PGPR: Current Vogue in Sustainable Crop Production

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Abstract

Nowadays a large scale of crop produce are pesticide ridden. Heavy application of these hazardous pesticides is not only very costly which leaves financial burden to the farmers but is also harmful to our biodiversity leading to loss of various endangered living species. However, growers are being trained worldwide, and they are progressively switching over their agriculture from chemical or conventional agriculture to organic or sustainable agriculture. Sustainable agriculture reveals crop cultivation with “no chemicals.” But organically cultivated produce are mirage due to their exorbitant prices, at least for the urban dwellers. To resolve this conundrum, the role of plant growth-promoting rhizobacteria (PGPR) has been discussed in the process of plant growth promotion, with their mechanisms and their importance in crop production on sustainable basis. The application of PGPR strain is conducive and creates thrust toward organic farming at every level of farmers, whether it be large landowner or small-scale farmers. However, PGPR strain performance varies from lab to field and even from field to field due to host specificity. Besides, some strains of PGPR have the potential to promote growth of a particular plant, while in another plant they do not respond. There are various ways that promote plant growth such as N_2 fixation, P solubilization, siderophore production, phytohormone production, and also the control of phytoparasitic pathogens. In addition to the beneficial role, some important aspects of negativity inducted by the PGPR have also been discussed. Sustainable agriculture, if done in the light of PGPR module, will not only remove the financial burden of the farmers but also prove to be conducive, congenial, and putative. Further studies to commercialize the potent strain of PGPR are stridently needed which will unravel certain yet to be explored mechanisms.

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21.1 Introduction

The total world population is expected to increase by 8.5 billion by 2030 (Anonymous 2015). This significant population increase is surmised due to unchecked and consistent increase in the population of developing or underdeveloped countries. This significant increase brings about the poverty and hunger. India has been home to 194.6 million undernourished people, the highest in the world (Anonymous 2015). To obviate this issue, sustainable crop production is the best weapon known so far against poverty and hunger especially powerful in underdeveloped countries. Microorganisms are the best living entities providing the best ecological services in the sustenance of ecological balance. Thus, a group of bacteria that help in plant growth promotion by exhibiting beneficial inputs on crop plant are known as plant growth-promoting rhizobacteria (PGPR) (Zhou et al. 2016). They do have some advanced diagnostic features such as colonization of the host's rhizosphere, rhizoplane, and the interior region of the root system. Besides, some bacteroides make the way to enter inside the root building up endophytic population which ultimately benefits the crop plants (Compant et al. 2005). Similarly, some bacterial species are able to enhance the root surface area providing essential nutrients that reach to the plant, thereby inducing plant productivity (Adesemoye and Kloepper 2009). The thread line toward the role of biofertilizers in nutrient uptake and environment stress management has provided a relaxation to the researchers up to some extent but not fully. Hence, we are in urgent need to manage these stresses through eco-friendly ways. Many countries are utilizing PGPR as biofertilizers in sustainable agriculture and also forcing nearby nations to use them in a proper way (Singh et al. 2011). However, there are some issues/factors to use PGPR, such as performance of strains under field conditions, because it has been seen that bacterial strains having the same biological potential do not respond under the field conditions that may be due to failure in the host's root colonization. To eliminate the food issues for the crowded population, natural biofertilizers in sustainable module are being used. It has been a well-established fact that application of suitable PGPR strain enhances the productivity under favorable climate conditions (Okon and Labandera-González 1994; Singh et al. 2011). A large number of genera of PGPR have been applied worldwide to check the potentiality in plant growth promotion and found to possess great potential in sustainable crop production such as silviculture, horticulture, and environmental remediation (Jeffries et al. 2003; Reed and Glick 2005; Fravel 2005; Aeron et al. 2011; Karličić et al. 2016). The role of different organic molecules released by PGPR like indoleacetic acid (Park et al. 2005; Shao et al. 2015), gibberellic acid (Mahmoud et al. 1984; Ortega-Baes and Rojas-Aréchiga 2007; Castillo et al. 2015), and cytokinins (Amara et al. 2015) is appreciable to various extents in agriculture. In addition, plant hormones such as IAA and cytokinin-producing PGPR are found to be conducive growth promoters of various horticultural crops, *Sesamum indicum*, *Trifolium repens*, *Arachis hypogaea*, *Cajanus cajan*, *Trigonella foenum*, *Mucuna pruriens*, *Pinus roxburghii*, and *Mimosa pudica* (Noel et al. 1996; Hirsch et al. 1997; Kumar et al. 2005). Growth stimulation in plant through PGPR has been observed through various mechanisms such as colonization of plant root, plant growth stimulation, and reduction in plant disease (Kloepper and Schroth 1978). To unravel the complex mechanisms involved in rhizobial interactions is a very important issue in the determination of the sustainability; however, some abiotic factors such as temperature, soil nature, smog, etc. can't be avoided. Because varying temperatures have good binding with aeration, pH gradient promotes the microbial growths (Shen et al. 2015).

Application of PGPR into soil must be evaluated meticulously. However, the indigenous strain may trigger defense mechanism induction which helps in the reduction of the pathogen potential by releasing root flavonoids (Parmar and Dufresne 2011). Therefore, during the microorganism selection, extreme care through rigorous filed studies to fully understand interactive traits is needed which may ease the expected turmoil. Besides, PGPR provide the potential role in the biotic and abiotic stress reduction, also help in the elimination of pesticides' residual effects, and thereby help in the plant and microflora development through sustainable ways (Khan 2005; Kang et al. 2010; Xun et al. 2015).

Moreover, for successful colonization and proliferation of PGPR, interaction among the microorganisms is necessary especially between the local strains. The bacterial population around the rhizosphere remains always higher than the population existing through the soil (Lynch and Leij 1990). These aspects have made a clear note that the higher amount of nutrient remains available around the root region. Conjoint application of compatible traits accelerates symbiotic activities which help in the enhanced nutrient acquisition by switching on some gene that allows recognition and release of root exudates (Verma and Yadav 2012).

21.2 The Rhizosphere: Dwelling Point for PGPR

The rhizosphere is considered to be the most important portion of the ecological habitat in soil where PGPR along with other microorganisms remain in close contact with the roots of the plant (Brink 2016). PGPR may have some specific alliances with plants which may have provided the role in growth enhancement. Production of some biomolecules for plant growth promotion such as phytohormones, metabolites, etc. may modify the rhizosphere microbiota and environment affecting microbial diversity associated with the rhizosphere (Frankenberger and Arshad 1995; Davison 1988). Different types of close association in bacteria with roots may be formed such as on root surface (rhizoplane) and soil just after the root (rhizosphere) (Brink 2016). PGPR respond to various processes like exchange of signal molecules and nutrients and colonize the root tissue creating a protection layer of root tissues. In addition, mucigel consists of plant mucilage, bacterial exopolymers, and soil particles of the immediate layer of rhizobacteria. It has been reported that plant roots covered by mucigel have higher water content than noncovered ones; hence, mucigel plays a crucial role in the root protection and protects from dehydration (Miller and Wood 1996). In addition, contents of root exudates help in the enrichment and selection of bacteria and ultimately help in the healthy rhizosphere formation. Plant root exudates act as source of carbon for microbial growth. Besides, there are certain organic molecules which perform chemotaxis of microbes within the rhizosphere. In addition, root exudates are much helpful in the maintenance of steady concentration of some flavonoids and mineral nutrients, flocked after decomposition of organics and other recycled wastes (Dakora and Phillips 2002). Thus depending upon the nature and types of organics, released flavonoids and other molecules, specific PGPR diversity develops into the rhizosphere. Several PGPR have the ability to attach with roots and extract the nutrients from soil making them available to the plants. More specifically, some strains of PGPR have been found to penetrate the root tissue and make direct communication with the organic nutrients present in the apoplast (Gupta et al. 2017).

21.3 Mechanisms of Actions

Generally there are two types of mechanisms involved in the plant growth promotion, i.e., (1) direct and (2) indirect.

21.3.1 Direct Mechanism

21.3.1.1 Nitrogen Fixation

Nitrogen (N) is an important element for growth and development; hence, it is surmised to be very essential. However, 78% N_2 present in the atmosphere is not available to the growing plants. Generally, N_2 is converted into a useable form through nitrogen fixation process where nitrogen changes to ammonia through nitrogenase enzyme (Kim and Rees 1994). Biological nitrogen fixers are ubiquitous in nature, and available around the world, they function at mild temperature (Raymond et al. 2004). They are economically sound, beneficial, eco-friendly, and alternative to hazardous pesticides. Around two-thirds of global nitrogen is fixed through biological nitrogen fixation process (Rubio and Ludden 2008).

Generally, two categories of nitrogen-fixing organisms are found: (1) symbiotic nitrogen-fixing bacteria (rhizobia) which includes members of the family *Rhizobiaceae* forming symbiosis with leguminous plants (Ahemad and Khan 2010; Zahran 2001) and nonleguminous plants (*Frankia*) and (2) nonsymbiotic nitrogen-fixing bacteria such as cyanobacteria, *Azotobacter*, *Azospirillum*, *Azoarcus*, *Gluconacetobacter diazotrophicus*, etc. (Bhattacharyya and Jha 2012). Although nitrogen-fixing bacteria make available only a short amount of the fixed nitrogen to the plants (Glick 2012), interestingly, some other type of symbiotic nitrogen-fixing bacteria infects the root and establishes symbiosis with the roots of crop plants.

In the establishment of the symbiotic relationship, dinitrogenase reductase containing iron protein and dinitrogenase having metal cofactors are involved (Minamisawa et al. 2016). Dinitrogenase reductase gives electrons with high reducing energy, while dinitrogenase forming metal cofactor uses these electrons to reduce N_2 to NH_3. There are three nitrogen-fixing cofactors such as (1) Mo-nitrogenase, (2) V-nitrogenase, and (3) Fe-nitrogenase. Structure wise, nitrogen-fixing living system varies from genus to genus; mostly nitrogen fixation process is completed by the activity of the molybdenum-nitrogenase (Bishop and Jorerger 1990). The nitrogen fixation process is carried out by an enzyme known as nitrogenase complex (Kim and Rees 1994).

21.3.1.2 Phosphate Solubilization

The second important plant growth-limiting nutrient is phosphorus (P) after nitrogen; this is available in plenty in both organic and inorganic forms (Khan et al. 2009). Despite having a large reservoir of P in the soil, the sufficient amount of P to the plant is not reachable due to availability of P into H_2PO_4 forms which are inaccessible to the plants (Bhattacharyya and Jha 2012). The insoluble P is available in the soil and remains in an inactive state as inorganic mineral forms like apatite or as organic forms such as inositol phosphate, phosphotriesterase, and phosphomonoesters (Glick 2012). To obviate the P deficiency in soils, farmers have started to apply phosphatic fertilizers in agricultural lands. Plants obtain fewer amounts of applied fertilizers, and the rest is rapidly converted into insoluble forms of P in the soil which are reserved again and reach beyond the catch limits of the plants (Mckenzie and Roberts 1990). Importantly, continuous application of P is not a solution because regular application of these P fertilizers is not only very costly to the farmers but is also an unsafe means to the environments. Moreover, organisms having phosphate-solubilizing activity, known as phosphate-solubilizing microorganisms (PSM), help in the availability of P to the plants (Khan et al. 2006). PSB are considered to be a supplier of P in P-limited soil and replenish the P through various means (Zaidi et al. 2009). Some bacteria such as *Serratia*, *Microbacterium*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Erwinia*, *Flavobacterium*, *Pseudomonas*, *Enterobacter*, *Rhizobium*, and *Beijerinckia* are known to be the important and ecologically sound rhizobacteria (Bhattacharyya and Jha 2012). Solubilization of inorganic phosphorus is carried out by the action of organic acids (low molecular weights) which have been synthesized by various PGPR groups (Zaidi et al. 2009). A large number of phosphatase enzymes catalyzing the hydrolysis phosphoric esters are involved in the mineralization (Glick 2012). Moreover, phosphate solubilization and mineralization may occur in the same bacterial species simultaneously (Tao et al. 2008).

21.3.1.3 Siderophore Production

Iron is a key element for all microorganisms to thrive well; however, certain lactobacilli, are an exception (Neilands 1995). In some environments, iron does not occur in the accessible form, but they are available in plenty as an inaccessible form (Rajkumar et al. 2010). Generally, bacteria catch iron atoms through organic molecules which act as an iron chelator, siderophores having high iron-binding affinities. Generally, water-soluble siderophores are common, and they are categorized into extracellular and intracellular siderophores (Khan et al. 2009). In gram-positive and gram-negative bacteria, Fe^{+3} in Fe^{3+}-siderophore complex on the membrane of bacteria is reduced to Fe^{2+} which is accessible to bacterial membrane, further released into the cell through gating mechanisms of inner and outer membrane of bacteria (Ansari et al. 2016). However, there may be loss of some amount of siderophores (Rajkumar et al. 2010; Neilands 1995). Hence, it may be concluded that siderophore acts as iron solubilizers under an iron-limited environment (Indiragandhi et al. 2008). Besides iron, some other heavy metals like Al, Cd, Cu, Ga, In, Pb, and Zn are being chelated by siderophores (Neubauer et al. 2000). In addition, siderophore complex enhances the solubility of metal concentration (Rajkumar et al. 2010). Therefore, bacterial released chelating molecules assist well in the alleviation of stress imposed on plant by heavy metals (Schmidt 1999). Plenty of research have advocated well for plant growth promotion as a result of siderophore releasing bacterial applications (Rajkumar et al. 2010; Ansari et al. 2016). Crowley and Kraemer (2007) reported that siderophores released by bacteria help iron to be made available to the oat, and the plant has mechanisms for utilization of complex under iron-deprived environment. Moreover, *Pseudomonas fluorescens* C7 enhanced the iron content significantly in plant tissue and improved plant yield (Vansuyt et al. 2007). Inoculation of *Pseudomonas* strain GRP3 on iron nutrition of *Vigna radiata* resulted in a decline in chlorotic injuries and enhanced plant growth (Sharma et al. 2003).

21.3.1.4 Phytohormone Production

Most of PGPR isolated from the soil especially rhizosphere have the ability to synthesize and release phytohormones like IAA as secondary molecules (Patten and Glick 1996). Generally, IAA released by PGPR may alter the growth and development of the plant because endogenous pool of plant IAA may be deviated by the enhanced acquisition of IAA (Glick 2012; Spaepen et al. 2007). Moreover, IAA also plays a crucial role in plant defense mechanisms against a wide range of phytopathogenic bacteria (Spaepen and Vanderleyden 2011). Thus, IAA released by PGPR is recognized as effective molecules and plays a role in pathogenesis and phytostimulation (Spaepen and Vanderleyden 2011). It has been reported that IAA is a significant factor in various cellular processes, such as cell division, differentiation, and vascular bundle formation, and also surmised that auxins play a role in the nodule formation (Glick 2012; Spaepen et al. 2007). It is reported that application of *Rhizobium leguminosarum* bv. *viciae* enhanced 60-fold more root nodules than uninoculated ones (Camerini et al. 2008). In spite of these, certain environmental factor regulates the IAA biosynthesis in different genera of PGPR (Spaepen et al. 2007).

21.3.1.5 1-Aminocyclopropane-1-Carboxylate (ACC) Deaminase

Ethylene is an essential hormone for carrying out normal plant growth and development (Khalid et al. 2006). This phytohormone is produced by almost all plants and plays an important role in the reduction of multifarious physiological changes in plants. In addition, ethylene is also considered to be a stress hormone (Saleem et al. 2007). It has been reported that under deprived conditions due to various environmental factors such as extreme drought, water logging, heavy metals, and pathogenicity, the ethylene reaches to its elevated level and affects negatively the plant, thereby reducing the crop growth and development (Saleem et al. 2007; Bhattacharyya and Jha 2012). PGPR possess enzymes, e.g., 1-aminocyclopropane-1-carboxylate (ACC) deaminase, to help in plant biomass enhancement by reducing the ethylene level (Nadeem et al. 2007; Zahir et al. 2008). Some bacterial strains possessing ACC deaminase activity have been documented such as *Acinetobacter*, *Achromobacter*, *Agrobacterium*, *Alcaligenes*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Pseudomonas*, *Ralstonia*, *Serratia*, *Rhizobium*, etc. (Shaharoona et al. 2007a, b; Nadeem et al. 2007; Zahir et al. 2008; Zahir et al. 2009; Kang et al. 2010). These bacterial genera have the ability to convert ACC to 2-oxobutanoate and NH_3 (Arshad et al. 2007). Various types of biotic and abiotic stress have been relaxed by ACC deaminase producers (Glick 2012; Lugtenberg and Kamilova 2009). Besides, these PGPR help in the root elongations, seed formation, and enhancement in root nodule formation (Nadeem et al. 2007; Shaharoona et al. 2008; Nadeem et al. 2009; Glick 2012).

21.3.2 Indirect Mechanism

Management of plant disease through the application of bioagents is an eco-friendly and novel approach (Lugtenberg and Kamilova 2009; Rizvi et al. 2016; Ansari et al. 2016). Significant indirect mechanisms of plant growth promotion in PGPR through biocontrol agents have been discussed (Glick 2012). Generally, food competitions, niche exclusions, induction of systemic resistance, and antifungal metabolite production are the main mode of biological control of PGPR. A large number of PGPR have been reported to produce antifungal metabolites such as HCN, phenazines, pyrrolnitrin, 2,4-diacetylphloroglucinol, pyoluteorin, viscosinamide, and tensin (Bhattacharyya and Jha 2012). In addition, proper synchronization of PGPR with root leads to development of plant resistance against some pathogenic bacteria, fungi, and viruses (Rizvi et al. 2016). This process is known as induced systemic resistance (ISR) (Lugtenberg and Kamilova 2009).

Under natural environment having stress, mechanisms used by the PGPR for plant growth promotion are common. However, under stress conditions some strains of PGPR fail to survive because of inability to tolerate the stress. But the significant increase in plant growth takes place by various mechanisms, for example, reduction in stress-induced ethylene level, production of exopolysaccharides, induced systemic resistance, etc. (Glick et al. 2007; Saharan and Nehra 2011; Sandhya et al. 2009; Saravanakumar et al. 2007; Upadhyay et al. 2011). As far as stress management is concerned, plant growth is affected by nutritional perturbations such as elevation in Na^+ which causes iron toxicity and disrupts the usual uptake of various essential ions. Some strains of PGPR protect crop plants from excessive Na^+ concentration by producing exopolysaccharides and through biofilm transformations which ultimately reduce Na^+ uptake (Geddie and Sutherland 1993; Khodair et al. 2008; Qurashi and Sabri 2012). In addition, PGPR protect plants from phytopathogens through various mechanisms such as antibiosis, competition, and parasitism (Beneduzi et al. 2012; Cassells and Rafferty-McArdle 2012;

Deshwal et al. 2003; Gula et al. 2013; Heydari and Pessarakli 2010; Khokhar et al. 2012; Perneel et al. 2008; Ping and Boland 2004). PGPR adopt one or more mechanisms for crop protection. PGPR check the phytopathogens' growth by antibiosis mechanisms where antimicrobial compounds inhibit pathogen's growth released by bacteria (Glick 1995). Similarly, PGPR have also been reported to check availability of iron required for pathogens which is necessary for plant growth. (Subba Rao 1993).

It is enough to conclude that PGPR accelerate plant growth by deploying some mechanisms and help in the crop protection from various deleterious plant pathogens which directly or indirectly affect the plant growth. In addition, there may be some specificity in the bacterial genera, i.e., some mechanisms may be present in one particular strain while absent in another.

21.4 Commercialization of PGPR

Different strains of bacteria have responded to various extents under different climatic environment. This may be due to different climatic factors and edaphic factor which are considered to affect the performance of beneficial PGPR (Zaidi et al. 2009). The importance of PGPR has generated an impetus to commercialize the PGPR in the industrial level so that potential strains of PGPR may be exploited from the soil and transferred to the farmers' even low scale of land (Table 21.1).

Table 21.1 Various strains of plant growth-promoting rhizobacteria (PGPR) exerting beneficial impact on plant health

S. no.	PGPR	Role	Reference
1	*Bacillus megaterium*, *Arthrobacter chlorophenolicus*, and *Enterobacter* sp.	Enhanced plant growth and yield attributed by solubilization of phosphorus; nitrogen fixation; production of phytohormones such as auxins, cytokinins and gibberellins; sequestering of iron by production of siderophores; and lowering of ethylene concentration	Idris et al. (2004)
2	*Azotobacter*, *Bacillus*, *Enterobacter*, and *Xanthobacter*	Significantly enhanced nitrogen accumulation, growth and grain yield of rice plants	Mirzai et al. (2010), Bal et al. (2013), Khalid et al. (2009), and Singh et al. (2011).
3	*Bacillus lentimorbus*	Enhanced plant growth as well as antioxidant capacity of the edible parts of spinach, carrots and lettuce, under salinity and drought stress	Nautiyal et al. (2008), Ahmad et al. (2013), and Naveed et al. (2014)

S. no.	PGPR	Role	Reference
4	*Pseudomonas aeruginosa*	Improved the growth of *Vigna radiata* (mung beans) plants under drought conditions. PGPR-inoculated plants tend to improve the water-use efficiency of plants. Hence, these bacteria can be beneficial to the environment in terms of reducing excessive usage of water	Sarma and Saikia (2014), Ahmad et al. (2013), and Naveed et al. (2014)
5	*Bacillus megaterium* and *Pantoea agglomerans*	Inoculation of these bacteria into maize roots increased the ability of the root to absorb water under the salinity conditions. Here, bacteria that can grow under hypersaline conditions were better able to colonize the root rhizospheres and external spaces of roots that are themselves exposed to high-salinity conditions	Marulanda et al. (2010) and Gond et al. (2015)
6	*Azospirillum brasilense*	Improved salt tolerance of the jojoba plant during in vitro rooting	Gonzalez et al. (2015)
7	*Azospirillum*	Inoculation of lettuce plants with *Azospirillum* sp. not only improved lettuce quality but also extended the storage life of a lettuce grown under salt stress	Gabriela et al. (2015)
8	*Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Corynebacterium*, *Pseudomonas*, *Rhizobium*, and *Serratia*	Beneficial to the whole rhizosphere microbiota through the highly nutritive and energetic rhizodepositions and, in turn, improved plant growth	Rawat and Mushtaq (2015)
9	*Pseudomonas fluorescens* and *Bacillus subtilis*	Soil application of both *P. fluorescens* and *B. subtilis* alone or in combination was able to reduce the nematode population and improve the onion growth	Munshid et al. (2013)
10	*Azotobacter* sp., *Bacillus cereus, B. megaterium, B. subtilis*	Individual and/or mixed treatment of PGPR when used as a soil drench treatment resulted in reduced root rot/wilt incidence and severity on some evergreen fruit transplants under greenhouse conditions compared with control. The mixed treatment of PGPR gave the highest protection against root rot/wilt diseases compared with the use of individual treatment. Also, all treatments significantly increased plant growth when compared with control treatment	Abdel-Monaim et al. (2014)
11	*Pseudomonas fluorescens*	Singly and in various combinations with botanical enhanced growth and productivity parameters of fenugreek (*Trigonella* sp.)	Rizvi et al. (2013)

(continued)

Table 21.1 (continued)

S. no.	PGPR	Role	Reference
12	*Azospirillum brasilense strain Cd*	Improved plant growth and nutrition as well as reduced root-knot nematode in roots in micropropagated banana	Rodrigues et al. (2008)
13	*Azospirillum brasilense* and *Rhizobium leguminosarum bv. ciceri*	Improved the nodulation of chickpea; the effect of this interaction was further enhanced by organic matter present in the growth medium	Fabbri and Del Gallo (1995)
14	*Azotobacter chroococcum*	Production of growth substances (auxin, gibberellin, etc.) and in turn enhanced crop production	Wani et al. (2013)
15	*Bacillus* spp.	Elicit induced systemic resistance (ISR) and also elicit plant growth promotion	Kloepper et al. (2004)
16	*Bacillus subtilis, Pseudomonas fluorescens*, and *Aspergillus awamori*	Significantly increased plant growth and chlorophyll contents of pathogen-inoculated tomato plants	Singh and Siddiqui (2015)

21.5 Pros and Cons of PGPR Applications

A critical observation pertaining to the administration of any foreign strain of PGPR is done in order to know up to what extent they have adaptability to the native strain. If they are incompatible with each other, there may be some perturbation regarding the performance of the bacteria. Besides, native strain initiates the development of resistance in the plant against deleterious phytopathogens by releasing flavonoids and phytoalexins (Parmar and Dufresne 2011). In order to understand the interactive character of the microorganisms and their utilization as a potential application, rigorous studies on field experiment are required. The rhizosphere is an ideal place for the proliferation of these microorganisms influenced by the various environmental factors like physical, chemical, and biological processes of the root (Sørensen 1997). These microorganisms nurture well in and around the root area of plants which may be due to root exudates which are then used by the microbial growth (Doornbos et al. 2012; Phillips et al. 2011).

21.5.1 Beneficial Aspects of PGPR

PGPR present in the soil environment can cause beneficial alterations in plant health either through the production of plant growth regulators or ameliorating the plant nutrition by enhancing nutrient uptake from the soil (Zahir et al. 2004). Besides, a large number of these rhizobacteria help the plant to overcome several biotic as well as abiotic stresses such as drought, salinity, flooding, and heavy metal toxicity, and hence they capacitate the plant to sustain under adverse environmental situations (Tiwari et al. 2016). Different free-living soil bacterial strains of a particular genus consist of similar metabolic potential of enhancing plant growth (Gamalero et al. 2009; Belimov et al. 2005; Ma et al. 2011; Nadeem et al. 2007; Sandhya et al. 2009; Zahir et al. 2008). PGPR minimize the detrimental effects of the plant pathogens through several mechanisms that in turn lead to healthy and disease-free plants, thereby improving the plant growth indirectly (Glick and Bashan 1997). This task of PGPR may be fulfilled either by the release of anti-pathogenic substances or by making the plant more resistant against attacking pathogen through activation of induced systemic resistance (Persello-Cartieaux et al. 2003). As far as direct growth promotion is concerned, PGPR adopt different pathways such as providing the host plant a useful compound or facilitating the plant to use the beneficial compounds already present in the soil (Kloepper et al. 1991). They can also help the plant by fixing atmospheric nitrogen and producing siderophores that chelate iron that gets available to the plants. PGPR have also been reported to produce phytohormones and solubilizing nutrients such as phosphorus, thus making it available to the plants (Patten and Glick 2002). The efficiency of these rhizobacteria is also determined by the host plants as well as the soil characteristics (Gamalero et al. 2009). Overall, PGPR enable them to promote plant growth and development by various ways. Some strains utilize more than one mechanism to go through normal as well as stressed environmental conditions. In addition to rhizobacterial strain, plant growth and development also rely on the types of interaction with the host plant and also with the soil environment.

21.5.2 Harmful Aspects of PGPR

PGPR play a valuable role in the sustenance of soil health and enhancement of plant growth and developments; they are also reported to show pernicious effects on plant growth and developmental process (Saharan and Nehra 2011). For instance, *Pseudomonas* species produce cyanide that is implicated to have both advantageous and detrimental effects. Cyanide-producing PGPR not only inhibit the growth of certain pathogens but also cause injurious impact on plant growth (Martínez-Viveros et al. 2010). Moreover, the auxin production by PGPR, depending on its concentration, may be beneficial or detrimental for plant health (Vacheron et al. 2013). A low concentration of auxin promotes plant growth, while at elevated level root retardation has been noticed (Patten and Glick 2002). Another compound rhizobitoxine released by *Bradyrhizobium elkanii* acts in both manners. Being an inhibitor of ethylene synthesis, it can mitigate the adverse effects of stress-induced ethylene on the formation of nodule (Vijayan et al. 2013). But in some cases such as foliar chlorosis in soya bean, it has also been reported to act as a toxin (Xiong and Fuhrmann 1996). Enormous varieties of biosurfactant produced by the microorganisms are being considered as an interesting group of materials for application in various areas of agriculture such as food, health care, biotechnology, and biomedical approaches (Banat et al. 2010). It has also been observed that simultaneous application of PGPR and fungi accelerates to be pathogenic, while PGPR individually remain nonpathogenic

(Banat et al. 2010). The above discussion flashes the light on the negative impacts of PGPR in addition to its positive role. However, these detrimental impacts may take place under certain specific conditions and that too by some distinct strains.

21.6 Conclusion and Future Prospects

High level of hazardous pesticide application is very costly and leaves financial burden to the farmers. Their application also leaves a mark of loss of red data list species. No doubt, different governments have initiated various steps to train the local farmers to cultivate their land in organic ways. Application of PGPR is one of the cost-effective and conducive ways. It is concluded that application of PGPR helps to enhance plant growth through various mechanisms like induction of IAA, P solubilization, and siderophore production. Sometimes it has been seen that consortia of different strains are much more effective than their sole application. More studies on PGPR will increase our knowledge of rhizosphere biology and will provide the new avenues to open for new door for the sustainable agriculture. Application of consortia of different strains of PGPR will help in the nutrient management.

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