Plant Growth-Promoting Rhizobacteria: Benign and Useful Substitute for Mitigation of Biotic and Abiotic Stresses

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Abstract

An incessant increase in global population along with a continuous augmentation in abiotic stress conditions, such as temperature, pH, salinity, etc., and limitation of natural resources has posed a serious threat to developing nations in terms of food security and enhanced nutritional value of the yield. Substantial crop losses in both qualitative and quantitative aspects due to the several prevalent phytopathogens are adding severity to the existing trouble. Confrontation with this ongoing problem initially led to the application of chemical fertilizers. However, hazardous aftereffects of the chemical fertilizers on the ecosystem have instigated a demand for a promising eco-friendly substitute that deals with both biotic and abiotic stresses. Rhizospheric microorganisms can be utilized as an effective alternative because they reside in soil and have the intrinsic property of upholding balanced ecosystem. These plant growth-promoting rhizobacteria (PGPRs) enhance plant growth even in poor and stressed environmental conditions by the formation of beneficial associations with the host through biological nitrogen fixation, phosphate solubilization, siderophore and hormone production, etc. They can also trigger host defense mechanism through induced systemic resistance (ISR). These PGPRs are also helpful for phytoremediation by various processes such as direct absorption, accumulation, etc. PGPRs are utilized in the fields of phytostimulation, biofertilization, and biocontrol activities.

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In the current chapter, we would aim to uphold the mechanisms opted by PGPR for effective plant growth promotion and defense under various abiotic as well as biotic stress conditions. In this context, we would also aim to delve in detail about the host-PGPR cross talk during the onset of stress conditions.

Keywords
Biotic stresses · Abiotic stresses · PGPR · Phytoremediation · Biocontrol

5.1 Introduction

By observing the steep increase in population growth curve with respect to time, it is very easy to predict the upcoming demand of food, fiber, fodder, and biomass by continuously decreasing arable land due to various anthropogenic activities (Abhilash et al. 2013). With an enormously growing population and limited resources, a major problem in front of developing countries is to provide food security with ecosystem stability. Both biotic such as pathogenic microorganisms, pests, weeds, etc. and abiotic stresses including low and high temperature, drought, salinity, flooding, ultraviolet light, air pollution, heavy metals, etc. are adding pressure to the crop production. Approximately 7–15% of the crops are damaged by various soilborne fungi, oomycetes, bacteria, and nematodes through various mechanisms such as destroying and damaging of root tips and root hairs, the release of toxins, etc. (Oerke 2005; Singh et al. 2014; Mishra et al. 2015). Increasing salt level in both land and irrigating water is the main problem faced by arid and semiarid areas due to which plant shows stunted growth as the photosynthetic unit becomes unable to work properly. Similar physiological modulations can be observed in plants against other abiotic stresses which ultimately lead to crop loss. These stresses cause a noticeable decrease of 50–82% in agricultural productivity and raise hindrance for the cultivation of new crops. To cope up with the abovementioned problems of the food crisis, malnutrition, etc., producers become inclined toward the unbalanced use of agrochemicals as an economically reliable substitute for crop protection. The enormous application of these chemical agents has led to severe negative impacts which include the development of pathogen resistance against applied agents, accumulation in the ecosystem due to non-degradation of the compounds, and therefore entry into the food chain. There is an urgent need to sustainably enhance the quality of crop production to meet future requirements and also protect the remaining cultivable soil from further degradation and contamination. Further, owing to the increasing awareness among people about harmful effects of these residues as well as the unavailability of chemical solutions against some phyto ailments apart from the continuously and rampantly increasing cost of pesticides, the search for a safer and eco-friendly alternative started which gave rise to biological control measures.

Currently, biological measures are one of the most emerging and sustainable methods among both agronomist and environmentalists for integrated plant growth and nutrient management systems to ease the burden on the environment. Among the numerous practices employed, application of plant growth-promoting rhizobacteria (PGPRs) is a potential measure as it prevents the plant from various phytopathogens as well as enhances the plant growth-promoting attributes due to their strong colonization affinity.

5.2 Plant Growth-Promoting Rhizobacteria (PGPRs)

The rhizosphere upholds a variety of microorganisms which can be deleterious, neutral, or beneficial (Fig. 5.1). Among numerous microfauna present in the soil, about 2–5% of free-living and rhizosphere-competent microbes providing plant growth promotional attributes even in the presence of competing microbes and phytopathogens are known as the PGPRs (Kloepper and Schroth 1978). Along with nutrients and water uptake, the root system of the host plants also secretes a variety of compounds in the rhizosphere (Walker et al. 2003) The rhizosphere PGPRs enhance the sustainability of soil for production of crops through various biotic activities that increase the nutrient turn over which in turn improve the soil structure. The main property of the PGPR which makes them more efficient is turning over of nutrients through their mobilization which enhances the sustainability for cultivation (Ahemad et al. 2009; Chandler et al. 2008). Further, several reports justify the sequestration of heavy metals and degradation of xenobiotics such as herbicides, pesticides, etc. by PGPRs, thereby leading to effective bioremediation (Ahemad 2012; Ahemed and Malik 2011; Hayat et al. 2010; Glick 2012). In this context, it is significant to notify the pursual of research on a global scale to yield biocontrol agents with numerous beneficial traits such as management of phytopathogens, plant growth promotion, heavy metal detoxification, abiotic stress tolerance, pesticide tolerance, etc. for the enhancement of sustainable agriculture (Chaudhary et al. 2012; Vaishnav et al. 2014). With all the promising plant growth promotional and biocontrol attributes, PGPRs can be used as an effective and

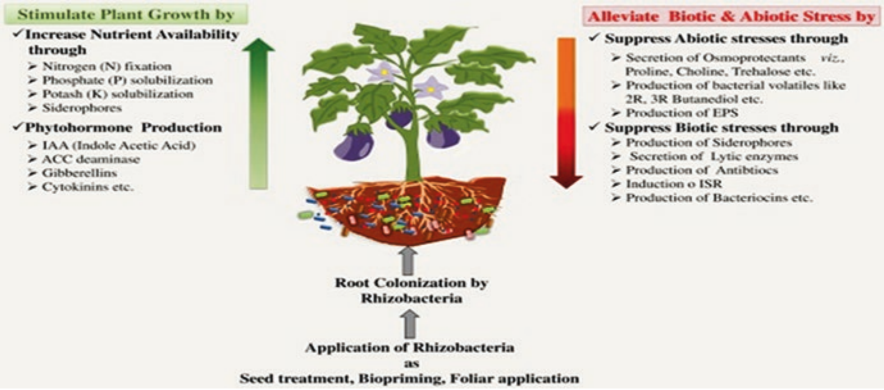

Fig. 5.1 Comparative assessment of beneficial attributes of PGPR as a respite against biotic and abiotic stress condition

eco-friendly tool for enhancing the sustainability of production, restoration of contaminated land, nutritional and food security, carbon sequestration, phytoremediation of heavily contaminated soils, and biofuel and biomass production. Presently numerous symbiotic microbes such as *Rhizobium* spp. and *Bradyrhizobium* spp. as well as nonsymbiotic microbes including *Pseudomonas*, *Bacillus*, *Azotobacter*, *Azospirillum*, and *Alcaligenes* are known globally for their application as inoculants possessing plant growth and stress-tolerant attributes (Ma et al. 2011a, b; Wani and Khan 2010; Mayak et al. 2004; Ray et al. 2016a, b, 2018b).

5.3 Mechanisms Implicated by PGPR

5.3.1 Root Colonization

A significant drawback consistently associated with PGPRs is their poor field performance owing to the inconsistency of rhizosphere colonization, particularly under field conditions (Schroth and Hancock 1981; Thomashow 1996a, b). Efficient root colonization is the primary step for effective proliferation and survival in the presence of other rhizospheric microflora as well as for establishing competence that provides effective biocontrol, plant-microbe cross talk, and enhanced PGPR efficiency (Parke 1991; Wipps 1997; Lugtenberg and Dekkers 1999). As the rhizospheric soil behave as sink for nutrients, plants release root exudates with diverse chemical compounds such as specific sugars, organic acids, amino acids, etc. which act as chemoattractants for numerous active soil microbes and synchronize the microbial presence in close proximity of root surface (Rovira 1965; Welbaum et al. 2004; Dakora and Phillips 2002). Due to the presence of these exudates, the symbiotic association takes place with the nearby rhizospheric microbial communities that promote plant growth and in turn obtaining major nutrients, such as carbon, nitrogen, phosphorus, etc., through the chemical compounds released by roots and root hairs (Nardi et al. 2000). When the PGPRs reach the root through their motile structures in response to the exudates which is known as rhizospheric effect (Hiltner 1904), some of them colonize the surface of roots and root hairs without causing harmful effects, thereby inhibiting the invasion of phytopathogens by means of nutrient and niche competition, whereas many of them have the ability to enter endodermis after crossing the barrier and exist as endophytes in different organs of the host plant (Hallman et al. 1997; Duffy 2001; Turnbull et al. 2001; Compant et al. 2005; Gray and Smith 2005; Ray et al. 2018a).

5.3.2 Growth-Promoting Attributes

Post-effective establishment and colonization, PGPRs enhance the growth and increase the productivity of host plant through various direct and indirect methods such as nutrient acquisition, regulating plant hormone and synthesis of various beneficial metabolites (Glick 2012).

5.3.2.1 Biological Nitrogen Fixation

With 78% of the fraction in the atmosphere, nitrogen is the most essential macromolecule required for plant growth and development which is fixed in plant utilizable forms through biological nitrogen fixation (BNF). In this process, atmospheric nitrogen is converted to ammonia with the help of microorganism borne nitrogenase enzyme system (Kim and Rees 1994). Nitrogenase is a two-component complex metalloenzyme system comprising of dinitrogenase reductase as iron protein and dinitrogenase as a metal cofactor, and on their basis, three different nitrogen-fixing systems have been reported, namely, Mo-nitrogenase, V-nitrogenase, and Fe-nitrogenase (Dean and Jacobson 1992; Kim and Rees 1994). Majority of BNF is performed by Mo-nitrogenase present in most of the PGPRs carrying nitrogen fixation in nonleguminous plants through the establishment of nonobligate interaction (Glick et al. 1999; Bishop and Jorerger 1990). Microorganism involved in BNF can be broadly divided into (a) symbiotic association with leguminous and (b) nonleguminous plants and (c) free-living as well as associate nonsymbiotic endophytes such as *Acetobacter*, *Azospirillum*, *Bacillus*, *Pseudomonas*, etc. which fix a minor portion of atmospheric nitrogen. Majority of unavailable atmospheric nitrogen is fixed through symbiotic nitrogen fixers such as *Rhizobia* in leguminous and *Frankia* in the nonleguminous plant (Saxena and Tilak 1998; Bhattacharya and Jha 2012; Glick 2012). A number of studies revealed two third biological fixation of atmospheric nitrogen globally, and remaining requirements are fulfilled by the Haber-Bosch method (Rubio and Ludden 2008). Treatment of plants and soil with PGPRs having the nitrogen-fixing ability is an economical and ecologically sustainable substitute of chemical fertilizers (Ladha et al. 1997).

5.3.2.2 Phosphate Solubilization Activity

The soil is the most abundant reservoir of both organic and inorganic form of phosphorus, the most essential macronutrient for plant growth promotion after nitrogen (Khan et al. 2009). Regardless of such an enormous reservoir, plants, in general, face scarcity of phosphorus as the roots only absorb monobasic and dibasic forms of the ion, while a major portion of phosphorus present in insoluble forms such as inositol phosphate, phosphomonoester, and triesters remain unutilized (Bhattacharya and Jha 2012). To deal with unavailability, farmers apply numerous phosphatic fertilizers, but only a little amount is absorbed by the plant with the remaining portion being turned into insoluble complexes (Mckenzie and Roberts 1990). Among numerous rhizospheric microflora, phosphate-solubilizing microorganisms (PSM) including *Bacillus*, *Enterobacter*, *Pseudomonas*, *Burkholderia*, *Flavobacterium*, *Rhizobium*, *Microbacterium*, *Serratia*, etc. can be applied as a substitute for sustainable agriculture since they can convert unavailable form of phosphorus to available form through the activity of low molecular weight organic acids produced by PSM (Zaidi et al. 2009). These PSM also synthesize numerous phosphatases for mineralization of organic phosphorus through phosphoric ester hydrolysis (Glick 2012). Numerous beneficial effects such as mineralization, enhanced efficiency of BNF through nodule formation, increased uptake of trace elements, etc. have been observed in the host plants treated with single or amalgamated PGPRs having phosphate-solubilizing property (Ahemad and Khan 2012; Vikramal and Hamzehzarghani 2008; Zaidi et al. 2009; Ahmad et al. 2008).

5.3.2.3 Production of Phytohormones

Plant hormones are the organic compounds which act as chemical messengers generated through various metabolic processes in one portion and get distributed all over the system. They are concentration and target specifically for optimum growth and development of a plant in different environmental conditions and therefore also termed as a plant growth regulator. On the basis of previous studies, phytohormones have been classified into five major classes: auxins, cytokinins, gibberellin, abscisic acid, and ethylene. Among these, IAA is the supreme indigenous auxin which regulates cellular processes (such as division, expansion, and differentiation), regulation of genes, organ development, pigment formation, metabolite synthesis, stress resistance, and several tropic responses (Ryu and Patten 2008; Ashrafuzzaman et al. 2009). Previous studies have reported the production and release of IAA by approximately 80% of rhizospheric microorganism as their secondary metabolite which may alter the intrinsic production of phytohormone and also change the permeability of plant cell wall for enhanced release of root exudates (Glick 2012; Spaepen et al. 2007). Apart from growth and development processes, IAA is also involved in defense mechanism and plant-microbe interaction (Santner and Estelle 2009; Spaepen and Vanderleyden 2011). Numerous microflora such as *Pseudomonas*, *Mycobacterium*, *Rhizobium*, *Bacillus*, and *Rhizobia* uphold the ability to produce IAA and influence the numerous processes of host plant ranging from phytostimulation to pathogenesis (Mandal et al. 2007). PGPRs with IAA-producing abilities can be applied as biofertilizer and/or bioenhancers as they elevate root expansion through lateral and adventitious root formation, thereby increasing surface area for increased uptake of nutrient and water. Apart from regulating cellular processes, IAA also stimulates vascular bundle formation and nodule formation (Glick 2012). Enhancement in seed germination and physio-morphological changes have been reported in the orchids which were treated with IAA-producing PGPRs such as *Azospirillum brasilense* and *Bradyrhizobium japonicum* (Cassa'na et al. 2009).

5.3.2.4 ACC Deaminase

As a plant growth hormone, ethylene is a crucial metabolite generated endogenously by almost all plants and involved in conventional growth and development of host plant. Besides being involved in growth, ethylene is also confirmed as stress hormone as it affects plant growth through defoliation and other noticeable changes mainly in seedlings during biotic and/or abiotic stress conditions (Saleem et al. 2007; Bhattarcharya and Jha 2012). Numerous PGPRs including *Acinetobacter*, *Achromobacter*, *Agrobacterium*, *Alcaligenes*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Pseudomonas*, etc. enhance plant growth through ACC deaminase activity. ACC deaminase is a pyridoxal 5-phosphate (PLP)-dependent polymeric enzyme which was initially reported in soil bacterium *Pseudomonas* (Honma and Shimomura 1978). A remarkable amount of ACC is released by the plant as root exudates in the soil to maintain the endogenous and external balance which in turn is utilized by PGPRs having ACC deaminase activity, thereby enhancing their proliferation (Glick et al. 1998). The enzyme utilizes the immediate precursor of ethylene and 1-aminocyclopropane-1-carboxylate and hydrolyzes it to α-ketobutyrate and ammonia which is further consumed as carbon and nitrogen sources by PGPRs (Arshad et al. 2007; Glick et al. 1998; Honma and Shimomura 1978). Further, according to Glick (2005), ACC deaminase activity varies in different organisms, and those with high activity bind inclusively to plant surfaces. Due to ACC deaminase activity of PGPRs, the endogenous level of ethylene reduces which in turn provides resistance against several stresses such as drought, salinity, flooding, high temperature, heavy metals, aromatic hydrocarbons, high radiations, wounding, insect predation, phytopathogens, etc. (Glick 2012; Lugtenberg and Kamilova 2009). Root elongation, shoot growth promotion, enhanced uptake of NPK, and increased nodulation with mycorrhizal colonization are some of the observable changes seen in plants inoculated with PGPRs (Nadeem et al. 2007, 2009; Glick 2014; Kumari et al. 2016).

5.3.3 Synthesis of Allelochemicals

Along with the growth promotion, PGPRs provide biocontrol activity through the secretion of allelochemicals which includes antibiotics, siderophores, biocidal volatiles, lytic enzymes, etc. (Bais et al. 2004; Glick 1995; Sturz and Christie 2003; Vaishnav et al. 2015, 2017).

5.3.3.1 Siderophore Production

Iron is an essential nutrient for all living forms with certain exceptions (Neiland 1995). In the rhizospheric region under aerobic environment, the ferric form of iron gets converted into insoluble hydroxides and oxyhydroxides, thereby raising the problem of iron scarcity (Rajkumar et al. 2010). Under limiting and competitive environment, rhizospheric microorganisms synthesize intra- and extracellular water-soluble peptidic iron chelator of low molecular weight, i.e., siderophore with different side chains and functional groups behaving as ligands with a different affinity (Crosa and Walsh 2002). Different edaphic and environmental factors such as amount and type of iron, pH of the soil, availability of macronutrients, the concentration of trace elements, etc. can regulate the synthesis of siderophores (Duffy and Defago 2000). These molecules can be classified into three major groups, namely, catecholates, hydroxamates, and carboxylates, on the basis of ligands utilized in ferric ion chelation (Xie et al. 2006). The efficiency of siderophore depends on the association constant of their complex formation with ferric ions. Rhizospheric siderophores uphold the higher value of association constant, thereby generating a severe iron-deficient condition for the pathogenic microorganism. Siderophores function as solubilizing agents for iron under limiting condition by reducing ferric ions to a ferrous ion which are further transported to cell interior through the gated membrane system. After this phenomenon, siderophores either get recycled or destroyed (Indiragandhi et al. 2008; Rajkumaret al. 2010; Neilands 1995). Along with iron sequestration, siderophores uphold the ability to form stable complexes with hazardous heavy metals such as Pb, Cd, Zn, Cu, Al, and Ga and radionuclide such as U, Np, etc. which are of alarming concern to the environment (Neubauer et al. 2000; Kiss and Farkas 1998).

5.3.3.2 Lytic Enzymes

Production and secretion of numerous enzymes from rhizospheric microorganism are involved in disrupting pathogenic membranes through hyperparasitic activity (Chernin and Chet 2002). Previous studies revealed that different enzymes including hydrolase, chitinase, lipases, pectinase, etc. attack pathogenic microorganisms through different mechanisms. Chitinase inhibits further spread of pathogen through hindering elongation of germ tube and spore germination (Frankwoski et al. 2001; Ordentlich et al. 1988). Some of the specific enzymes such as laminarinase are released by PGPRs alone or in combination with other enzymes to restrict specific pathogenic microorganism (Lim et al. 1991). Certain forms of glucanase, i.e., β1–3, β1–4, and β1–6, along with certain proteases directly target the glucans present in the fungal cell wall and destroy its integrity (Valois et al. 1996; Simons et al. 1997; Frankowski et al. 2001; Kamensky et al. 2003).

5.3.3.3 Antibiotic Production

Among the various methods applied by rhizospheric microorganisms to check proliferation of phytopathogens, antibiosis including the production and secretion of antibiotics is most commonly applied (Glick et al. 2007a, b; Lugtenberg and Kamilova 2009; Whipps 2001). Antibiotics are low molecular weight heterogeneous organic compounds, or metabolites primarily governed by nutrient availability and other environmental factors (Thomashow 1996; Duffy 2001). Even at low concentrations, these metabolites possess antimicrobial, antiviral, insecticidal, cytotoxic, antioxidant, antitumor, antihelminthic, and plant growth-promoting properties (de Bruijn et al. 2007; Raaijmaker et al. 2010). Broadly, these antibiotics can be classified into volatile and nonvolatile compounds which are further grouped into various subclasses. Nonvolatile antibiotics include polyketides, heterocyclic nitrogenous compounds, phenylpyrrole, cyclic lipopeptides, lipopeptide, and amino polyols, whereas hydrogen cyanide, aldehydes, alcohols, ketones, and sulfides are grouped under volatile antibiotics (Defago 1993; de Souza et al. 2003; Nielsen and Sorensen 2003; Raaijmakerset al. 2002). *Pseudomonas*, *Bacillus*, *Streptomyces*, *Burkholderia*, *Brevibacterium*, and several other microorganisms have been reported to produce and secrete antibiotics of a broad spectrum range (Keel et al. 1997; Haas and Keel 2003; Bender et al. 1999; Sutherland et al. 1985; Anjaiah et al. 1998).

5.4 PGPR Resistance to Biotic and Abiotic Stresses

A thorough understanding of the various mechanisms undertaken by PGPRs, particularly to resist biotic or abiotic stresses, is of paramount importance, more so because of the congregative nature of stress imposition. This would include not only the molecular identification of the bacterial strains involved but also the physiological as well as molecular mechanisms employed during the host-PGPR interaction.

5.4.1 Biotic Stress

Rhizospheric microbiota, particularly PGPRs, enable the augmentation of the inherent ability of plants to defend themselves against phytopathogens, apart from being a suitable alternative against chemical fertilizers (Sarma et al. 2015; Jain et al. 2012; Spence et al. 2014). In this context, management of phytopathogens through a microbial consortium or the use of endophytes has shown much promise. While endophytes have the inherent ability to provide plant protection and immunity enhancement due to their tendency of remaining sheltered within the plant interior (Ray et al. 2018a, b), microbial consortia remain in the vicinity of environmental stress but a strong promise to combat phytopathogens (Whipps 2001; Gossen et al. 2001; Stockwell et al. 2011). Several reports justify the plant growth promotional and improved disease resisting potential of PGPRs, such as *Pseudomonas* spp., *Trichoderma* spp., *Bacillus* spp., etc., on a variety of host plants, such as chickpea, pea, pigeon pea, okra, radish, tomato, wheat, pepper, *Arabidopsis*, etc. (Duffy et al. 1996; Rudresh et al. 2005; Jetiyanon 2007; Kannan and Sureendar 2009; Jain et al. 2012; Singh et al, 2013; Chauhan and Bagyaraj 2015).

The chief mechanism behind stimulation of the innate defense response of host plants by PGPRs is through induction of induced systemic resistance, operating in response to a microbial elicitor (Shoresh et al. 2010). In this context, Jain et al. (2012) reported enhancement of defense enzymes, particularly peroxidase, polyphenol oxidase, superoxide dismutase, glucanase, chitinase, etc., as well as phenol accumulation and lignin deposition in response to priming with a consortial mixture of PGPRs. In another study by Jain et al. (2015), the microbial consortia have been reported to recuperate the oxidative burst pathway inhibited by oxalic acid, the chief pathogenic factor of *Sclerotium rolfsii*/*Sclerotinia sclerotiorum*. Thus, the above studies clearly justify that PGPRs not only induce an augmented form of defense response within the host but also enable the quenching of factors responsible for induction of oxidative stress response within the host (Hammerschmidt 2005; Singh et al. 2013).

5.4.2 Abiotic Stress

Stress in nature is not a single phenomenon but a cumulative effect of various minor and major factors acting in togetherness (Mahajan and Tuteja 2005). While several natural stresses, such as drought, salt, flooding, and high/low temperature, have resulted in lowering of plant growth, certain anthropogenic activities have led to an additional confrontation with heavy metal stress, thereby declining crop yield and productivity by a significant level (Ramegowda and Senthil-Kumar 2015). Further, heavy metals sediment in soils and lead to groundwater contamination, thereby causing human health hazards. In other words, abiotic stresses may be considered as a root cause of loss of yield of several major crops (Bray 2004).

5.4.2.1 Drought Stress

Incessant reduction of rainfall year after year has led to a significant lowering of soil moisture content. Currently, even temperate regions are devising novel strategies to enhance the use of soil moisture content (Bray 2004; Farooq et al. 2009; Azcon et al. 2013; Panwar et al. 2014). Plant photosynthesis and nutrient uptake depend on a large scale on water availability in soil. Drastic reduction of soil moisture content or appearance of drought conditions severely hampers the basic requirements of the plant. For instance, water scarcity simultaneously increases the solute concentration within the plant cells, or a reduction in water potential, which in turn affect shoot and root elongation of plants. Further, water deficiency lowers carbon dioxide access by plants, thereby resulting in reactive oxygen species formation, such as superoxide, peroxide, and hydroxyl radical within plant cells, which in turn leads to apoptotic cell death of the plant (Sgherri et al. 2000).

In the above context, PGPR, such as *Pseudomonas mendocina* and *Glomus intraradices* or *G. mosseae*, was reported to release catalase enzyme and quench ROS produced within lettuce plants grown under severe drought conditions (Kohler et al. 2008). Thus PGPR may be considered as augmentation of defense enzymes in plants, such as peroxidase, polyphenol oxidase, etc. which further lead to protection of plant cell membrane and genomic DNA from oxidative damage (Bowler et al. 1992). Apart from individual PGPR, microbial consortia play a greater role in redemption from drought stress and in the improvement of plant growth. For instance, according to Figueiredo et al. (2008), a consortial mixture of beneficial PGPRs improved the overall health and nodulation of *Phaseolus vulgaris* under drought conditions as compared to inoculation with *Rhizobium* only. While report suggested PGPR treatment recuperated leaf water potential, biomass content, as well as sugar, proline, and amino acid content and loss of electrolyte leakage from plants (Sandhya et al. 2010; Vaishnav et al. 2018), treatment with consortial mixture of PGPR (*Bacillus lentus*, *Pseudomonadales* sp., and *Azospirillum brasilense*) augmented antioxidant activity as well as photosynthetic capacity along with the aforementioned properties in *Ocimum basilicum* (Heidari and Golpayengani 2012). Moreover, according to Stefan et al. (2013), consortial inoculation of PGPR improved superoxide dismutase and peroxidase activity in runner bean.

5.4.2.2 Salinity Stress

Presence of excessive amount of cations, such Na^+, K^+, Ca^{2+}, Mg^{2+}, etc., as well as anions, such as Cl^-, CO_3^{2-}, NO_3^-, SO_4^{2-}, and HCO_3^-, in agricultural soils may be defined as saline stress (Yadav et al. 2011). As per the US Department of Agriculture (USDA) standards, soil having an electrical conductivity (EC) 4 dS m^{-1} or higher may be considered as saline soil (Seidahmed et al. 2013). Numerous reports imply saline stress as the chief cause of (a) development of drought-like situation on owing to shortage of water; (b) development of the payment of high ionic content in plants, thereby perturbing the normal physiological pathway; and (c) unavailability of other soil nutrients due to high salt concentration (Vaishnav et al. 2016). Munns (2002) reported stunted growth in plants exposed to salt stress due to lowering of water content with a simultaneous elevation in salt content. Further, accumulation of Na^+ ion content within host tissues led to additional necrosis (Parida and Das 2005) apart from interfering with the root cell plasma membrane, thereby causing stunted root growth and nutrient uptake (Yadav et al. 2011).

In the above context, priming of plants with PGPRs offers a plausible respite against salt stress (Kumari et al. 2015). Han and Lee (2005) reported that priming of lettuce plants with *Serratia* sp. and *Rhizobium* sp. did not adversely affect the growth and physiological parameters of the plant under salt stress conditions. Similarly, an enhanced nodule formation was observed in common bean and soybean at 25 mM salt concentrations upon priming with a consortial mixture of *R. tropici* (CIAT899) or *R. etli* (ISP42) and *Ensifer fredii* (*Sinorhizobium*) SMH12 and HH103 with *Chryseobacterium balustinum* Aur9 (Estevezi et al. 2009). In another report by Bano and Fatima (2009), priming of maize varieties with *Pseudomonas* sp. and *Rhizobium* sp. augmented plant growth promotional parameters even under salt stress. Similarly, a significant increase in growth promotional parameters of wheat plants under salinity stress was observed upon priming with a consortium of *Pseudomonas fluorescens*, *Enterobacter cloacae*, *Serratia ficaria*, and *P. putida* (Nadeem et al. 2013a, b).

5.4.2.3 Heavy Metal Stress

The industrial revolution, as well as some of the anthropogenic activities, has resulted in a significant increase in heavy metals and radionuclides in the soil. Few among these such as molybdenum (Mo), iron (Fe), and manganese (Mn) are reported to be essential for the photosystem, yet others, such as cadmium (Cd), mercury (Hg), chromium (Cr) etc., are particularly considered as nonessential elements. Extreme accumulation of particularly the nonessential elements not only affects the soil microflora (Oliveira and Pampulha 2006; Wani and Khan 2010; Cheng 2003) but also get translocated to different photo organelles, thereby causing disruption of membranes and simultaneous disintegration of cell organelles as well as a complete collapse of the essential physiological functions, such as photosynthesis, protein synthesis, etc. (Bray 2004; Morsy et al. 2013). Various studies have particularly focused on PGPR as effective bioremediation as well as enhancers of plant growth (He and Yang 2007; Madhaiyan et al. 2007). Dary et al. (2010) suggested augmented yield, biomass, as well as nitrogen content in plants treated with consortia of *Bradyrhizobium* sp., *Ochrobactrum cytisi*, and metal-tolerant *Pseudomonas* sp. In yet another report by Singh et al. (2010), mung bean treated with metal-tolerant PGPR exhibited augmentation in growth and biomass when grown in cadmium-infected soil. Similarly, Marques et al. (2013) reported lower metal accumulation within tissues of *Helianthus annuus* treated with *Ralstonia eutropha* and *Chryseobacterium hispalense* when grown in Cd- and Zn-infected soil.

5.5 Application and Future Prospects

Application of PGPR such as *Pseudomonas* spp., *Bacillus* spp. *Rhizobium* spp., *Mesorhizobium*, *Bradyrhizobium*, *Azospirillum*, *Azotobacter*, etc. has been reported to increase seed weight, yield, plant height, leaf area, shoot dry weight, and root growth significantly in several crops, such as maize, mung bean, soybean, wheat, groundnut, chickpea, cotton, and *Brassica* spp. (Ahemad and Khan 2010; Ahemad and Kibret 2014; Gholami et al. 2009; Zahir et al. 2010). Mechanisms, such as nitrogen fixation, phosphate solubilization, potassium solubilization, siderophore biosynthesis, IAA production, ACC deaminase synthesis, cytokinin, and gibberellin production, are responsible for plant growth promotion and enhanced crop yield (Bashan and Holguin 1997). Plant disease management mediated by PGPR will curtail the pesticide load and reduce disease in an eco-friendly manner, particularly by posing competition for nutrients, induced systemic resistance, metabolites production, etc. (Lugtenberg and Kamilova 2009). Accumulation of hazardous substances possesses a major threat to the environment. Phytoremediation involves the use of plants or plant product to degrade hazardous substances accumulated in the environment (Cunningham et al. 1995). The compromised growth of plants at contaminated sites can be overcome by application of PGPR (Burd et al. 2000). PGPRs, such as *Agrobacterium radiobacter*, *Azospirillum* spp., *Pseudomonas* spp., *Enterobacter* spp., have been reported to speed up detoxification of contaminants, including cadmium, lead, nickel, chromium, and zinc by increased uptake as well as promotion of growth and biomass accumulation in barley, maize, rye, canola, and tomato grown on contaminated site (Belimov et al. 1998; Belimov and Dietz 2000; Hoflich and Metz 1997; Burd et al. 1998; Lucy et al. 2004). Further, PGPR can survive and promote plant growth in a colder climate with the help of antifreeze proteins and aid in survival under salinity and drought stress by ACC deaminase mediated lowering of ethylene level (De Freitas and Germida 1990; Hamaoui et al. 2001; Vaishnav et al. 2016). PGPR has the ability to promote plant growth under abiotic stresses such as drought, flood, extreme temperature, high light, the presence of toxic metals and organic contaminants, and radiation and biotic stresses: insect predation, the nematodes, fungi, bacteria, and viruses (Glick 2012). Thus the above property of PGPR equips it as potential biofertilizer, biocontrol agent, psychostimulant, and phytoremediator.

Continuously increasing demand for food grain production, the simultaneous buildup of chemical residue in the food chain has led to environmental pollution. The shift toward environmental friendly methods of disease management has thus become the need of the hour. In this context, according to Tewari and Arora (2013), future research needs to be directed toward bioengineering of rhizospheric biology to achieve the desired level of crop yield by manipulating microbes as well as their microclimate. Development of ready-to-use formulation of microbial consortia could be quiet effective over its single products in plant stress reduction. Researches need to be focused on optimizing shelf life, conditions for growth, enhanced crop yield, tolerance to unfavorable environmental conditions, and development of cost-effective PGPR products affordable to farmers. The molecular and biotechnological approaches need to be exploited to explore the rhizospheric biology and attain the desired level of microbial disease control. Bioinoculants of higher efficacy need to be developed for high-value crops such as flowers, fruits, and vegetables. Further, according to Nadeem et al. (2013), the low-temperature stress may be recuperated by exploiting ice-nucleating plant growth-promoting rhizobacteria (Nadeem et al. 2013). In addition, researches need to be focused on potassium-solubilizing plant growth-promoting rhizobacteria for an augmented utilization of potassium, the third most essential macronutrient after nitrogen and phosphorus. A better understanding of plant growth-promoting rhizobacteria needs to be developed regarding the mechanism of action, plant growth promotion, ecology, and growth-stimulating effect on the plant. These will help us in the identification, screening, and development of potential commercial formulations to combat phytopathogens and maintain a sustainable agroecosystem (Nelson 2004; Gupta et al. 2015).

5.6 Conclusion

After having a glance of applications and future prospects, we can conclude that PGPRs have a multidimensional approach in favor of living organisms and the environment. Their efficiency can further be enhanced through their optimization and acclimatization in the provided space. Different inoculation system can be applied on PGPR to maintain their establishment and improve their efficiency. After the competency test, strains with the different feature can be used in combination to survive diverse and extreme environmental condition. Further detailed studies will come up with a more potent rhizobacterial strain to survive diverse ecological situations. Studies at the genetic level can provide us with a next-generation solution through forward or reverse genetics. On a precise note, PGPRs either in combination or alone could be a better and safer alternative to the chemical means.

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