Vallad and Goodman 2004; Van Loon and Bakker 2006; Choudhary et al. 2007)

It is thought that the inducing rhizobacteria in the plant roots produce signal, which spreads systemically within the plant and increases the defensive capacity of the distant tissues from the subsequent infection by the pathogens. ISR thus extended the protective action of PGPR from their antagonistic activity against soil-borne pathogens in the rhizosphere to a defense-stimulating effect above the surface of the ground tissues against foliar pathogens (Van Loon and Bakker 2006).

ISR appears phenotypically similar to SAR, which is the phenomenon that once a plant has been infected by a pathogen and been able to effectively resist it, it has become more resistant to subsequent challenge inoculation by the same and other pathogens and, in some instances, even insects (Sticher et al. 1997; Van Loon et al. 1998; Van Loon and Bakker 2006). SAR occurs in distal plant parts following localized infection by a necrotizing pathogen. It is controlled by a signaling pathway that depends upon the accumulation of salicylic acid and the regulatory protein NPR1. In contrast, ISR is induced by selected strains of nonpathogenic PGPR. ISR functions independent from SA, but requires NPR1 and is regulated by jasmonic acid and ethylene (Walters and Heil 2007).

To reduce crop loss, pesticides are generally used. They are cost-effective and thus have become an integral part of modern agriculture. Environmental and human health-related concerns associated with use of hazardous chemicals have necessitated the search for eco-friendly alternatives. Such approaches must enhance and sustain agricultural productivity and at the same time be safe from environmental and health perspectives (Raj et al. 2003a).

Therefore, for economic reasons biological crop protectants can only seldom compete with highly effective chemicals. However, ISR is only one of the mechanisms that may be mobilized to counteract plant pathogens in an environmentally friendly and durable way. Integrating ISR-triggering PGPR into disease management programs in conjunction with other strategies will be a worthwhile approach to explore (Van Loon and Bakker 2006).

3.2 Suppression of Plant Diseases, Insects, and Nematodes by PGPR

Biocontrol is the process by which a pathogenic organism is maintained at low inoculum density or controlled or eradicated by beneficial organisms. Several microorganisms such as PGPR and insects present in the natural environment serve as potential biocontrol agents.

3.2.1 Bacterial Plant Diseases

The bacteria associated with plants exist as epiphytes, endophytes, and pathogens. Phytopathogens are comparatively few in both type and number, and all bacterial phytopathogens described to date fall within the domain Bacteria, formerly known as the *Eubacteria*. Bacterial phytopathogens that possesses a cell wall can be

subdivided into Gram-positive (*Clavibacter*, *Curtobacterium*, *Rathayibacter*, and *Streptomyces*) and Gram-negative (*Acidovorax*, *Agrobacterium*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Pantoea*, *Pseudomonas*, *Ralstonia*, and *Xanthomonas*) (Saddler 2002).

Bacterial soft rot of vegetables; blackleg of potato; fire blight of pome fruits; angular leaf spot or black arm, of cotton; bacterial blights of bean, lack rot of crucifers, southern bacterial wilt, bacterial wilt of cucurbits, ring rot of potato, bacterial canker of tomato, crown gall, hairy root, and cane gall, and common scab of potato are the more common bacterial diseases (Walker 1957; Waller et al. 2002).

Several cultural practises such as crop rotation, mixed cropping and intercropping, selection of cultivar, tillage, planting time, fertilization and irrigation, or highly effective chemical substances affect some diseases in different ways depending on the form of their application (Termorshuizen 2002). Recently, many microorganisms are increasingly used as inoculants for biocontrol (Romero et al. 2003; Chinnasamy 2005; Aliye et al. 2008; Xue et al. 2009). PGPR are nonpathogenic, environmental-friendly, cheaper to produce and easy to handle, and may create long-lasting effects (Chinnasamy 2005).

For instance, tomato is prone to a number of bacterial diseases, among which bacterial canker disease caused by *Clavibacter michiganensis* ssp. *michiganensis* is one of the most important diseases and nearly 100% crop loss can occur (Boudyach et al. 2001; Umesha 2006). Utkhede and Koch (2004) reported that treatments with *B. subtilis* (Quadra 136 and 137) and *Trichoderma harzianum* (R), *Rhodosporidium diobovatum* (S33), applied as a spray at 0.3, 0.6, 10 g^{-1}, have the ability to prevent the incidence of bacterial canker of tomato plants caused by *C. michiganensis* subsp. *michiganensis* under greenhouse conditions. Similarly, tomato seeds were treated with PGPR strains *B. subtilis* GBO3, *B. amyloliquefaciens* IN937a and *Brevibacillus brevis* IPC11 were recorded for maximum disease protection for bacterial canker under greenhouse conditions (Girish and Umesha 2005). Recent studies about the relations with bacterial diseases and PGPR are given in Table 2.

3.2.2 Fungal Plant Diseases

Fungal pathogens found on plants can be classified in different taxonomic groups. A few fungal pathogens such as rusts, powdery and downy mildews are obligate parasites. However, most of the plant pathogens are necrotrophs, killing plant tissues for their nutrition (Waller and Cannon 2002).

Exclusion or eradication of a disease from production areas, highly effective chemical substances or biological control of plant diseases have been suggested to protect the plants from fungal pathogens. Recently, PGPRs are increasingly and extensively used in biological control of fungal plant diseases (Altindag et al. 2006; Lourenco et al. 2006; Saravanakumar et al. 2007; Akgul and Mirik 2008; Sang et al. 2008; Dutta et al. 2008).

For example, apricot is the most important fruit crop grown in Anatolia, with approximately 600,000 tons of fruit produced annually, and Turkey dominates

Table 2 Examples of suppression of bacterial diseases by PGPR in different plant species

Phytopathogens	Species	PGPR	References
Pseudomonas syringae pv. *lachrymans*	Cucumber	*Pseudomonas putida* 89B-27 *Serratia marcescens* 90–166	Liu et al. (1995)
Pseudomonas syringae pv. *glycinea*	Soy bean	*Pseudomonas* sp. *Erwinia herbicola*	May et al. (1996)
Xanthomonas albilineans	Sugar cane	*Pentoena dispersa*	Zhang and Birch (1997)
Erwinia amylovora	Apple	*Erwinia herbicola* C9-1 *Pseudomonas fluorescens* A506	Pusey (1997)
		Single-strain treatments and three-way mixture of *Bacillus pumilus* INR7, *Curtobacterium flaccumfaciens* ME1 and *Bacillus subtilis* GB03	Raupach and Kloepper (1998, 2000)
Ralstonia solanacearum	Tomato	*Bacillus subtilis* B2G	Lemessa and Zeller (2007)
		Pseudomonas sp. (APF1) *Acinetobacter* sp. (Xa6) *Enterobacter* sp. (Xy3)	Xue et al. (2009)
Clavibacter michiganensis subsp. *michiganensis*		*Azospirillum brasilense* Sp7	Romero et al. (2003)
Xanthomonas campestris pv. *vesicatoria*		*Azospirillum* sp. (BNM-65)	
Ralstonia solanacearum	Eucalyptus	*Pseudomonas fluorescens* WCS417r *Pseudomonas putida* WCS358r	Ran et al. (2005)
	Potato	*Bacillus subtilis* PFMRI *Paenibacillus macerans* BS-DFS and PF9	Aliye et al. (2008)
Xanthomonas axonopodis pv. *malvacearum*	Cotton	*Bacillus cereus* MT5-5, MT5-6, L2-1 *Achromobacter xylosoxidans* L2-2, *Brevibacterium* sp. MT5-11	Ishida et al. (2008)

apricot production in the world (Ercisli 2009). Therewithal, brown rot caused by *Moniliana laxa* Ehr. is one of the most destructive diseases of apricot in Turkey. This pathogen is able to destroy the whole annual crop in the phase of blossom, although it can kill shoots up to 30 cm beyond the initial blossom infection, and management of brown rot in Turkey is in general carried out by fungicide application (Gulcan et al. 1999). Altindag et al. (2006) suggested that *Burkholdria gladii* OSU 7 has the potential to be used as biopesticide for effective management of brown rot disease on apricot.

Similarly, pepper (*Capsicum annum* L.) is one of the most important market vegetables grown worldwide, but the yield and quality of marketable peppers are frequently limited by Phytophthora blight. The incidence of this disease has

continued to increase production areas since the pathogen can infect roots, crowns, and even foliar parts of pepper plants through splashing rains or overhead irrigation waters (Ristaino and Johnston 1999; Hausbeck and Lamour 2004). Control of this disease has usually depended on chemical and cultural measures such as use of phenylamide fungicides or metalaxyl as well as crop rotation, soil amendments, use of protective mulches and water management (Matheron and Porchas 2000; Hausbeck and Lamour 2004). In a recent study, Sang et al. (2008) reported that *Pseudomonas corrugata* (CCR04 and CCR80), *Chryseobacterium indologenes* (ISE14), and *Flavobacterium* sp. (GSE09) showed consistently good control efficacy against *Phytophthora capsici*. Also, these strains could be applied by either drench or root-dip treatment as alternatives to agricultural chemicals to control Phytophthora blight of pepper. In another recent study, Akgul and Mirik (2008) also reported that *Bacillus megaterium* strains could be used for biocontrol of *Phytophthora capsici*.

The combination of *Pseudomonas* strains Pf1, TDK1, and PY15 was more effective in reducing sheath rot (*Sarocladium oryzae*) disease in rice plants compared with individual strains under glasshouse and field conditions (Saravanakumar et al. 2009).

Hernandez-Rodriguez et al. (2008) obtained that *Burkholderia* sp. MBf21, MBp1, MBf15, and *P. fluorescens* MPp4 stood out for their plant growth stimulation in maize and for the biological control exerted on *Fusarium verticillioides* M1. The strains *Burkholderia* sp. MBf21 and MBf15 showed the best results in disease suppression, which was achieved up to 80%.

The combined use of PGPR (*Bacillus cereus* strain BS 03 and a *Pseudomonas aeruginosa* strain RRLJ 04) and rhizobia (strain RH 2) were recommended for induction of systemic resistance against fusarial wilt (*Fusarium udum*) in pigeon pea (Dutta et al. 2008). Recent studies and more examples about the suppression of fungal diseases by PGPR are given in Table 3.

3.2.3 Viral Plant Diseases

Viruses are obligate parasites of submicroscopic size, with one dimension smaller than 200 nm. Virus particles, or virions, consist of segments of double or single-stranded RNA or DNA encased in protein structures, in some cases with lipid and additional substances (Waller 2002). So far at least 700 plant viruses has been discovered, many of which cause catastrophic diseases and have wide host ranges. They have been classified into three families and 32 groups (Martelli 1992; Waller 2002).

Some chemicals are used to produce virus-free plant material because they inhibit virus replication in agricultural crops. However, there are no therapeutic agents or viricides that can be applied to plants to control virus diseases. Consequently, control measures are based mainly on avoiding infection by using host plant resistance or disrupting the epidemic cycle of the disease. The use of

Table 3 Examples of suppression of fungal diseases by PGPR in different plant species

Phytopathogens	Species	PGPR	References
Rhizoctonia solani sclerotia	Cyclamen	*Serratia marcescens* B2	Someya et al. (2000)
Fusarium oxysporum f. sp. *cyclaminis*			
Fusarium oxysporium	Soybean	*Pseudomonas* PMZ2 *Bradyrhizobium japonicum*	Zaidi (2003)
Sclerospora graminicola	Pearl millet	*Bacillus pumilus* INR7 and SE34 *Bacillus subtilis* GB03	Raj et al. (2003b)
		Pseudomonas fluorescens UOM SAR 14	Raj et al. (2004)
Cronartium quercuum f.sp. *fusiforme*	Loblolly pine	*Bacillus pumilus* SE34 and T4	Enebak and Carey (2004)
Puccinia psidii	Eucalyptus	*Pseudomonas aeruginosa* FL2 *Pseudomonas* sp. MF4	Teixeira et al. (2005)
Didymella bryoniae	Muskmelon	Pseudomonas fluorescens	Sudisha et al. (2006)
Pythium ultimum, *Pythium debaryanum*, *Rhizoctonia solani*, *Fusarium oxysporum*, *Phytophthora capsici*, *Botrytis cinerea*, *Botrytis allii*, *Cladosporium fulvum*, *Aspergillus* sp.	Sesame (in vitro)	*Paenibacillus polymyxa* E681	Ryu et al. (2006)
Exobasidium vexans	Tea	*Pseudomonas fluorescens* Pf1	Saravanakumar et al. (2007)
Fusarium spp. *Didymella bryoniae* *Myrothecium* spp.	Watermelon	*Bacillus subtilis* GBO-3 and *Brevibacillus brevis* IPC-11 *Bacillus pumilus* SE34 and T4	Lokesh et al. (2007)
Fusarium oxysporum f. sp. *lycopersici*	Tomato	*Paenibacillus lentimorbus* GBR158	Son et al. (2008)
Phytopthora capsici	Red pepper	*Bacillus subtilis* R33 and R13	Lee et al. (2008b)
Phytopthora capsici	Chili pepper	*Paenibacillus polymyxa* GBR-462	Kim et al. (2009)
Fusarium oxysporum L sp. *lycopersici*	Tomato	*Azospirillum brasilense* *Bacillus subtilis*	Abo-Elyousr and Mohamed (2009)
Rhizoctonia solani	Wheat	*Azotobacter* sp. WPR-51	Fatima et al. (2009)

genetically resistant cultivars provides effective control of many viral diseases. Mechanisms of resistance vary, some are explained to effects on vectors, whereas others may inhibit viral replication (Waller 2002).

Kirankumar et al. (2008) reported that *Pseudomonas* B-25 was highly efficient in promoting growth, fruit yield, and nutrient uptake of tomato in the presence of tobacco mosaic virus (TMV) pathogen, and the incidence of pathogenesis was markedly less after PGPR treatment. Similarly, biological control using PGPR

protected tomato plants against cucumber mosaic virus (CMV) under greenhouse and to a limited extent in the field conditions (Sikora and Murphy 2005). In another research, *P. fluorescens* strains were investigated for biocontrol efficacy against tomato spotted wilt virus (TSWV) in tomato. Virus concentration value clearly showed a reduction in viral antigen concentration in *P. fluorescens*-treated tomato plants corresponding to reduced disease ratings. All the *P. fluorescens*-treated tomato plants also showed enhanced growth and yield compared with control plants. Hence, it was suggested that PGPR could play a major role in reducing TSWV and increasing yield in tomato plants (Kandan et al. 2005). Banana bunchy top disease (BBTD) caused by Banana bunchy top virus (BBTV) is the most serious virus disease of banana plantations world wide. *P. fluorescens* Pf1 and CHA0 were significantly effective in reducing BBTV under field conditions, recording 33.33% infection with 60% reduction over control (Harish et al. 2008).

In a greenhouse experiment, *P. fluorescens* FB11 and *Rhizobium leguminosarum* FBG05 were tested alone and in combination as seed inoculants to induce systemic resistance in faba bean against bean yellow mosaic potyvirus (BYMV). The results demonstrated that BYMV challenged plants emerged from *Pseudomonas* inoculated seeds not only showed a pronounced and significant reduction in percent disease incidence but also a significant reduction in virus concentration in the challenged plants, compared with the nonbacterized seeds. *Rhizobium* alone also showed a significant reduction in both in percent disease incidence and in viral concentration value, but the reduction was less pronounced than that resulting from *Pseudomonas* inoculation (Elbadry et al. 2006).

In a recent study, the PGPR combinations (combinations included *B. subtilis* GB03 and IN937b, *B. pumilus* SE34, INR7 and T4, *B. amyloliquefaciens* IN937a) formulated with chitosan were referred to as biopreparations. The result indicated that treatment of tomato plants with biopreparations resulted in significant enhancement of plant growth and protection against infection by CMV (Murphy et al. 2003). Zehnder et al. (2000) reported that CMV symptom development was significantly reduced on PGPR-treated (*B. pumilus* SE34, *Kluyvera cryocrescens* IN114, *B. amyloliquefaciens* IN937a, and *B. subtilus* IN937b) plants compared with control, but the percentage of infected plants and tomato yields were not significantly different among treatments, suggested that PGPR-mediated induced resistance against CMV infection following mechanical inoculation into tomato can be maintained under field conditions.

Tomato plants treated with PGPR (*B. amyloliquefaciens* 937a, *B. subtills* 937b, and *B. pumilus* SE34), applied as an industrially formulated seed treatment, a spore preparation mixed with potting medium (referred to as powder), or a combined seed-powder treatment, were evaluated under field conditions for induced resistance to tomato mottle virus (ToMoV), resulted in reduced ToMoV incidence and disease severity. In some cases, a corresponding increase in fruit yield was observed. The use of PGPR could become a component of an integrated program for management of this virus in tomato (Murphy et al. 2000)

It was known that there are no highly effective chemical substances that can be applied to plants to control viral disease of agricultural or horticultural crops. For

exclusion or eradication of a viral disease from production areas, highly effective chemical substances cannot be suggested; however, biological control with PGPR may be suggested to protect these areas or plants from viral pathogens. Nevertheless, it is recommended that more work must be conducted because of the complexity and variability of virus diseases.

3.2.4 Nematodes

Plant–parasitic nematodes cause serious crop losses in production areas,e.g., yield loss of tomato due to root-knot nematodes (*Meloidogyne* spp.) ranges from 39.7 to 46.0% in India (Reddy 1985), and are among the most important agricultural pests (Koenning et al. 1999; Siddiqui and Akhtar 2008). The control of nematodes is difficult because nematodes mostly inhabit the soil and generally attack and settle around or inside the roots of the plants. During the last few decades, plant disease control has been based largely on the use of chemicals (Siddiqui et al. 2001). Although chemical nematicides are effective, easy to apply, and show rapid effects, they have begun to be withdrawn from the market in some developed countries owing to concerns about public health and environmental safety (Schneider et al. 2003; Nico et al. 2004). The search for novel, environmentally friendly alternatives with which to manage plant–parasitic nematode populations has, therefore, become increasingly important (Tian et al. 2007).

Biological control using microbial antagonists is one potential alternative to chemical nematicides (Burkett-Cadena et al. 2008). PGPR can also be used for the biological control of plant parasitic nematodes. Among the biological control agents that have been assessed are *B*. spp. and *Pseudomonas* spp. dominant populations in the rhizosphere that are able to antogonize nematodes (Tian et al. 2007).

Recently, rhizobacteria-mediated ISR in plants has been shown to be active against nematode pests. Plant growth-promoting rhizobacteria can bring about ISR by strengthening the physical and mechanical resistance of the cell wall of plants. They also change the physiological and biochemical ability of the host to promote the synthesis of defence chemicals against the challenge pathogen (van Loon et al. 1998; Ramamoorthy et al. 2001; Tian et al. 2007). Siddiqui and Shaukat (2004) concluded that fluorescent Pseudomonads ISR against root-knot nematode via a signal transduction pathway, which is independent of SA accumulation in roots.

In other words, PGPR may suppress pests and pathogens of plants and promote plant growth. For example, *P. aeruginosa* and *B. subtilis* exhibited nematicidal activity by killing the second stage larvae of *Meloidogyne javanica* to a varying degree. Especially, *B. subtilis* significantly suppressed root-knot infection and nematode population densities under greenhouse and field conditions and thereby enhanced plant growth and yield in mungbean (Siddiqui et al. 2001).

In a different example, *P. putida* promoted tomato growth in nematode-infected and nematode-free plants but growth promotion was higher in the infected ones. *P. putida* was better in reducing galling and nematode multiplication than arbuscular mycorrhizal fungus (Siddiqui and Akhtar 2008).

In another recent study, Li et al. (2005) reported that *Brevibacillus brevis* and *B. subtilis* exhibited strong nematicidal activity by killing the second stage larvae of *Meloidogyne javanica* to varying degrees in the greenhouse. The toxic principles of bacterium *B. subtilis* B7 that showed the highest juvenile mortality were partially characterized.

The influence of *P. fluorescens* as the treatment on the seed germination, migration, and penetration of *Meloidogyne incognita* in aubergine was evaluated under laboratory conditions. The results revealed that *P. fluorescens* promoted germination (87.5%) and was effective in reducing root penetration by *M. incognita* and the number of gall formation was also controlled by 70.3% (Inam-ul-Haq et al. 2003).

Rhizobacteria reported to show antagonistic effects against nematodes include members of different genera are given in Table 4.

3.2.5 Insects

Next to phytochemical insecticides, biocontrol agents of microbial origin play a role in pest management (Gandhi et al. 2006). Among the biocontrol agents, the strains of PGPR, *P. fluorescens* is the promising one (Commarea et al. 2002). They activate systemic resistance (Raupach and Kloepper 1998) by inducing plants' latent defense mechanisms and to control insect pests (Zehnder et al. 1997; Commarea et al. 2002) in addition to exerting beneficial effect on plant growth promotion (Gandhi et al. 2006).

Herman et al. (2008) notified that there are several examples of plants treated with PGPR, which showed a decrease in insect herbivory. Zehnder et al. (1997) used PGPR to reduce feeding by the spotted cucumber beetle, *Diabrotica undecimpunctata howardi* Barber. Boughton et al. (2006) reported that plants treated with defence elicitors caused the green peach aphid, *Myzus persicae*, to significantly decrease in their population growth when compared with that of the control plants. Similarly, Herman et al. (2008) notified that *B. subtilis* and *B. amyloliquefaciens* could be useful in *Myzus persicae* management program, for pepper plants grown in locations with consistently high aphid pressure. Additionally, white clover and *Medicago* plants grown in the presence of a *Pseudomonas*-like PGPR were better able to resist the effects of blue-green aphids (Kempster et al. 2002).

The talc-based formulation of two *P. fluorescens* PF1, FP7 and its mixture were tested against leaffolder in rice. The application of talc-formulation through seed, root, soil, and foliar spray significantly reduced leaffolder incidence both under greenhouse and field conditions. The mixture of two strains performed better than the individual strains. Additionally, *Pseudomonas* treated leaves altered the feeding behavior of leaffolder larvae and reduced larval and pupal weight, increased larval mortality and incidence of malformed adults under in vitro conditions. An increased population of natural enemies of leaffolder and predatory spider was noticed in *Pseudomonas* treated plots under field conditions, which yielded 12–21% more rice (Commarea et al. 2002). PGPR belonging to *Pseudomonas* spp. are being exploited

Table 4 Reported PGPR show antagonistic effects against nematodes

Nematodes	Species	PGPR	References
Meloidogyne incognita	Lettuce and tomato	*Pseudomonas* sp. W34 *Bacillus cereus* S18	Hoffmann-Hergarten et al. (1998)
Globodera pallida	Potato	*Agrobacterium radiobacter* G12A *Rhizobium etli* G12	Hackenberg et al. (1999) Reitz et al. (2000)
Meloidogyne incognita	Tomato and banana	*Bacillus cereus*, *B. subtilis*, *Pseudomonas fluorescens*, *Pseudomonas chlororaphis* *Burkholderia cepacia*	Jonathan et al. (2000)
	Bell pepper	*Burkholderia cepacia* Bc-2 *Burkholderia cepacia* Bc-F	Meyer et al. (2001)
Meloidogyne javanica	Tomato	*Pseudomonas aeruginosa* IE-6S(+) *Pseudomonas fluorescens* CHA0 *Pseudomonas aeruginosa* strain 7NSK2 *Pseudomonas fluorescens* CHA0	Siddiqui and Shaukat (2002) Siddiqui and Shaukat (2003) Siddiqui and Shaukat (2004)
Globodera rostochiensis	Potato	*Pseudomonas oryzihabitans*	Andreoglou et al. (2003)
Meloidogyne javanica	Lentil	*Pseudomonas putida*, *P. alcaligenes*, *Paenibacillus polymyxa*, *Bacillus pumilus*	Siddiqui et al. (2007)
Meloidogyne incognita	Tomato and soybean	*Pseudomonas fluorescens* CHA0	Siddiqui et al. (2005)
	Tomato	*Rhizobium etli* G12 *Bacillus amyloliquefaciens* FZB42	Reimann et al. (2008) Burkett-Cadena et al. (2008)
	Chickpea	*Pseudomonas alcaligenes* *Bacillus pumilus*	Akhtar and Siddiqui (2008)
Meloidogyne javanica	Chickpea	*Pseudomonas putida* 3604 *Pseudomonas alcaligenes* 493	Siddiqui and Akhtar (2009a)
Meloidogyne incognita	Tomato	*Bacillus subtilis*, *Paenibacillus polymyxa* *Burkholderia cepacia*	Siddiqui and Akhtar (2009b)
	Chickpea	*Pseudomonas putida* *Pseudomonas alcaligenes*	Akhtar and Siddiqui (2009)

commercially for plant protection to induce ISR against various pests and diseases. The performance of PGPR has been successful against certain pathogens, insect, and nematode pests under field conditions (Ramamoorthy et al. 2001). Murphy et al. (2000) studied the effects of PGPR treatment on whitefly nymphs number in field trials in Florida. They recorded significantly lower numbers of whitefly nymphs on PGPR-treated plants compared with the untreated tomato.

The metabolic pathways associated with insect-active secondary plant metabolites may be affected by induction of SAR or ISR, which could in turn effect changes in plant concentrations of insect feeding stimulants. Because induction of SAR and ISR involves different metabolic pathways, it is not unexpected that plants

treated with PGPR or other elicitors will vary in their suitability as insect host plants (Stout et al. 2002).

Consequently, it can be said that PGPR would be of great potential, especially to conserve natural enemies and to avoid potential problems encountered when some insecticides fail to control populations that have developed resistance (Wang et al. 2002).

4 Conclusions and Future Prospects

Since Kloepper and Schroth (1978) reported that microbial communities that exert benefit for plant growth have been called PGPR, there has been an increasing effort in advancing bacterial inoculants such as *Azotobacter*, *Azoarcus*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Gluconacetobacter*, *Klebsiella*, *Pseudomonas*, *Serratia*, *Rhizobium*, etc., for plant growth promotion in agriculture. Significant advances in the explanation of the mechanisms involved in plant growth promotion have been made, especially when using molecular biology approaches (Dobbelaere and Okon 2003). Mechanisms involved in plant growth promotion include biological nitrogen fixation, solubilization of insoluble phosphates, production of phytohormones, suppression of diseases, rooting of cuttings, increase germination and emergence of seeds under different conditions, promoted nutrient uptake of roots, total biomass of the plants, induce early flowering, increase in yield, etc.

Different PGPR have been examined under controlled and field conditions, and generally plant growth promotion such as yield increases in different crops, reduction of fertilizer and pesticides have been clearly demonstrated. The scientific basis of PGPR should continue to be investigated, tested, and explored for better and effective use of strains in the future, and free exchange of PGPR strains between researchers and countries (Podile and Kishore 2006) may help this. There is good possibility that the commercial mix of PGPR for various aims such as improved crop yield or suppression of pests and disease developed will be used extensively in the production of different crops in sustainable and environment friendly agriculture.

References

Abo-Elyousr KAM, Mohamed HM (2009) Biological control of *Fusarium* wilt in tomato by plant growth-promoting yeasts and rhizobacteria. Plant Pathol J 25:199–204

Akgul DS, Mirik M (2008) Biocontrol of *Phytophthora capsici* on pepper plants by *Bacillus megaterium* strains. J Plant Pathol 90:29–34

Akhtar MS, Siddiqui ZA (2008) *Glomus intraradices*, *Pseudomonas alcaligenes*, and *Bacillus pumilus*: effective agents for the control of root-rot disease complex of chickpea (*Cicer arietinum* L.). J Gen Plant Pathol 74:53–60. doi:10.1007/s10327-007-0062-4

Akhtar MS, Siddiqui ZA (2009) Use of plant growth-promoting rhizobacteria for the biocontrol of root-rot disease complex of chickpea. Australas Plant Path 38:44–50. doi:10.1071/AP08075

Alam MS, Cui ZJ, Yamagishi T, Ishii R (2001) Grain yield and related physiological characteristics of rice plants *Oryza sativa* L. inoculated with free-living rhizobacteria. Plant Prod Sci 4:126–130

Alexander M (1977) Introduction to soil microbiology. Wiley, New York

Aliye N, Fininsa C, Hiskias Y (2008) Evaluation of rhizosphere bacterial antagonists for their potential to bioprotect potato (*Solanum tuberosum*) against bacterial wilt (*Ralstonia solanacearum*). Biol Control 47:282–288. doi:10.1016/j.biocontrol.2008.09.003

Altindag M, Sahin M, Esitken A, Ercisli S, Guleryuz M, Donmez MF, Sahin F (2006) Biological control of brown rot (*Moniliana laxa* Ehr.) on apricot (*Prunus armeniaca* L. cv. Hacıhaliloğlu) by *Bacillus*, *Burkholdria*, and *Pseudomonas* application under in vitro and in vivo conditions. Biol Control 38:369–372. doi:10.1016/j.biocontrol.2006.04.015

Amir HG, Shamsuddin ZH, Halimi MS, Marziah M, Ramlan MF (2005) Enhancement in nutrient accumulation and growth of oil palm seedlings caused by PGPR under field nursery conditions. Commun Soil Sci Plan 36(15–16):2059–2066. doi:10.1080/00103620500194270

Andreoglou FI, Vagelas IK, Wood M, Samaliev HY, Gowen SR (2003) Influence of temperature on the motility of *Pseudomonas oryzihabitans* and control of *Globodera rostochiensis*. Soil Biol Biochem 35:1095–1101. doi:10.1016/S0038-0717(03)00157-3

Antoun H, Prevost D (2005) Ecology of plant growth promoting rhizobacteria. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, Netherlands, pp 1–38

Arshad M, Shaharoona B, Mahmood T (2008) Inoculation with *Pseudomonas* spp. containing ACC-Deaminase partially eliminates the effects of drought stress on growth, yield, and ripening of pea (*Pisum sativum* L.). Pedosphere 18:611–620

Atzhorn R, Crozier A, Wheeler CT, Sandberg G (1988) Production of gibberellins and indole-3-acetic acid by *Rhizobium phaseoli* in relation to nodulation of *Phaseolus vulgaris* roots. Planta 175:532–538

Barazani O, Friedman J (1999) Is IAA the major root growth factor secreted from plant-growth-mediating bacteria? J Chem Ecol 25:2397–2406

Basavaraju O, Rao ARM, Shankarappa TH (2002) Effect of *Azotobacter* inoculation and nitrogen levels on growth and yield of radish (*Raphanus sativus* L.). In: Rajak R (ed) Proceedings of microbial technology for sustainable development and productivity. Biotechnology of Microbes and Sustainable Utilization, Jabalpur, pp 155–160

Bashan Y, Holguin G (1997) *Azospirillum*-plant relationships: environmental and physiological advances (1990–1996). Can J Microbiol 43:103–121

Bashan Y, Holguin G, de-Bashan LE (2004) *Azospirillum*-plant relationships: physiological, molecular, agricultural, and environmental advances (1997–2003). Can J Microbiol 50:521–577. doi:10.1139/W04-035

Bashan Y, Levanony H (1990) Current status of *Azospirillum* inoculation technology: *Azospirillum* as a challenge for agriculture. Can J Microbiol 36:591–608

Bassil NV, Proebsting WM, Moore LW, Lightfoot DA (1991) Propagation of hazelnut stem cuttings using *Agrobacterium rhizogenes*. HortScience 26:1058–1060

Bastian F, Cohen A, Piccoli P, Luna V, Baraldi R, Bottini R (1998) Production of indole-3-acetic acid and gibberellins A1 and A3 by *Acetobacter diazotrophicus* and *Herbaspirillum seropedicae* in chemically defined media. Plant Growth Regul 24:7–11

Begum M, Rai VR, Lokesh S (2003) Effect of plant growth promoting rhizobacteria on seedborne fungal pathogens in okra. Indian Phytopathol 56:156–158

Belimov AA, Dodd IC, Hontzeas N, Theobald JC, Safronova VI, Davies WJ (2009) Rhizosphere bacteria containing 1-aminocyclopropane-1-carboxylate deaminase increase yield of plants grown in drying soil via both local and systemic hormone signalling. New Phytol 181:413–423. doi:10.1111/j.1469-8137.2008.02657.x

Belimov AA, Dodd IC, Safronova VI, Hontzeas N, Davies WJ (2007) *Pseudomonas brassicacearum* strain Am3 containing 1-aminocyclopropane-1-carboxylate deaminase can show both pathogenic and growth-promoting properties in its interaction with tomato. J Exp Bot 58:1485–1495. doi:10.1093/jxb/erm010

Belimov AA, Kojemiakov PA, Chuvarliyeva CV (1995) Interaction between barley and mixed cultures of nitrogen fixing and phosphate-solubilizing bacteria. Plant Soil 17:29–37

Bent E, Tuzun S, Chanway CP, Enebak S (2001) Alterations in plant growth and in root hormone levels of lodgepole pines inoculated with rhizobacteria. Can J Microbiol 47:793–800

Bertrand H, Nalin R, Bally R, Cleyet-Marel JC (2001) Isolation and identification of the most efficient plant growth-promoting bacteria associated with canola (*Brassica napa)*. Biol Fertil Soils 33:152–156

Bonaterra A, Ruz L, Badosa E, Pinochet J, Montesinos E (2003) Growth promotion of *Prunus* rootstocks by root treatment with specific bacterial strains. Plant Soil 255:555–569

Bottini R, Fulchieri M, Pearce D, Pharis RP (1989) Identification of gibberellins A1, A3, and iso-A3 in cultures of *Azospirillum lipoferum*. Plant Physiol 90:45–47

Boudyach EH, Fatmi M, Akhayat O, Benizri E, Aoumar AAB (2001) Selection of antagonistic bacteria of *Clavibacter michiganensis* ssp *michiganensis* and evaluation of their efficiency against bacterial canker of tomato. Biocontrol Sci Technol 11:141–149. doi:10.1080/09583150020029817

Boughton AJ, Hoover K, Felton GW (2006) Impact of chemical elicitor applications on greenhouse tomato plants and population growth of the green peach aphid, *Myzus persicae*. Entomol Exp Appl 120:175–188

Burdman S, Jurkevitch E, Okon Y (2000) Recent advences in the use of plant growth promoting rhizobacteria (PGPR) in agriculture. In: Subba Rao NS, Dommergues YR (eds) Microbial interactions in agriculture and forestry, vol 2. Science publishers Inc., Enfield, New Hampshire, pp 229–250

Burkett-Cadena M, Kokalis-Burelle N, Lawrence KS, van Santen E, Kloepper JW (2008) Suppressiveness of root-knot nematodes mediated by rhizobacteria. Biol Control 47:55–59. doi:10.1016/j.biocontrol.2008.07.008

Cakmakci R, Dönmez F, Aydın A, Şahin F (2006) Growth promotion of plants by plant growth-promoting rhizobacteria under greenhouse and two different field soil conditions. Soil Biol Biochem 38(6):1482–1487. doi:10.1016/j.soilbio.2005.09.019

Cakmakci R, Erat M, Erdogan U, Donmez MF (2007) The influence of plant growth-promoting rhizobacteria on growth and enzyme activities in wheat and spinach plants. J Plant Nutr Soil Sci 170:288–295. doi:10.1002/jpln.200625105

Cakmakci R, Kantar F, Sahin F (2001) Effect of N_2-fixing bacterial inoculations on yield of sugar beet and barley. J Plant Nutr Soil Sci 164:527–531

Canbolat MY, Bilen S, Cakmakci R, Sahin F, Aydin A (2006) Effect of plant growth-promoting bacteria and soil compaction on barley seedling growth, nutrient uptake, soil properties and rhizosphere microflora. Biol Fertil Soils 42:350–357. doi:10.1007/s00374-005-0034-9

Cattelan AJ, Hartel PG, Fuhrmann JJ (1999) Screening for plant growth-promoting rhizobacteria to promote early soybean growth. Soil Sci Soc Am J 63:1670–1680

Chelius MK, Triplett EW (2000) Immunolocalization of dinitrogenase reductase produced by Klebsiella pneumoniae in association with *Zea mays* L. Appl Environ Microb 66:783–787

Chen YP, Rekha PD, Arun AB, Shen FT, Lai WA, Young CC (2006) Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl Soil Ecol 34:33–41. doi:10.1016/j.apsoil.2005.12.002

Chinnasamy G (2005) A proteomics perspective on biocontrol and plant defense mechanism. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, Netherlands, pp 233–256

Choudhary DK, Prakash A, Johri BN (2007) Induced systemic resistance (ISR) in plants: mechanism of action. Indian J Microbiol 47:289–297. doi:10.1007/s12088-007-0054-2

Chung H, Park M, Madhaiyan M, Seshadri S, Song J, Cho H, Sa T (2005) Isolation and characterization of phosphate solubilizing bacteria from the rhizosphere of crop plants of Korea. Soil Biol Biochem 37:1970–1974. doi:10.1016/j.soilbio.2005.02.025

Commarea RR, Nandakumara R, Kandana A, Sureshb S, Bharathib M, Raguchandera T, Samiyappana R (2002) *Pseudomonas fluorescens* based bio-formulation for the management of sheath blight disease and leaffolder insect in rice. Crop Prot 21:671–677

Costacurta A, Vanderleyden J (1995) Synthesis of phytohormones by plant-associated bacteria. Crit Rev Microbiol 21:1–18

Couvillon GA (1998) Rooting responses to different treatments. Acta Hort 227:187–196

de Araujo FF (2008) Seed inoculation with *Bacillus subtilis*, formulated with oyster meal and growth of corn, soybean and cotton. Ciênc Agrotec 32:456–462

de Freitas JR (2000) Yield and N assimilation of winter wheat (*Triticum aestivum* L., var. Norstar) inoculated with rhizobacteria. Pedobiologia 44:97–104

de Salamone IEG, Hynes RK, Nelson LM (2001) Cytokinin production by plant growth promoting rhizobacteria and selected mutants. Can J Microbiol 47:404–411

Decateau RD (2000) Vegetable crops. Prentice-Hall Inc, Upper Saddle River, New Jersey

Dell'Amico E, Cavalca L, Andreoni V (2005) Analysis of rhizobacterial communities in perennial *Graminaceae* from polluted water meadow soil, and screening of metal resistant, potentially plant growth-promoting bacteria. FEMS Microbiol Ecol 52:153–162. doi:10.1016/j.femsec.2004.11.005

Dobbelaere S, Okon Y (2003) The plant growth promoting effect and plant responses. In: Elmerich C, Newton WE (eds) Associative and endophytic nitrogen-fixing bacteria and cyanobacterial associations. Kluwer Academic, Netherlands, pp 1–26

Dobbelaere S, Vanderleyden J, Okon Y (2003) Plant growth-promoting effects of diazotrophs in the rhizosphere. Crit Rev Plant Sci 22:107–149

Döbereiner J (1997) Biological nitrogen fixation in the tropics: social and economic contributions. Soil Biol Biochem 29:771–774

Dong Y, Iniguez AL, Triplett EW (2003) Quantitative assessments of the host range and strain specificity of endophytic colonization by *Klebsiella pneumoniae* 342. Plant Soil 257:49–59

Dursun A, Ekinci M, Donmez MF (2008) Effects of inoculation bacteria on chemical content, yield and growth in rocket (*Eruca vesicaria* subsp *sativa*). Asian J Chem 20:3197–3202

Dutta S, Mishra AK, Kumar BSD (2008) Induction of systemic resistance against fusarial wilt in pigeon pea through interaction of plant growth promoting rhizobacteria and rhizobia. Soil Biol Biochem 40:452–461. doi:10.1016/j.soilbio.2007.09.009

Egamberdiyeva D, Qarshieva D, Davranov K (2004) Growth and yield of soybean varieties inoculated with *Bradyrhizobium* spp in N-deficient calcareous soils. Biol Fert Soils 40:144–146. doi:10.1007/s00374-004-0755-1

Elbadry M, Taha RM, Eldougdoug KA, Gamal-Eldin H (2006) Induction of systemic resistance in faba bean (*Vicia faba* L.) to bean yellow mosaic potyvirus (BYMV) via seed bacterization with plant growth promoting rhizobacteria. J Plant Dis Protect 113:247–251

El-Khawas H, Adachi K (1999) Identification and quantification of auxins in culture media of *Azospirillum* and *Klebsiella* and their effect on rice roots. Biol Fert Soils 28:377–381

Elkoca E, Kantar F, Sahin F (2008) Influence of nitrogen fixing and phosphorus solubilizing bacteria on the nodulation, plant growth, and yield of chickpea. J Plant Nutr 31:157–171. doi:10.1080/01904160701742097

Elmerich C (1984) Molecular biology and ecology of diazotrophs associated with non-leguminous plants. Biotechnol 11:967–978. doi:10.1038/nbt1184-967

Enebak SA, Carey WA (2004) Plant growth-promoting rhizobacteria may reduce fusiform rust infection in nursery-grown loblolly pine seedlings. South J Appl Forest 28:185–188

Ercisli S (2009) Apricot culture in Turkey. Sci Res Essays 4:715–719

Ercisli S, Esitken A, Cangi R, Sahin F (2003) Adventitious root formation of kiwifruit in relation to sampling date, IBA and *Agrobacterium rubi* inoculation. Plant Growth Regul 41:133–137

Ercisli S, Esitken A, Sahin F (2000) Effect of IBA and bacteria (*Agrobacterium rubi*) on the rooting of cuttings of sour cherry cv. Kutahya. Bahce 29:75–80

Ercisli S, Esitken A, Sahin F (2004) Exogenous IBA and inoculation with *Agrobacterium rubi* stimulate adventitious root formation on hardwood stem cuttings of two rose genotypes. HortScience 39:533–534

Erturk Y, Ercisli S, Sekban R, Haznedar A, Donmez MF (2008) The effect of plant growth promoting rhizobacteria (PGPR) on rooting and root growth of tea (*Camellia sinensis* var. *Sinensis*) cuttings. Roum Biotechnol Lett 13:3747–3756

Esitken A, Ercisli S, Karlidag H, Sahin F (2005) Potential use of plant growth promoting rhizobacteria (PGPR) in organic apricot production. In: Libek A, Kaufmane E, Sasnauskas A (eds) International conference on environmentally friendly fruit growing. Tartu, Estonia, pp 90–97

Esitken A, Ercisli S, Sevik I, Sahin F (2003a) Effect of Indole-3-butyric acid and different strains of *Agrobacterium rubi* on adventive root formation from softwood and semi-hardwood wild sour cherry cuttings. Turk J Agric Forest 27:37–42

Esitken A, Karlidag H, Ercisli S, Turan M, Sahin F (2003b) The effect of spraying a growth promoting bacterium on the yield, growth and nutrient element composition of leaves of apricot (*Prunus armeniaca* L. cv. Hacihaliloglu). Aust J Agr Res 54:377–380. doi:10.1071/AR02098

Esitken A, Pirlak L, Turan M, Sahin F (2006) Effects of floral and foliar application of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrition of sweet cherry. Sci Hortic 110:324–327. doi:10.1016/j.scienta.2006.07.023

Fatima Z, Saleemi M, Zia M, Sultan T, Aslam M, Rehman RU, Chaudhary MF (2009) Antifungal activity of plant growth-promoting rhizobacteria isolates against *Rhizoctonia solani* in wheat. Afr J Biotechnol 8:219–225

Figueiredo MV, Martinez CR B, Burity HA, Chanway CP (2008) Plant growth-promoting rhizobacteria for improving nodulation and nitrogen fixation in the common bean (*Phaseolus vulgaris* L.). World J Microb Biot 24:1187–1193. doi:10.1007/s11274-007-9591-4

Gandhi PI, Gunasekaran K, Tongmin S (2006) Neem oil as a potential seed dresser for managing Homopterous sucking pests of Okra (*Abelmoschus esculentus* (L.) Moench). J Pest Sci 79:103–111. doi:10.1007/s10340-006-0122-0

Gang W, Kloepper JW, Tuzun S (1991) Induction of systemic resistance of cucumber to *Colletotrichum orbiculare* by selected strains of plant growth-promoting rhizobacteria. Phytopathology 81:1508–1512

Garcia JAL, Domenech J, Santamaría C, Camacho M, Daza A, Gutierrez Mañero FJ (2004a) Growth of forest plants (pine and holm-oak) inoculated with rhizobacteria: relationship with microbial community structure and biological activity of its rhizosphere. Environ Exp Bot 52:239–251. doi:10.1016/j.envexpbot.2004.02.003

Garcia JAL, Probanza A, Ramos B, Barriuso J, Gutierrez Mañero FJ (2004b) Effects of inoculation with plant growth promoting rhizobacteria (PGPRs) and *Sinorhizobium fredii* on biological nitrogen fixation, nodulation and growth of *Glycine max* cv. Osumi. Plant Soil 267:143–153

Gaudin V, Vrain D, Jouanin L (1994) Bacterial genes modifying hormonal balance in plant. Plant Physiol Biochem 32:11–29

Girish N, Umesha S (2005) Effect of plant growth promoting rhizobacteria on bacterial canker of tomato. Arch Phytopathol Plant Protect 38:235–243

Glick BR, Jacobson CB, Schwarze MMK, Pasternak JJ (1994) 1-Aminocyclopropane-1-carboxylic acid deaminase mutants of the plant growth promoting rhizobacterium *Pseudomonas putida* GR12-2 do not stimulate canola root elongation. Can J Microbiol 40:911–915

Glick BR (1995) The enhancement of plant growth by free-living bacteria. Can J Microbiol 41:109–17

Glick BR, Penrose DM, Li JP (1998) A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. J Theor Biol 190:63–68. doi:10.1006/jtbi.1997.0532

Gulcan R, Mısırlı A, Demir T (1999) A research on resistance of Hacıhaliloğlu apricot variety against Monilinia (*Sclerotinia laxa*, Aderh et Ruhl) through cross pollination. Acta Hort 488:673–676

Guo JH, Qi HY, Guo YH, Ge HL, Gong LY, Zhang LX (2004) Biocontrol of tomato wilt by plant growth-promoting rhizobacteria. Biol Control 29:66–72. doi:10.1016/S1049-9644(03)00124-5

Gutierrez-Manero FJ, Ramos-Solano B, Probanza A, Mehouachi J, Tadeo FR, Talon M (2001) The plant-growth promoting rhizobacteria *Bacillus pumilus* and *Bacillus licheniformis* produce high amounts of physiologically active gibberellins. Physiol Plant 111:206–211

Gyaneshwar P, Naresh Kumar G, Parekh LJ, Poole PS (2002) Role soil microorganisms in improving P nutrition of plant. Plant Soil 245:83–93

Hackenberg C, Vrain TC, Sikora RA (1999) Rhizosphere colonization pattern of *Agrobacterium radiobacter* strain G12A, an antagonistic rhizobacterium to the potato cyst nematode *Globodera pallid*. Microbiol Res 154:57–61

Hafeez FY, Safdar ME, Chaudhry AU, Malik KA (2004) Rhizobial inoculation improves seedling emergence, nutrient uptake and growth of cotton. Aust J Exp Agric 44:617–622. doi:10.1071/EA03074

Halder AK, Mishra AK, Bhattacharyya P, Chakrabartty PK (1990) Solubilization of rock phosphate by *Rhizobium* and *Bradyrhizobium*. J Gen Appl Microbiol 36:81–92

Hamaoui B, Abbadi JM, Burdman S, Rashid A, Sarig S, Okon Y (2001) Effects of inoculation with *Azospirillum brasilense* on chickpeas (*Cicer arietinum*) and faba beans (*Vicia faba*) under different growth conditions. Agronomie 21:553–560

Hameeda B, Harini G, Rupela OP, Wani SP, Reddy G (2008) Growth promotion of maize by phosphate solubilizing bacteria isolated from composts and macrofauna. Microbiol Res 163:234–242. doi:10.1016/j.micres.2006.05.009

Harish S, Kavino M, Kumar N, Saravanakumar D, Soorianathasundaram K, Samiyappan R (2008) Biohardening with plant growth promoting rhizosphere and endophytic bacteria induces systemic resistance against banana bunchy top virus. Appl Soil Ecol 39:187–200. doi:10.1016/j.apsoil.2007.12.006

Hatta M, Beyl CA, Garton S, Diner AM (1996) Induction of roots on jujube softwood cuttings using *Agrobacterium rhizogenes*. J Hort Sci 71:881–886

Hausbeck MK, Lamour KH (2004) *Phytophthora capsici* on vegetable crops: research progress and management challenges. Plant Dis 88:1292–1303

Hecht-Buchholz C (1998) The apoplast-habitat of endophytic dinitrogen-fixing bacteria and their significance for the nitrogen nutrition of nonlegumious plants. J Plant Nutr Soil Sci 161:509–520

Herman MAB, Nault BA, Smart CD (2008) Effects of plant growth-promoting rhizobacteria on bell pepper production and green peach aphid infestations in New York. Crop Prot 27:996–1002. doi:10.1016/j.cropro.2007.12.004

Hernandez-Rodriguez A, Heydrich-Perez M, Acebo-Guerrero Y, Velazquez-del Valle MG, Hernandez-Lauzardo AN (2008) Antagonistic activity of Cuban native rhizobacteria against *Fusarium verticillioides* (Sacc.) Nirenb. in maize (*Zea mays* L.). Appl Soil Ecol 39:180–186. doi:10.1016/j.apsoil.2007.12.008

Hoffmann-Hergarten S, Gulati MK, Sikora RA (1998) Yield response and biological control of Meloidogyne incognita on lettuce and tomato with rhizobacteria. Z Pflanzenk Pflan 105:349–358

Inam-ul-Haq M, Tariq JA, Javed N, Khan NA, Imran-ul-Haq Khan HU (2003) In-vitro interrelationship between plant growth promoting rhizobacteria and root knot nematode (*Meloidogyne incognita*) and their effect on growth parameters of brinjal. Mycopath 1:191–193

Ishida AKN, de Souza RM, de Resende MLV, Zacaroni AB, Boas CHV, de Souza JT (2008) Rhizobacteria to control cotton bacterial blight. Ciênc Agrotec 32:149–156

Janzen RA, Rood SB, Dormaar JF, McGill WB (1992) *Azospirillum brasilense* produces gibberellin in pure culture on chemically defined medium and in co-culture on straw. Soil Biol Biochem 24:1061–1064

Jetiyanon K, Kloepper JW (2002) Mixtures of plant growth-promoting rhizobacteria for induction of systemic resistance against multiple plant diseases. Biol Control 24:285–291

Jeun YC, Park KS, Kim CH, Fowler WD, Kloepper JW (2004) Cytological observations of cucumber plants during induced resistance elicited by rhizobacteria. Biol Control 29:34–42. doi:10.1016/S1049-9644(03)00082-3

Jonathan EI, Barker KR, Abdel-Alim FF, Vrain TC, Dickson DW (2000) Biological control of *Meloidogyne incognita* on tomato and banana with rhizobacteria actinomycetes, and *Pasteuria penetrans*. Nematropica 30:231–240

Joo GJ, Kim YM, Lee IJ, Song KS, Rhee IK (2004) Growth promotion of red pepper plug seedlings and the production of gibberellins by *Bacillus cereus*, *Bacillus macroides* and *Bacillus pumilus*. Biotechnol Lett 26:487–491

Kandan A, Ramiah M, Vasanthi VJ, Radjacommare R, Nandakumar R, Ramanathan A, Samiyappan R (2005) Use of *Pseudomonas fluorescens*-based formulations for management of tomato spotted wilt virus (TSWV) and enhanced yield in tomato. Biocontrol Sci Technol 15 (6):553–569. doi:10.1080/09583150500088546

Karlıdağ H, Esitken A, Turan M, Sahin F (2007) Effects of root inoculation of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient element contents of leaves of apple. Sci Hortic 114:16–20. doi:10.1016/j.scienta.2007.04.013

Kaushik R, Saxena AK, Tilak KVBR (2000) Selection of Tn5::lacZ mutants isogenic to wild type *Azospirillum brasilense* strains capable of growing at sub-optimal temperature. World J Microb Biot 16:567–570

Kaymak HC, Guvenc I, Yarali F, Donmez MF (2009) The effects of bio-priming with PGPR on germination of radish (*Raphanus sativus* L.) seeds under saline conditions. Turk J Agric Forest 33:173–179

Kaymak HC, Yarali F, Guvenc I, Donmez MF (2008) The effect of inoculation with plant growth rhizobacteria (PGPR) on root formation of mint (*Mentha piperita* L.) cuttings. Afr J Biotechnol 7:4479–4483

Kempster VN, Scott ES, Davies KA (2002) Evidence for systemic, cross-resistance in white clover (*Trifolium repens*) and annual medic (*Medicago truncatula* var *truncatula*) induced by biological and chemical agents. Biocontrol Sci Technol 12:615–623. doi:10.1080/0958315021000016270

Kennedy IR, Pereg-Gerk LL, Wood C, Deaker R, Gilchrist K, Katupitiya S (1997) Biological nitrogen fixation in nonleguminous field crops: facilitating the evolution between *Azospirillum* and wheat. Plant Soil 194:65–79

Kennedy RW, Chellapillai KL (1998) Synergistic effect of VAM, *Azospirillum*, and phosphobacteria on growth response and nutrient uptake of shola tree species. Indian J Forest 21:308–312

Khan AG (2005) Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. J Trace Elem Med Biol 18:355–364. doi:10.1016/j.jtemb.2005.02.006

Kim KY, Jordan D, McDonald GA (1998) *Enterobacter agglomerans*, phosphate solubilising bacteria, and microbial activity in soil: effect of carbon sources. Soil Biol Biochem 30:995–1003

Kim SG, Khan Z, Jeon YH, Kim YH (2009) Inhibitory effect of *Paenibacillus polymyxa* GBR-462 on *Phytophthora capsici* causing *Phytophthora* Blight in Chili Pepper. J Phytopathol 157:329–337. doi:10.1111/j.1439-0434.2008.01490.x

Kirankumar R, Jagadeesh KS, Krishnaraj PU, Patil MS (2008) Enhanced growth promotion of tomato and nutrient uptake by plant growth promoting rhizobacterial isolates in presence of tobacco mosaic virus pathogen. Karnataka J Agric Sci 21:309–311

Klee HJ, Hayford MB, Kretzmer KA, Barry GF, Kiskore GM (1991) Control of ethylene synthesis by expression of a bacterial enzyme in transgenic tomato plants. Plant Cell 3:1187–1193

Kloepper JW, Gutierrez-Estrada A, McInroy JA (2007) Photoperiod regulates elicitation of growth promotion but not induced resistance by plant growth-promoting rhizobacteria. Can J Microbiol 53:159–167. doi:10.1139/W06-114

Kloepper JW, Schroth MN (1978) Plant growth-promoting rhizobacteria on radishes. In: Proceedings of the fourth international conference on plant pathogen bacteria. vol 2, INRA, p 879–882

Koenning SR, Overstreet C, Noling JW, Donald PA, Becker JO, Fortnum BA (1999) Survey of crop losses in response to phytoparasitic nematodes in the United States for 1994. J Nematol 31:587–618

Kokalis-Burelle N, Vavrina EN, Rosskopf EN, Shelby RA (2002) Field evaluation of plant growth-promoting rhizobacteria amended transplant mixes and soil solarization for tomato and pepper production in Florida. Plant Soil 238:257–266

Köse C, Guleryuz M, Sahn F, Demirtas I (2003) Effects of some plant growth promoting rhizobacteria (PGPR) on rooting of grapevine rootstocks. Acta Agrobot 56:47–52

Kumar V, Narula N (1999) Solubilization of inorganic phosphates and growth emergence of wheat as affected by *Azotobacter chrococcum*. Biol Fert Soils 28:301–305

Kumar S, Pandey P, Maheshwari DK (2009) Reduction in dose of chemical fertilizers and growth enhancement of sesame (*Sesamum indicum* L.) with application of rhizospheric competent *Pseudomonas aeruginosa* LES4. Eur J Soil Biol 45:334–340

Kunc F, Macura J (1988) Mechanisms of adaptation and selection of microorganisms in the soil. In: Vancura V, Kunc F (eds) Soil microbial associations. Elsevier, Amsterdam, pp 281–299

Lee KH, Koh RH, Soh HG (2008a) Enhancement of growth and yield of tomato *Rhodopseudomonas* sp. under greenhouse conditions. J Microbiol 46:641–646. doi:10.1007/s12275-008-0159-2

Lee KJ, Kamala-Kannan S, Sub HS, Seong CK, Lee GW (2008b) Biological control of *Phytophthora* blight in red pepper (*Capsicum annuum* L) using *Bacillus subtilis*. World J Microb Biot 24:1139–1145. doi:10.1007/s11274-007-9585-2

Lemessa F, Zeller W (2007) Screening rhizobacteria for biological control of *Ralstonia solanacearum* in Ethiopia. Biol Control 42:336–344. doi:10.1016/j.biocontrol.2007.05.014

Li B, Xie GL, Soad A, Coosemans J (2005) Suppression of *Meloidogyne javanica* by antagonistic and plant growth-promoting rhizobacteria. J Zhejiang Univ Sci B 6:496–501. doi:10.1631/jzus.2005.B0496

Liu L, Kloepper JW, Tuzun S (1995) Induction of systemic resistance in cucumber against bacterial angular leaf-spot by plant growth-promoting rhizobacteria. Phytopathology 85:843–847

Lokesh S, Bharath BG, Raghavendra VB, Govindappa M (2007) Importance of plant growth-promoting rhizobacteria in enhancing the seed germination and growth of watermelon attacked by fungal pathogens. Acta Agron Hung 55:243–249

Lourenco V, Maffia LA, Romeiro RD, Mizubuti ESG (2006) Biocontrol of tomato late blight with the combination of epiphytic antagonists and rhizobacteria. Biol Control 38:331–340. doi:10.1016/j.biocontrol.2006.04.005

Lucy M, Reed E, Glick BR (2004) Applications of free living plant growth-promoting rhizobacteria. Anton Leeuw Int J G 86:1–25

Mantelin S, Touraine B (2004) Plant growth-promoting bacteria and nitrate availability: impacts on root development and nitrate uptake. J Exp Bot 55:27–34. doi:10.1093/jxb/erh010

Manulis S, Valinski L, Gafni Y, Hershenhorn J (1991) Indole-3-acetic acid biosynthetic patways in erwinia herbicola in relation to pathogenity in *Gypsophia paniculata*. Physiol Mol Plant P 39:161–171

Martelli GP (1992) Classification and nomenclature of plant viruses state of the art. Plant Dis 76:436–442

Matheron ME, Porchas M (2000) Impact of azoxystrobin, dimethomorph, fluazinam, fosetyl-Al, and metalaxyl on growth sporulation and zoospore cyst germination of three *Phytophthora* spp. Plant Dis 84:454–458

May R, Völksck B, Kampmann G (1996) Antagonistic activities of epiphytic bacteria from soy bean leaves against *Pseudomonas syringae* pv. *syringae* in vitro and in planta. Microb Ecol 34:118–124

Mayak S, Tirosh T, Glick BR (1999) Effect of wild-type and mutant plant growth- promoting rhizobacteria on the rooting of mung bean cuttings. J Plant Growth Regul 18:49–53

Mehnaz S, MirzaMS HJ, Bally R, Normand P, Bano A, Malik KA (2001) Isolation and 16S rRNA sequence analysis of the beneficial bacteria from the rhizosphere of rice. Can J Microbiol 472:110–117

Meyer SLF, Roberts DP, Chitwood DJ, Carta LK, Lumsden RD, Mao WL (2001) Application of *Burkholderia cepacia* and *Trichoderma virens*, alone and in combinations, against *Meloidogyne incognita* on bell pepper. Nematropica 31:75–86

Mirza MS, Ahmad W, Latif F, Haurat J, Bally R, Normajd P, Malik KA (2001) Isolation, partial characterization, and the effect of plant growth-promoting bacteria (PGPB) on micropropagated sugarcane in vitro. Plant Soil 237:47–54

Murphy JF, Reddy MS, Ryu CM, Kloepper JW, Li RH (2003) Rhizobacteria-mediated growth promotion of tomato leads to protection against Cucumber mosaic virus. Phytopathology 93:1301–1307

Murphy JF, Zehnder GW, Schuster DJ, Sikora EJ, Polston JE, Kloepper JW (2000) Plant growth-promoting rhizobacterial mediated protection in tomato against tomato mottle virus. Plant Dis 84:779–784

Nadeem SM, Zahir ZA, Naveed M, Arshad M (2007) Preliminary investigations on inducing salt tolerance in maize through inoculation with rhizobacteria containing ACC deaminase activity. Can J Microbiol 53:141–1149. doi:10.1139/W07-081

Naveed M, Khalid M, Jones DL, Ahmad R, Zahir ZA (2008) Relative efficacy of *Pseudomonas* spp., containing ACC-Deaminase for improving growth and yield of maize (*Zea mays* L.) in the presence of organic fertilizer. Pak J Bot 40:1243–1251

Nelson LM (2004) Plant growth promoting rhizobacteria (PGPR): prospects for new inoculants. Crop Management. doi:10.1094/CM-2004-0301-05-RV

Nico AI, Rafael RM, Jiménez-Díaza M, Castillo P (2004) Control of root-knot nematodes by composted agro-industrial wastes in potting mixtures. Crop Prot 23:581–587. doi:10.1016/j.cropro.2003.11.005

Noel TC, Sheng C, Yost CK, Pharis RP, Hynes MF (1996) *Rhizobium leguminosarum* as a plant growth-promoting rhizobacterium: direct growth promotion of canola and lettuce. Can J Microbiol 42:279–283

Orhan E, Esitken A, Ercisli S, Sahin F (2007) Effects of indole-3-butyric acid (IBA), bacteria and, radicle tip-cutting on lateral root induction in *Pistacia vera*. J Hortic Sci Biotech 82:2–4

Orhan E, Esitken A, Ercisli S, Turan M, Sahin F (2006) Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically growing raspberry. Sci Hortic 111:38–43. doi:10.1016/j.scienta.2006.09.002

Öztürk A, Caglar O, Sahin F (2003) Yield response of wheat and barley to inoculation of plant growth promoting rhizobacteria at various levels of nitrogen fertilization. J Plant Nutr Soil Sci 166:262–266

Pal SS (1998) Interaction of an acid tolerant strain of phosphate solubilizing bacteria with a few acid tolerant crops. Plant Soil 198:169–177. doi:10.1023/A:1004318814385

Patten CL, Glick BR (1996) Bacterial biosynthesis of indole-3-acetic acid. Can J Microbiol 42:207–220

Peix A, Rivas-Boyerob AA, Mateos PF, Rodriguez-Barrueco C, Martínez-Molina E, Velazquez E (2001) Growth promotion of chickpea and barley by a phosphate solubilizing strain of *Mesorhizobium mediterraneum* under growth chamber conditions. Soil Biol Biochem 33:103–110

Pırlak L, Turan M, Sahin F, Esitken A (2007) Floral and foliar application of plant growth promoting rhizobacteria (PGPR) to apples increases yield, growth, and nutrient element contents of leaves. J Sustain Agric 30:145–155. doi:10.1300/J064v30n04-11

Podile AR, Kishore GK (2006) Plant growth-promoting rhizobacteria. In: Gnanamanickam SS (ed) Plant-associated bacteria: rhizosphere bacteria. Springer, Netherlands, pp 195–230

Pusey PL (1997) Crap apple Blossoms as a model for research on biological control of fire blight. Phytopathology 87:1096–1102

Radwan FI (1998) Response of some maize cultivars to VAmycorrhizal inoculation, biofertilization and soil nitrogen application. Alex J Agric Res 43:43–56

Raj NS, Shetty NP, Shetty HS (2004) Seed bio-priming with *Pseudomonas fluorescens* isolates enhances growth of pearl millet plants and induces resistance against downy mildew. Int J Pest Manag 50:41–48. doi:10.1080/09670870310001626365

Raj SN, Chaluvaraju G, Amruthesh KN, Shetty HS, Reddy MS, Kloepper JW (2003a) Induction of growth promotion and resistance against downy mildew on pearl millet (*Pennisetum glaucum*) by rhizobacteria. Plant Dis 87:380–384

Raj SN, Deepak SA, Basavaraju P, Shetty HS, Reddy MS, Kloepper JW (2003b) Comparative performance of formulations of plant growth promoting rhizobacteria in growth promotion and suppression of downy mildew in pearl millet. Crop Prot 22:579–588

Rajkumar M, Lee WH, Lee KJ (2005) Screening of bacterial antagonists for biological control of *Phytophthora* blight of pepper. J Basic Microb 45:55–63. doi:10.1002/jobm.200410445

Ramamoorthy V, Viswanathan R, Raghuchander T, Prakasam V, Samiyappan R (2001) Induction of systemic resistance by plant growth promoting rhizobacteria in crop plants against pests and diseases. Crop Prot 20:1–11

Ramirez LEF, Mellado JC (2005) Bacterial biofertilizers. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, Netherlands, pp 143–172

Ran LX, Liu CY, Wu GJ, van Loon LC, Bakker PAHM (2005) Suppression of bacterial wilt in *Eucalyptus urophylla* by fluorescent *Pseudomonas* spp. in China. Biol Control 32:111–120. doi:10.1016/j.biocontrol.2004.08.007

Raupach GS, Kloepper JW (1998) Mixtures of plant growth promoting rhizobacteria enhance biological control of multiple cucumber pathogens. Phytopathology 88:1158–1164

Raupach GS, Kloepper JW (2000) Biocontrol of cucumber diseases in the field by plant growth-promoting rhizobacteria with and without methyl bromide fumigation. Plant Dis 84:1073–1075

Reddy DDR (1985) Analysis of crop losses in tomato due to *Meloidogyne incognita*. Indian J Nematol 15:55–59

Reimann S, Hauschild R, Hildebrandt U, Sikora RA (2008) Interrelationships between *Rhizobium etli* G12 and *Glomus intraradices* and multitrophic effects in the biological control of the root-knot nematode *Meloidogyne incognita* on tomato. J Plant Dis Protect 115:108–113

Reitz M, Rudolph K, Schroder I, Hoffmann-Hergarten S, Hallmann J, Sikora RA (2000) Lipopolysaccharides of *Rhizobium etli* strain G12 act in potato roots as an inducing agent of systemic resistance to infection by the cyst nematode *Globodera pallid*. Appl Environ Microbiol 66:3515–3518

Reyes I, Alvarez L, El-Ayoubi H, Valery A (2008) Selection and evaluation of growth promoting rhizobacteria on pepper and maize. Bioagro 20:37–48

Rinallo C, Mittempergher L, Frugis G, Mariotti D (1999) Clonal propagation in the genus *Ulmus*: improvement of rooting ability by *Agrobacterium rhizogenes* T-DNA genes. J Hortic Sci Biotech 74:502–506

Ristaino JB, Johnston SA (1999) Ecologically based approaches to management of *Phytophthora* blight on bell pepper. Plant Dis 83:1080–1089

Rodríguez H, Fraga R (1999) Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnol Adv 17:319–339

Rodriguez H, Gonzalez T, Goire I, Bashan Y (2004) Gluconic acid production and phosphate solubilization by the plant growth-promoting bacterium *Azospirillum* spp. Naturewissenschaften 91:552–555. doi:10.1007/s00114-004-0566-0

Rodriguez H, Vessely S, Shah S, Glick BR (2008) Effect of a Nickel-tolerant ACC deaminase-producing *Pseudomonas* strain on growth of nontransformed and transgenic Canola plants. Curr Microbiol 57:170–174. doi:10.1007/s00284-008-9181-1

Rodriguez MN, Villalonga RD, Castillo RAJ, Marques AJL, Gonzalez LR, Llanes SP, Peguero FM (2001) Influence of application of a biofertilizer based on *Azospirillum* on germination of seed and production of vegetable crops. Centro Agricola 28:38–41

Romero AM, Correa OS, Moccia S, Rivas JG (2003) Effect of *Azospirillum*-mediated plant growth promotion on the development of bacterial diseases on fresh-market and cherry tomato. J Appl Microbiol 95(4):832–838. doi:10.1046/j.1365-2672.2003.02053.x

Ryu CM, Kima J, Choi O, Kima SH, Park CS (2006) Improvement of biological control capacity of *Paenibacillus polymyxa* E681 by seed pelleting on sesame. Biol Control 39:282–289. doi:10.1016/j.biocontrol.2006.04.014

Saddler G (2002) Bacteria and plant disease. In: Waller JM, Lenné JM, Waller SJ (eds) Plant pathologist's pocketbook, 3rd edn. CABI Publishing, Wallingford, Oxon, UK, pp 94–106

Şahin F, Çakmakçi R, Kantar F (2004) Sugar beet and barley yields in relation to inoculation with N2-fixing and phosphate solubilizing bacteria. Plant Soil 265:123–129

Salantur A, Ozturk A, Akten S, Sahin F, Donmez F (2005) Effect of inoculation with non-indigenous and indigenous Rhizobacteria of Erzurum (Turkey) origin on growth and yield of spring barley. Plant Soil 275:147–156. doi:10.1007/s11104-005-8094-z

Saleem M, Arshad M, Hussain S, Bhatti AS (2007) Perspective of plant growth promoting rhizobacteria (PGPR) containing ACC deaminase in stress agriculture. J Ind Microbiol Biotechnol 34:635–648. doi:10.1007/s10295-007-0240-6

Saleh SS, Glick BR (2001) Involvement of gacS and rpoS in enhancement of the plant growth-promoting capabilities of *Enterobacter cloacae* CAL2 and UW4. Can J Microbiol 47:698–705

Sang MK, Chun SC, Kim KD (2008) Biological control of Phytophthora blight of pepper by antagonistic rhizobacteria selected from a sequential screening procedure. Biol Control 46:424–433. doi:10.1016/j.biocontrol.2008.03.017

Saravanakumar D, Lavanya N, Muthumeena K, Raguchander T, Samiyappan R (2009) Fluorescent pseudomonad mixtures mediate disease resistance in rice plants against sheath rot (*Sarocladium oryzae*) disease. Biocontrol 54:273–286. doi:10.1007/s10526-008-9166-9

Saravanakumar D, Vijayakumar C, Kumar N, Samiyappan R (2007) PGPR-induced defense responses in the tea plant against blister blight disease. Crop Prot 26:556–565. doi:10.1016/j.cropro.2006.05.007

Schneider SM, Rosskopf EN, Leesch JG, Chellemi DO, Bull CT, Mazzola M (2003) United States department of agriculture - agricultural research service research on alternatives to methyl bromide: pre-plant and post-harvest. Pest Manag Sci 59:814–826. doi:10.1002/ps.728

Siddiqui IA, Ehetshamul-Haque S, Shaukat SS (2001) Use of rhizobacteria in the control of root rot-root knot disease complex of mungbean. J Phytopathol 149:337–346

Siddiqui IA, Haas D, Heeb S (2005) Extracellular protease of *Pseudomonas fluorescens* CHA0, a biocontrol factor with activity against the root-knot nematode *Meloidogyne incognita*. Appl Environ Microbiol 71:5646–5649. doi:10.1128/AEM.71.9.5646-5649.2005

Siddiqui IA, Shaukat SS (2002) Rhizobacteria-mediated induction of systemic resistance (ISR) in tomato against *Meloidogyne javanica*. J Phytopathol 150:469–473

Siddiqui IA, Shaukat SS (2003) Suppression of root-knot disease by *Pseudomonas* fluorescens CHA0 in tomato: importance of bacterial secondary metabolite 2, 4-diacetylphloroglucinol. Soil Biol Biochem 35:1615–1623. doi:10.1016/j.soilbio.2003.08.006

Siddiqui IA, Shaukat SS (2004) Systemic resistance in tomato induced by biocontrol bacteria against the root-knot nematode, *Meloidogyne javanica* is independent of salicylic acid production. J Phytopathol 152:48–54

Siddiqui ZA, Akhtar MS (2008) Effects of organic wastes, *Glomus intraradices* and *Pseudomonas putida* on the growth of tomato and on the reproduction of the root-knot nematode *Meloidogyne incognita*. Phytoparasitica 36:460–471

Siddiqui ZA, Akhtar MS (2009a) Effect of plant growth promoting rhizobacteria, nematode parasitic fungi and root-nodule bacterium on root-knot nematodes *Meloidogyne javanica* and growth of chickpea. Biocontrol Sci Technol 19:511–521. doi:10.1080/09583150902887792

Siddiqui ZA, Akhtar MS (2009b) Effects of antagonistic fungi and plant growth-promoting rhizobacteria on growth of tomato and reproduction of the root-knot nematode, *Meloidogyne incognita*. Australas Plant Pathol 38:22–28. doi:10.1071/AP08072

Siddiqui ZA, Baghel G, Akhtar MS (2007) Biocontrol of *Meloidogyne javanica* by *Rhizobium* and plant growth-promoting rhizobacteria on lentil. World J Microb Biot 23:435–441. doi:10.1007/s11274-006-9244-z

Siddiqui ZA, Mahmood I (2001) Effects of rhizobacteria and root symbionts on the reproduction of *Meloidogyne javanica* and growth of chickpea. Bioresour Technol 79:41–45

Sikora EJ, Murphy JF (2005) Identification and management of cucumber mosaic virus in Alabama. Acta Hort 695:191–194

Sivritepe HO, Dourado AM (1995) The effect of priming treatments on the viability and accumulation of chromosomal damage in aged pea seeds. Ann Bot 75:165–171

Someya N, Kataoka N, Komagata T, Hirayae K, Hibi T, Akutsu K (2000) Biological control of cyclamen soilborne diseases by *Serratia marcescens* strain B2. Plant Dis 84(3):334–340

Son SH, Khan Z, Vim SG, Kim YH (2008) Effects of seed treatment with rhizobacterium, *Paenibacillus* species on management of root-knot nematode-*Fusarium* wilt fungus disease complex in tomato plants. Russ J Nematol 16:97–105

Sorensen J (1997) The rhizosphere as a habitat for soil microorganisms. In: van Elsas JD, Trevors JT, Welington EMH (eds) Modern soil ecology. Marcel Dekker Inc., New York, pp 21–46

Sticher L, Mauch-Mani B, Métraux JP (1997) Systemic acquired resistance. Annu Rev Phytopathol 35:235–270

Stout MJ, Zehnder GW, Baur ME (2002) Potential for the use of elicitors of plant resistance in arthropod management programs. Arch Insect Biochem 51:222–235. doi:10.1002/arch.10066

Sturz AV, Mathenson BG, Arsenault W, Kimpinski J, Christie BR (2001) Weeds as a source of plant growth promoting rhizobacteria in agricultural soils. Can J Microbiol 47:1013–1024

Sudhakar P, Chattopadhyay GN, Gangwar SK, Ghosh JK (2000) Effect of foliar application of *Azotobacter*, *Azospirillum* and *Beijerinckia* on leaf yield and quality of mulberry (*Morus alba*). J Agr Sci 134:227–234

Sudisha J, Niranjana SR, Umesha S, Prakash HS, Shetty HS (2006) Transmission of seed-borne infection of muskmelon by *Didymella bryoniae* and effect of seed treatments on disease incidence and fruit yield. Biol Control 37:196–205. doi:10.1016/j.biocontrol.2005.11.018

Sundara B, Natarajan V, Hari K (2002) Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugarcane and sugar yields. Field Crop Res 77:43–49

Swaider JM, Ware GW, McCollum JP (1992) Producing vegetable crops. Interstate Publishers Inc, Danville, IL

Teixeira DA, Alfenas AC, Mafia RG, Maffia LA, Ferreira EM (2005) Evidence of induction of systemic resistance to eucalyptus rust by plant growth promoting rhizobacteria. Fitopatol Bras 30:350–356. doi:10.1590/S0100-41582005000400003

Termorshuizen AJ (2002) Cultural control. In: Waller JM, Lenné JM, Waller SJ (eds) Plant pathologist's pocketbook, 3rd edn. CABI Publishing, CAB International, Wallingford, Oxon, UK, pp 318–327

Tian B, Yang J, Ke-Qin Z (2007) Bacteria used in the biological control of plant-parasitic nematodes: populations, mechanisms ofaction, and future prospects. FEMS Microbiol Ecol 61:197–213. doi:10.1111/j.1574-6941.2007.00349.x

Timmusk Someya NS, Nicander B, Granhall U, Tillberg E (1999) Cytokinin production by *Paenibacillus polymyxa*. Soil Biol Biochem 31:1847–1852

Umesha S (2006) Occurrence of bacterial canker in tomato fields of Karnataka and effect of biological seed treatment on disease incidence. Crop Prot 25:375–381. doi:10.1016/j.cropro.2005.06.005

Utkhede R, Koch C (2004) Biological treatments to control bacterial canker of greenhouse tomatoes. Biocontrol 49:305–313

Vallad GE, Goodman RM (2004) Systemic acquired resistance and induced systemic resistance in conventional agriculture. Crop Sci 44:1920–1934

van Loon LC, Bakker PAHM (2006) Induced systemic resistance as a mechanism of disease suppression by rhizobacteria. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, Netherlands, pp 39–66

van Loon LC, Bakker PAHM, Pieterse CMJ (1998) Systemic resistance induced by rhizosphere bacteria. Annu Rev Phytopathol 36:453–483

van Peer R, Niemann GJ, Schippers B (1991) Induced resistance and phytoalexin accumulation in biological control of fusarium wilt of carnation by *Pseudomonas* sp. strain WCS417r. Phytopathology 81:728–734

Vargas DP, Ferrera-Cerrato R, Almaraz-Suarez JJ, Gonzalez AG (2001) Inoculation of plant growth-promoting bacteria in lettuce. Terra 19:327–335

Verma SC, Ladha JK, Tripathi AK (2001) Evaluation of plant growth promoting and colonization ability of endophytic diazotrophs from deep water rice. J Biotechnol 91:127–141

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Walker JC (1957) Plant pathology, 2nd edn. McGraw-Hill Book Company Inc., New York

Waller JM (2002) Virus diseases. In: Waller JM, Lenné JM, Waller SJ (eds) Plant pathologist's pocketbook, 3rd edn. CABI Publishing, CAB International, Wallingford, Oxon, UK, pp 108–125

Waller JM, Cannon PF (2002) Fungi as plant pathogens. In: Waller JM, Lenné JM, Waller SJ (eds) Plant pathologist's pocketbook, 3rd edn. CABI Publishing, Wallingford, Oxon, UK, pp 318–327

Waller JM, Lenné JM, Waller SJ (2002) Plant pathologist's pocketbook, 3rd edn. CABI Publishing, Wallingford, Oxon

Walters D, Heil M (2007) Costs and trade-offs associated with induced resistance. Physiol Mol Plant P 71:3–17. doi:10.1016/j.pmpp. 2007.09.008

Wang KY, Liu TX, Yu CH, Jiang XY, Yi MQ (2002) Resistance of *Aphis gossypii* (Homoptera: Aphididae) to fenvalerate and imidacloprid and activities of detoxification enzymes on cotton and cucumber. J Econ Entomol 95:407–413

WenXing H, Tuo Y, HongYang S, LiNa S (2008) PGPR bio-fertilizers producing and its effect on *Avena sativa* growth and quality development. Acta Pratac Sin 17:75–84

Whitelaw MA (2000) Growth promotion of plants inoculated with phosphate-solubilizing fungi. Adv Agron 69:99–151

Xue QY, Chen Y, Li SM, Chen LF, Ding GC, Guo DW, Guo JH (2009) Evaluation of the strains of *Acinetobacter* and *Enterobacter* as potential biocontrol agents against *Ralstonia* wilt of tomato. Biol Control 48:252–258. doi:10.1016/j.biocontrol.2008.11.004

Yang JW, Kloepper JW, Ryu CM (2009) Rhizosphere bacteria help plants tolerate abiotic stress. Trends Plant Sci 14:1–4. doi:10.1016/j.tplants.2008.10.004

Yıldırım E, Turan M, Donmez MF (2008) Mitigation of salt stress in radish (*Raphanus sativus* l.) by plant growth promoting rhizobacteria. Roum Biotechnol Lett 13:3933–3943

Zahir ZA, Ghani U, Naveed M, Nadeem SM, Asghar HN (2009) Comparative effectiveness of *Pseudomonas* and *Serratia* sp. containing ACC-deaminase for improving growth and yield of wheat (*Triticum aestivum* L.) under salt-stressed conditions. Arch Microbiol 191:415–424. doi:10.1007/s00203-009-0466-y

Zahir ZA, Munir A, Asghar HN, Shaharoona B, Arshad M (2008) Effectiveness of rhizobacteria containing ACC deaminase for growth promotion of peas (*Pisum sativum*) under drought conditions. J Microb Biotechnol 18:958–963

Zaidi SFA (2003) Biocontrol of *Fusarium oxysporium* by plant growth promoting rhizobacteria (PGPRs) in soybean. Ann Agr Res 24:676–678

Zehnder G, Kloepper J, Tuzun S, Yao C, Wei G, Chambliss O, Shelby R (1997) Insect feeding on cucumber mediated by rhizobacteria-induced plant resistance. Ent Exp Appl 83:81–85

Zehnder GW, Yao CB, Murphy JF, Sikora ER, Kloepper JW (2000) Induction of resistance in tomato against cucumber mosaic cucumovirus by plant growth-promoting rhizobacteria. Biocontrol 45:127–137

Zhang L, Birch RG (1997) Mechanisms of biocontrol by *Pentoena dispersa* of sugar cane leaf scald disease caused by *Xanthomonas albilineans*. J Appl Microbiol 82:448–454

Zhuang X, Chen J, Shim H, Bai Z (2007) New advances in plant growth-promoting rhizobacteria for bioremediation. Environ Int 33:406–413. doi:10.1016/j.envint.2006.12.005