Chapter 6
Plant Growth Promoting Rhizobacteria (PGPR): Modern Prospects for Sustainable Agriculture

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Abstract Plant and soil microbiome interactions are in the great demand around the globe. Bacteria that colonize in the plant roots or in the rhizosphere and promote plant growth directly by nutrient immobilization or worked as defense regulator are referred to as plant growth-promoting rhizobacteria (PGPR). During the past couple of decades, PGPR have emerged as a potent alternative to chemical fertilizer in an eco-friendly manner. Therefore, they are abundantly accepted in agriculture, horticulture, silviculture, and environmental cleanup strategies. The rhizosphere ecology is influenced by a myriad of abiotic and biotic factors in natural and agricultural soils, and these factors can, in turn, modulate PGPR effects on plant health. Manipulating this rhizospheric microbiome through rhizo-engineering has materialized as a contemporary methodology to decipher the structural, functional, and ecological behavior of rhizospheric PGPR populations. In this chapter, we have

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tried to explore the latest developments in the technologies related to PGPR, for its well acceptance for sustainable agriculture and plant health.

Keywords PGPR · Rhizospheric microbiome · Ecology · Sustainable agriculture · Plant health

6.1 Introduction

6.1.1 Concept and Definition

The soil is a dynamic living matrix, and it is not only an essential resource in agriculture and food security, but it is also toward the maintenance of all the life process. The soil is home to thousands of bacterial species. Root colonizing bacteria (rhizobacteria) that exert beneficial effects on plant development via direct or indirect mechanisms have been defined as plant growth promoting rhizobacteria (PGPR). These root colonizing bacteria (endophytic and epiphytic) have been proven to exert influence on soil security (Ahkami et al. 2017; Wallenstein 2017), seed germination under drought stress (Delshadi et al. 2017), and cleanup strategies (Thijs et al. 2016); antagonize pathogens; decrease plant diseases; enhance plant resistance to diseases, salt stress, coldness, and heavy metal toxicity; and improve crop growth, development, yield, and quality through directly synthesizing hormones, antibiotics, and other secondary metabolites and by regulating plant related gene expressions and others (Gupta and Dikshit 2010; du Jardin 2015; Haymer 2015; Kumary and Raj 2016; Vejan et al. 2016).

6.1.2 Agriculture and PGPR

The role of these PGPR formulations has been well documented this decade to improve crop productivity, plant health, and soil quality as well as in many agricultural crops, vegetable, and fruits (von der Weid et al. 2000; Orhan et al. 2006; Rana et al. 2011; Zhang et al. 2012; Sharma et al. 2014) (Table 6.1). The microbes (PGPR) and rhizosphere have interaction, i.e., rhizo-engineering and other techniques are the recent advances in this sector to meet global food and eco-friendly strategies for green earth/global warming (Haymer 2015; Thijs et al. 2016; Ahkami et al. 2017; Ahmadi et al. 2017; Reeves 2017; Timmusk et al. 2017; Wallenstein 2017). According to the Food and Agriculture Organization (FAO), the estimated world population for 2025 will be nearly 8.5 × 109 inhabitants. Such an increase will inevitably require the substantial additional agricultural production of 2.4 × 109 t/year (Timmusk et al. 2017). The changing climate and overpopulation have led to the crisis of nutrient availability and food security for humans especially in developing countries (Çakmakçi et al. 2007; De et al. 2015; Reeves 2017).

Table 6.1 List of PGPR used in different crops (grain, pulses, fruits, vegetable, and herbs)

PGPR	Crop	Country	Mechanism of action	Significance	References
Azospirrilum spp., *Azoarcus*, *Brevibacterium*, *Bradyrhizobium*, *Burkholderia* sp., *Diazotroph*, *Herbaspirillum*, *Lysinibacillus*, *Pseudomonas* sp., *Rhizobium* spp., *Xylanilyticus*	Rice (*Oryza sativa*)	India, Egypt, Malaysia, Pakistan, Indonesia	Indole acetic acid (IAA) production, overexpression of RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase), resulted in growth promotion activities, siderophore production, nitrogenase activity, phosphate solubilization	Increased yield of rice, few proteins induced growth promotion, seedling vigor enhanced, antibiotic and fungicide resistance induced, drought resistance, increased nutrient uptake, antibiotic, salt and fungicide resistance	Kandasamy et al. (2009), Gopalakrishnan et al. (2012), Hasan et al. (2014), Sharma et al. (2014), Elekhtyar (2015), Tan et al. (2015) and Yuwariah (2017)
Arthrobacter, *Azorhizobium* ORS 571, *Azospirillum brasilense* SP245, *Bacillus* spp., *A. brasilense* sp. 245, *Bacillus* spp., *Bacillus* spp.,[a] *Providencia* spp., *Brevundim pnatas*., *Bacillus subtilis* SU47, *Klebsiella*, *Enterobacter*, *Flavobacterium* sp., *Pseudomonas* spp., *Dietzia natronolimnaea*	Wheat (*Triticum aestivum*)	Germany, Belgium, India, Pakistan, Turkey, Korea, China, Uzbekistan	IAA production, phosphate solubilization, increased nutrient uptake, ACC (1-aminocyclopropane-1-carboxylate) deaminase activity, siderophore activity, nitrogen fixation	Increased yield of wheat, induced growth promotion, quality enhancement, seedling vigor, antibiotic and fungicide resistance, drought resistance, salt tolerance, antioxidant activity	Elliott and Lynch (1985), Egamberdieva (2010), Rana et al. (2011), Zhang et al. (2012), Yandigeri et al. (2012), Abbasi (2015), Hassan et al. (2015), Bharti et al. (2016), Gontia-Mishra et al. (2016), Ahmad et al. (2017) and Qiu et al. (2017)
Bacillus strains	Raspberry (*Rubus idaeus*)	Turkey	IAA production, nitrogenase activity, phosphate solubilization	Increased plant growth and nutrient in raspberry, increased nutrient uptake	Orhan et al. (2006)
Lipoferum, *Azospirillum*, *A. brasilense*, *Pseudomonas putida*, *P. fluorescens*, *Paenibacillus polymyxa*, *P. thivervalensis*, *Serratia marcescens*	Maize (*Zea mays*)	Iran, Pakistan, Brazil, India	IAA production, siderophore, phosphate solubilization, hydrolytic enzymes	Increased plant height and leaf area, increased salt tolerance	von der Weid et al. (2000), Gholami et al. (2009), Nadeem et al. (2009), and Shahzad et al. (2013)

(continued)

Table 6.1 (continued)

PGPR	Crop	Country	Mechanism of action	Significance	References
Agrobacterium rubi, *Burkholderia gladioli*, *Pseudomonas putida*, *Bacillus subtilis*, *Bacillus megaterium*	Mint (*Mentha piperita L.*)	Turkey	IAA production, nitrogenase activity, phosphate solubilization	Increased overall growth and dry mass yield, increased nutrient uptake	Zhang et al. (2004)
Bacillus megaterium TV-3D, *B. megaterium* TV-91C, *Pantoea agglomerans* RK-92, *B. subtilis* TV-17C, *B. megaterium* TV-87A, *B. megaterium* KBA-10	Cauliflower (*Brassica oleracea L.*)	Turkey	IAA production, nitrogenase activity, phosphate solubilization	IAA production, nitrogenase activity, phosphate solubilization, increased nutrient uptake	Ekinci et al. (2014)
Bacillus spp., *Paenibacillus* spp., *Bacillus subtilis*	Pepper (*Piper nigrum*)	Korea, USA, India	IAA production, siderophore activity nitrogenase activity, phosphate solubilization	Antibacterial and antifungal activities were induced, yield in plant growth parameters like fruit quality, etc., increased nutrient uptake, antibiotic, salt and fungicide resistance	Kokalis–Burelle et al. (2002), Paul and Sarma (2006) and Lim and Kim (2013)
Bacillus, *Pseudomonas*, *Rhizobium*, *Azotobacter*	Green gram (*Vigna radiata*)	India	IAA production, siderophore activity nitrogenase activity, phosphate solubilization	Increased plant growth and yield of gram, increased nutrient uptake, antibiotic, biocontrol, salt and fungicide resistance	
Bacillus spp., *Paenibacillus*, PGPR *strains* 90-166, SE34, and C-9	Tobacco (*Nicotiana tabacum*)	China, India, USA	IAA production, siderophore production, nitrogenase activity, phosphate solubilization	Antiviral and overall growth promotion, increased nutrient uptake, antibiotic, salt and viral resistance	Zhang et al. (2004)

Azotobacter chroococcum, *Bacillus subtilis*, *Aeromonas salmonicida*, *Burkholderia cepacia*, *Ochrobactrum anthropi*, *Pseudomonas* sp., *Shewanella putrefaciens*, *Sphingomonas paucimobilis*, *Stenotrophomonas maltophilia*, *Brevibacterium*, *Burkholderia*, *Delftia*, *Leucobacter*, *Pseudomonas*, *Sinorhizobium and Variovorax*	Sugarcane (*Saccharum officinarum*)	India, China, Mexico	Indole acetic acid production, siderophore production, nitrogenase activity, phosphate solubilization	Saline resistance, increased growth, enhance soil properties, nitrogen fixation, increased nutrient uptake, antibiotic, salt resistance	Dhanraj (2013), De et al. (2015), Wang et al. (2016) and Solanki et al. (2017)
Pseudomonas jessenii PS06, *Mesorhizobium ciceri* C-2/2, *Pseudomonas putida*, *Burkholderia*, *Bacillus amyloliquefaciens*	Chickpea (*Cicer arietinum*)	India, China, Spain	IAA production, siderophore production, phosphate solubilization, hydrolytic enzymes	The co-inoculation treatment increased the seed yield and nodule fresh weight, antagonistic against pathogens	Kokalis–Burelle et al. (2002), Paul and Sarma (2006), and Joseph et al. (2012)
Pseudomonas fluorescens japonicum CB 1809, USDA110, *Azospirillum* sp., *Bacillus pumilus*, *Rhizobium japonicum, Azotobacter chroococcum*, *Azospirillum brasilense*	Soyabean (*Glycine max*)	India, Thailand, Myanmar, Argentina, Romania, Iran, Ethiopia, USA	Production of phytohormones (auxins, cytokinins, and gibberellins), N-fixing and phosphate solubilizing, antibiotics production, and antagonism against microbes	Increased plant growth, more nodulation, increased seed protein, water stress tolerance, drought resistance	Aung et al. (2013), Naseri et al. (2013), Masciarelli Llanes and Luna (2014) and Zahedi and Abbasi (2015)
Enterobacter cloacae, *Pseudomonas* sp., *Bacillus* sp.	Indian mustard and pumpkin	India	Production of phytohormones (auxins, cytokinins, and gibberellins), N-fixing, and phosphate solubilizing	Stimulated plant growth and decreased Cr (VI) content	Ahemad and Kibret (2014)

(continued)

Table 6.1 (continued)

PGPR	Crop	Country	Mechanism of action	Significance	References
Bacillus, *Bacillus amyloliquefaciens*, *Bacillus subtilis*, *Bacillus pumilus*, *Pseudomonas fluorescens*, *Serratia marcescens*	Tomato (*Solanum lycopersicum*)	India, AL, Egypt, Brazil	IAA production, siderophore production, nitrogenase activity, phosphate solubilization, antiviral activity	Increased yield and nutrient content, biocontrol of viral pathogens, increased nutrient uptake	Gagné et al. (1993), Murphy et al. (2000), Mena-Violante and Olalde-Portugal (2007), Vinothkumar et al. (2012), Solanki et al. (2012a, b), Agrawal and Agrawal (2013), Almaghrabi et al. (2013), Hyder et al. (2015), Solanki et al. (2015) and Moustaine et al. (2017)
Bacillus amyloliquefaciens, *Bacillus* spp.	Cotton (*Gossypium*)	USA, China, Germany, Iran	Production of phytohormones (auxins, cytokinins, and gibberellins), N-fixing and phosphate solubilizing, antibiotic activity	Overall growth and biocontrol of pathogens	Fahimi et al. (2014)
Pseudomonas fluorescens, *Azotobacter chroococcum* HKN-5, *Bacillus megaterium* HKP-1, *Bacillus mucillaginosus* HKK-1 sp. 4MKS8, *Klebsiella*, *Enterobacter sakazakii* 8MR5, *Pseudomonas oxytoca* 10MKR7	Indian mustard (*Brassica juncea*), Rape seed (*Brassica napus*)	India	Production of phytohormones (auxins, cytokinins, and gibberellins), N-fixing and phosphate solubilizing, antibiotic activity	Promoted the plant growth under chromium stress, protected plant from metal toxicity	Ahemad and Kibret (2014)

Pseudomonas stutzeri, *Bacillus subtilis*, *Stenotrophomonas maltophilia*, *B. amyloliquefaciens*, *P. fluorescens*, *B. megaterium*, *Variovorax paradoxus*, *Stenotrophomonas maltophilia* HW2	Cucumber (*Cucumis sativus*)	India, Pakistan, USA, China	ACC-deaminase activity, siderophore, and IAA production	Enhanced growth, significantly suppressed phytophthora crown rot, increased salt tolerance, antiviral against mottle mosaic virus	Zhang et al. (2004)
Bacillus amyloliquefaciens, *Bacillus megaterium* M3 *and* MIX *(Bacillus subtilis* OSU142, *B. megaterium* M3, *Azospirillum brasilense* Sp245	Barley (*Hordeum vulgare*)	Egypt, Turkey	Biofilm formation	Increased yield, growth of seedlings, salinity tolerance	Kasim et al. (2016)
E. cloacae, *B acillus drentensis*, *Rhizobium*, *B. pumilus* Sol-1, *Alcaligenes sp.* Mal-4, *Providencia vermicola* Ama-2, *Brevundimonas* Kro13, *Kluyvera ascorbata* SUD165, *Pseudomonas putida*, *Ochrobactrum*, *B. cereus*	Mung bean (*Vigna radiata)*	Saudi Arabia, Egypt, Bangladesh, Pakistan, India	N-fixing and phosphate solubilizing, IAA production, acetylene reducing activity, siderophore production, ACC-deaminase activity, nitrogenase activity, phosphate solubilization, increased nutrient uptake	improving gaseous exchange, water relations, photosynthetic pigments, growth, and seed yield for mung bean under saline irrigation conditions, stimulated the plant growth reduced Pb and Cd uptake, lowers the toxicity of chromium to seedlings by reducing Cr (VI) to Cr (III)	Akhtar and Ali (2011) and Mahmood et al. (2016)

(continued)

Table 6.1 (continued)

PGPR	Crop	Country	Mechanism of action	Significance	References
Pseudomonas putida BA-8, *Bacillus simplex* T7	Grapes (*Vitaceae family*)	Turkey	IAA production, N- fixing and phosphate solubilizing, antibiotic activity	Improvement in the grafting capacity at nursery conditions	Sabir (2013)
Pseudomonas BA-8, *Bacillus* OSU-142, *Agrobacterium rubi* A-18, *Burkholderia gladioli* OSU-7, *Pseudomonas putida* BA-8	Apple (*Malus domestica*)	Turkey, Brazil	Production of phytohormones (auxins, cytokinins, and gibberellins), N-fixing and phosphate solubilizing, antibiotic activity	Increased fruit quality, nutrient enhancement, biocontrol agent, antagonistic activity	Haden et al. (2007) and Karakurt and Aslantas (2010)

[a]Reported first time as PGPR in particular crop

6.2 Mode of Action

Plant roots exude a huge diversity of organic nutrients (organic acids, phytosiderophores, sugars, vitamins, amino acids, nucleosides, mucilage) and signals that attract microbial populations, especially those able to metabolize plant-exuded compounds and proliferate in this microbial habitat (Ahemad and Kibret 2014; Hasan et al. 2014). The rhizospheric soil bacteria which surrounds the plant root competes for this nutritional boon and in turn the effect plant's growth, yield, and defense mechanisms either as free living microbes or in the mutualistic relationship with plant root (Endophytic/epiphytic) (Vejan et al. 2016). These rhizobacteria affect plant development. About 2–5% of rhizobacteria, when reintroduced by plant inoculation in a soil containing competitive microflora, exert a beneficial effect on plant growth and are termed plant growth promoting rhizobacteria (PGPR).

The mode of action of PGPR is mainly of two types: the direct mechanism which directly supports the plant growth in a direct mode. This mechanism includes nitrogen fixation, phytohormone production, phosphate solubilization, and increasing iron availability used for plant growth promotion. PGPR can indirectly enhance plant growth by eliminating pathogens or by inducing plant defense responses (Narasimhan et al. 2003; Gupta and Dikshit 2010; Haymer 2015; Thijs et al. 2016; Delshadi et al. 2017; Reeves 2017; Tariq et al. 2017; Timmusk et al. 2017).

6.3 Recent Developments in the Application of PGPR

6.3.1 Role of PGPR as Biostimulant

According to European Commission, agroecology, i.e., studying and designing agricultural systems based on the interaction of their biophysical, technical, and socioeconomic components, is recommended to meet the food security of increasing population and to maintain soil security. The word biostimulant was apparently coined by horticulture specialists for describing substances promoting plant growth without being nutrients, soil improvers, or pesticides (du Jardin 2015). PGPR-based biostimulants are widely accepted in agricultural practice this decade (Brown and Saa 2015). According to *Global Biostimulant Strategic Business report 2016–2022*, there are more than 80 global companies involved in biostimulant production and manufacturing covering Canada, Japan, Europe, Asia Pacific, Latin America, and the rest of the world (Novozymes, Monsanto, Lallemand, IIsa sPA etc). According to a report, the biostimulant market is projected to reach USD 2.91 billion by 2021, at a CAGR of 10.4% from 2016 to 2021.

PGPR based biostimulants enhance nutrient uptake and stress tolerance like drought, salinity, etc. and improve crop quality by direct or indirect mechanisms (Brown and Saa 2015; du Jardin 2015). There are many registered formulations of PGPR in the market including the species *Pseudomonas*, *Bacillus*, *Enterobacter*, *Klebsiella*, *Azobacter*, *Variovorax*, *Azosprillum*, and *Serratia* (Nakkeeran et al. 2006; Barea 2015; Bishnoi 2015; FAO 2016; Fixers and Solubilizers 2016; Le Mire et al. 2016), but the utilization of PGPR in the agriculture industry represents only a small fraction of agricultural practice worldwide (Meena et al. 2016).

6.3.2 Cleanup Strategies (Role in Phytoremediation)

The green technology to improve the contaminated soil involves mutual interactions of plant and microorganisms. Phytoremediation is an environmentally sustainable, solar-powered, and cost-effective soil remediation technology which relies on the ability of plants to intercept, take-up, accumulate, sequestrate, stabilize, or translocate contaminants. Phytoremediation is influenced by various abiotic and biotic conditions like pH of soil, soil components, nutrient availability, type of plant selection, and type of contaminants (Thijs et al. 2016). Recently, it has been documented that phytoremediation success rate is highly dependable on plant microbiome (Hou et al. 2015). When PGPR are introduced to a contaminated site, they increase the potential for plants that grow there to sequester heavy metals and to recycle nutrients, maintain soil structure, detoxify chemicals, and control diseases and pests; PGPR also decreases the toxicity of metals by changing their bioavailability in plants. The plants, in turn, provide the microorganisms with root exudates such as free amino acids, proteins, carbohydrates, alcohols, vitamins, and hormones, which are important sources of their nutrition (Tak et al. 2013). Biological application of PGPR for phytoremediation of heavy metals and salt-impacted soil has been reported by researchers (Nakkeeran et al. 2006; Barea 2015; Le Mire et al. 2016). Plant and microbiome interactions are nowadays being studied as the metaorganism approach, to find most promising ways to improve the success rate of phytoremediations. PGPR-based metaorganism approach assembles the role of (a) plant host selection, (b) root exudates, (c) study of single or microbial consortium in situ, and (d) molecular study of PGPR strains (Narasimhan et al. 2003; Arora 2015; Thijs et al. 2016).

6.3.3 As Biocontrol

According to Beattie, bacteria that reduce the incidence or severity of plant diseases are often referred to as biocontrol agents, whereas those that exhibit antagonistic activity toward a pathogen are defined as antagonists (Beneduzi et al. 2012). The major disadvantage of chemical pesticides is its residual persistence in the soil which raises food safety concerns among the consumers. In recent years, PGPR-based biocontrol agent has proven its ecologically sound and effective solution to Integrated Pest management Programs (IPM) with so many beneficial advantages like cost-effectiveness, biodegradability and self-perpetuating, host specific, easy in handling, and safe to use (Beneduzi et al. 2012). The PGPR synthesis hydrolytic enzymes, increases competition for nutrients, regulates the plant hormone ethylene level through ACC-deaminase enzyme, and produces siderophores to counteract the plant pathogens present surrounding the rhizosphere (Kumari et al. 2016; Yang et al. 2009; Haghighi et al. 2011; Anand et al. 2016; Le Mire et al. 2016). There are many examples of effective control of soil-borne diseases by means of PGPR (Haas and Defago 2005). Several species have been reported to show antagonistic activity in major crops like wheat, tomato, soya bean, tobacco, pepper, etc. (Zhang et al. 2004; Haas and Defago 2005; Domenech et al. 2006; Gupta and Dikshit 2010). There are a large number of biocontrol agents available in the international market (Bio-Save®, RhizoVital ® 42 liquid, Galltrol-A, BlightBan C9-1 etc.), but currently, the scenario is not good as only 7% of total biocontrol formulation made per year is reaching in the hand of farmers. According to the international bio-intelligence reports (2017), global biocontrol market is $2.8 Bn today growing to over $11 Bn in 2025. It is estimated that microbial will continue to make up nearly 60% of the market through 2025. North America and Europe itself will cover 2/3 part of the whole biocontrol international market. The drastic climatic changes have affected the plant microbe interactions in the recent decade; this is one of the most challenging aspects in studying PGPR strains for the formulation as biocontrol agents (Reeves 2017). Recently, researchers around the globe are focusing toward implementation of new technologies for the development of effective biocontrol agents. The latest applications of molecular genetic technologies in the area of genetically based control methods now also include cutting-edge systems for genome editing and the use of RNA inhibition for selectively knocking out the expression of individual genes (Haymer 2015). Nanomaterial-based biocontrol has also proven its impact as upcoming biocontrol agents in years.

6.4 Current Scenario of PGPR Research

6.4.1 Challenges

The role of PGPR based bio-formulations has shown great potential toward sustainable agriculture and the most accepted alternative to chemical fertilizers, biopesticide/biocontrol agents, and other chemical-based simulators. During the past couple of decades, PGPR have begun to replace the use of chemicals in agriculture, horticulture, silviculture, and environmental cleanup strategies. They have the positive impact of plant's physiological conditions through the mechanism of action of these microbes. During the years 1990–2000, most of the researches on PGPR was based on the isolation and inoculation of PGPR into rhizosphere to get better yield in crops (wheat, rice, maize some vegetables, fruits, and herbs), some reports are available about the molecular mechanism of action of these microbes; in the later decade, biotechnological approach to modify isolated PGPR was also reported (Gagné et al.

1993; Murphy et al. 2000; von der Weid et al. 2000). During the decade 2000–2010, researchers were more focused on the application part, i.e., cleanup strategies, as defense inducer and as biofertilizer mainly, during this phase few of commercial product of PGPR came into international market (Zhang et al. 2004; Haden et al. 2007; Gupta and Dikshit 2010). Recently, 2010 onward, a new term "rhizo-engineering" has been introduced to uncover the microbiome interaction that is still not clearly elucidated (Ahmadi et al. 2017). The use of nanoparticle in PGPR research has also shown a promising technology, but cost-effective and quality nano-product is still expected (Delshadi et al. 2017; Reeves 2017). The unique properties of nano-sized particles with respect to their physical, chemical, and biological properties compared to those at a larger scale provide the potential to protect plants, detect plant diseases, monitor plant growth, enhance food quality, increase food production, and reduce waste (Vejan et al. 2016). Majority of researches are confined either to laboratory or green house scale; hence these should be taken up to the field level. However, there are few reports on transition of PGPR-based bioformulations, but has limited success rate (Gagné et al. 1993; Murphy et al. 2000; von der Weid et al. 2000). Another major challenge in the application of this microbial product's application is the screening of microbes, their formulation, and its marketing. Researches have to trigger the following aspects to accelerate the PGPR commercialization (Fig. 6.1).

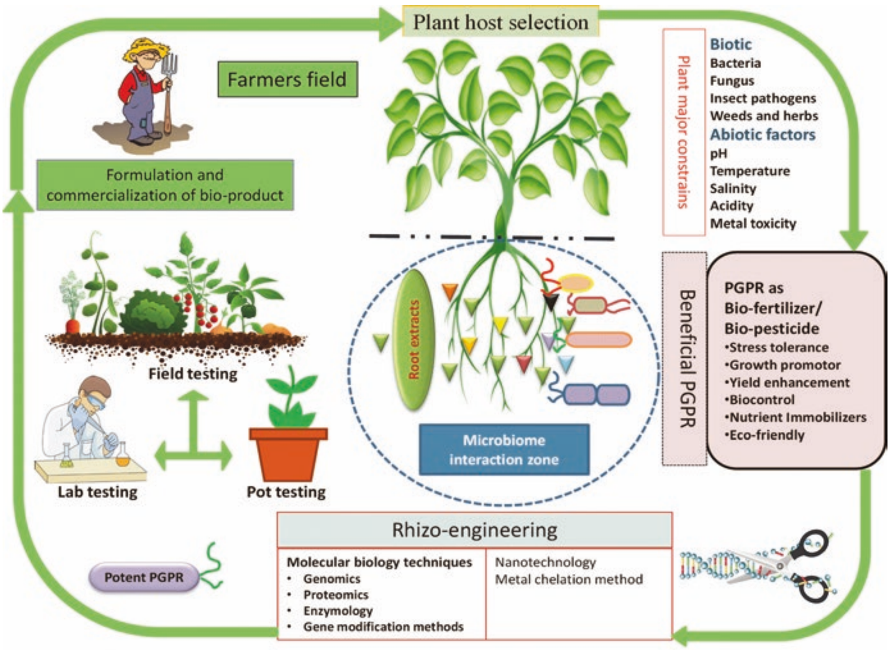

Fig. 6.1 Different challenges and applications of PGPR research

6.4.2 Future Work Should Be Focused On

6.4.2.1 At Laboratory and Field Level

- Understanding of microbiome interactions especially their diversity.
- Molecular data availability.
- Study on the effect of environmental stresses on microbiome and the mechanism of action.
- Application of recent technologies like rhizo-engineering, nanotechnology, and metaproteomics to get the most efficient and eco-friendly formulations.
- However, the approaches focused for a long time on each organism individually rather than an integrated metaorganism approach in an ecological perspective.
- The formulation is also an important parameter to be focused in the coming years, like the type of formulation and their acceptance at physiological and ecological level.
- Field level experiments to be taken up at large scale.
- The addition of ice-nucleating plant growth-promoting rhizobacteria could be an effective technology for enhancing plant growth at low temperature.

6.4.2.2 For Commercialization

- Cost-effective products with good shelf life.
- Eco-friendly.
- Safety database availability for easy registration process.
- Farmers need more knowledge about this product: like why it is better than chemical fertilizers because beneficial effects attract farmers' interest.
- Changing farmer perception may bring about the change.
- The farmers and feild person must have been trainted about PGPR bioformulations, its advantages and of-course economical acceptibility.
- Growth in commercialization is hindered by lack of thorough research so the transition of laboratory work to the farmers of field is a must.

In the near future, it is expected that metatranscriptomics and metaproteomics will develop significantly and will allow further progress in the understanding of the activity and ecological behavior of natural PGPR populations within the rhizosphere.

6.5 Conclusions

The campaign for the application of PGPR has been started from the last few decades, to achieve sustainable agriculture and plant's health under biotic and abiotic stress. However, before PGPR can contribute the desired benefits, scientists need to learn more and explore ways and means for their better utilization in the farmers' fields. Future research should focus on managing plant-microbe interactions, for example, innovative improvements in root environments, particularly with respect to their mode of action and adaptability to conditions under extreme environments. Rhizo-engineering and metatranscriptomics use of safest nanoparticle to introduce new formulation and screening of bacterial strains through molecular techniques like proteomics and docking methods will be the focused area of researchers in the coming years. Another major aspect is the transition of this product in the hand of local farmers, which will depend on easy registration regulatory processes.

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