Plant Growth-Promoting Rhizobacteria (PGPR) and Fungi (PGPF): Potential Biological Control Agents of Diseases and Pests

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11.1 Introduction

Microorganisms distressing plant health, i.e., plant pathogens are one of the key threats for sustainable global food production and ecosystem sustainability. These pathogenic microbes cause approximately 25% reduction in the global crop yield every year (Lugtenberg 2015). To increase the food production, fiber and biomaterial, strategies of plant pests and diseases (DP) management are crucial. Recently, the concern about global food security is growing and the total world production of food has to be increased by 70% until 2050 (Ingram 2011; Keinan and Clark 2012). The total food requirement in the world will keep on rising for upcoming 40 years with increasing human populations (Rahman et al. 2018). Globally, the food production system is accountable for loss of terrestrial biodiversity about 60% and increasing greenhouse gas emissions by 25% (Westhoek et al. 2016). There is a need to develop relatively reliable and more sustainable agricultural methods that can reduce the dependence on chemical pesticides.

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The microbes demonstrate different modes of antagonistic properties (Table 11.1) by producing antimicrobial compounds or by competing with phytopathogens commonly known as biocontrol agents or biological control agents (BCAs). There is a growing interest in BCAs as viable alternatives for DP management because of the harmful effects of chemical pesticides (Waghunde et al. 2016). The recent findings provide evidence of some bacterial and fungal endophytes which act as a nutrient distributor, tolerance enhancer under drought and abiotic stress, and promoter of growth and yield in plants (Jaber and Araj 2017; Waghunde et al. 2017; Bamisile et al. 2018). The application of entomopathogenic fungi as BCAs has been effective in DP management that also supports plant growth-promoting (PGP) activity (summarized in Tables 11.2 and 11.3). Therefore, more attention has been given to plant growth-promoting rhizobacteria and fungi (PGPR and PGPF, respectively) to replace or supplement agrochemicals in recent times. Their interactions with plants and phytopathogens lead to the activation of plant defense mechanisms such as induced systemic or systemic acquired resistance (ISR or SAR) pathways. The PGPR and PGPF help plants by many other ways such as decomposition of organic matter, increasing availability of nutrients, mineral solubilization, producing numerous phytohormones, and biocontrol of phytopathogens (Sivasakhti et al. 2014). The application of PGPR/PGPF is progressively increasing in agriculture and also offers a smart and economical way to substitute chemically synthesized pesticides and fertilizers (Borah et al. 2018).

This chapter is presented as the advanced survey of the literature currently available on the BCAs for DP management. The application of beneficial PGPR/PGPF reported in different host plants for the plant health management (PHM) are summarized. This work reviews the effects of PGPR and PGPF on host plants and their active role in plant DP management. It also addresses the possible mechanisms of protection and recent advancement conferred by these beneficial microbes as BCAs. Moreover, this chapter addresses the current trends in application and overall adoption of bacterial, fungal, and other microbials for DP management.

Table 11.1 Antagonisms exhibited by biological control agents

Type	Mechanism
Direct antagonism	Parasitism—symbiotic interaction between two phylogenetically unrelated organisms
	Hyperparasitism—parasites using other parasites as their host
	Commensalism—one partner benefits while other is neither benefited nor harmed
Indirect antagonism	Competition—interaction harmful to both the partners
	SAR—systemic acquired resistance
	ISR—induced systemic resistance
Mixed path antagonism	Antibiosis, lytic enzyme production, siderophore production, organic, and inorganic volatile substances

Table 11.2 Recent studies reporting biocontrol activities of PGPR, PGPF and other microbes against different phytopathogens are summarized

Biological control agents	Phytopathogens	Mechanism	Plant species	References
Bacteria				
Pseudomonas stutzeri (E25), *S. maltophilia* (CR71)	*Botrytis cinerea* (gray mold)	VOCs	Tomato	Rojas-Solís et al. (2018)
Azotobacter salinestris	*Fusarium* sp.	Antifungal substances, HCN, siderophores	—	Chennappa et al. (2018)
Bacillus amyloliquefaciens and *B. pumilus*	*P. syringae* pv. aptata (leaf spot)	Surfactin, fengycin A, iturin A	Sugar beet	Nikolić et al. (2018)
Azotobacter salinestris	*Fusarium species*	Antifungal substances, HCN, siderophores	—	Chennappa et al. (2018)
B. amyloliquefaciens ALB 629	*Rhizoctonia solani* (damping-off and web blight)	—	Common bean	Martins et al. (2018)
Bacillus mojavensis RRC101	*Fusarium verticillioides*	VOCs	Maize	Rath et al. (2018)
P. aeruginosa, *Bacillus* sp.	*Rhizoctonia solani* (root rot)	Antibiotic production	Mung	Kumari et al. (2018)
B. amyloliquefaciens subsp. *plantarum* 32a	*Agrobacterium tumefaciens* (crown gall)	Surfactin, iturin, difficidin polyketide, bacilysin dipeptide	Tomato	Abdallah et al. (2018)
Pseudomonas sp. CWD B, D, N; *Serratia* sp. CWD C	*Botrytis cinerea* and *Aspergillus niger*	Hydrolytic enzymes, siderophores, HCN	Pea and tomato	Tabli et al. (2018)
Pseudomonas putida, *P. fluorescens*, *P. aeruginosa*	*Dematophora necatrix*, *Fusarium oxysporum*, *Phytophthora cactorum* and *Pythium ultimum*	Phenazine, Pyrrolnitrin, DAPG	Apple	Sharma et al. (2017a, b, c)
Bacillus velezensis CC09	*Blumeria graminis* (powdery mildew)	—	Wheat	Cai et al. (2017)
Bacillus velezensis S3-1	*Botrytis cinerea*	Surfactin, iturin and fengycin	Tomato	Jin et al. (2017a, b)
Bacillus amyloliquefaciens CPA-8	*Monilinia laxa*, *M. fructicola*, *Botrytis cinerea*	VOCs	Cherry	Gotor-Vila et al. (2017)

(continued)

Table 11.2 (continued)

Biological control agents	Phytopathogens	Mechanism	Plant species	References
Pseudomonas sp. MCC 3145	*C. circinans*, *C. dematium*, *Fusarium oxysporum*, *R. solani*, *S. sclerotiorum*	PCA	Rice	Patil et al. (2017)
Bacillus amyloliquefaciens PGPBacCA1	*Sclerotium rolfsii*, *Sclerotinia sclerotiorum*, *Rhizoctonia solani*, *Fusarium solani*, *Penicillium* sp.	Surfactin, iturin and fengycin	Common bean	Torres et al. (2017)
Rhizobium sp.	*Fusarium*, *Rhizoctonia*, *Sclerotium*, *Macrophomina*	Antibiotics, HCN, mycolytic enzymes, siderophore	Legume plants	Das et al. (2017)
Bacillus amyloliquefaciens	*Sclerotium rolfsii*, *Sclerotinia sclerotiurum*, *Rhizoctonia solani*, *Fusarium solani*, *Macrophomina phaseolina*,	Surfactin, iturin, fengycin, kurstatin, polymyxin,	Common bean	Sabaté et al. (2017)
B. subtilis LHS11 and FX2	*Sclerotinia sclerotiorum* (stem rot)	Antibiosis	Rapeseed	Sun, et al. (2017)
Bacillus subtilis 9407	*Botryosphaeria dothidea* (apple ring rot)	Fengycin	Apple	Fan et al. (2017)
Paraburkholderia phytofirmans PsJN	*Pseudomonas syringae* pv. tomato DC3000	ISR	*Arabidopsis*	Timmermann et al. (2017)
Bacillus velezensis RC 218	*Fusarium graminearum* (head blight)	Fengycin, iturin, ericin	Wheat	Palazzini et al. 2016
Pseudomonas protegens S4LiBe and S5LiBe	*Botrytis cinerea*, *Verticillium dahliae*, *F. graminearum*, *Aspergillus niger*, *A. flavus*	Siderophores, chitinase, polymer degrading enzymes	—	Bensidhoum et al. (2016)
Pseudomonas chlororaphis MCC2693	*Alternaria alternata*, *Phytophthora* sp., *Fusarium solani*, *F. oxysporum*	PCA,, HCN, ammonia, siderophores, lytic enzymes	Wheat	Jain and Pandey (2016)
Bacillus amyloliquefaciens ZM9	*Ralstonia solanacearum* (bacterial wilt)	Surfactin	Tobacco	Wu et al. (2016)
Bacillus amyloliquefaciens SB14	*Rhizoctonia solani* AG-4 and AG2-2	Antibiotics, lytic enzymes, VOCs	Sugar beet	Karimi et al. (2016)
Bacillus sp.	*Fusarium oxysporum*, *R. solani*, *Botrytis cinerea* R16, *Galactomyces geotrichum* MUCL 28959, *Verticillium longisporum* O1	Fengycins, surfactins, mycosubtilin, bacillomycin, kurstakins	Date palm	El Arbi et al. (2016)

Bacillus subtilis B1	*Lasiodiplodia theobromae* (bluish black discoloration)	Surfactin, fengycin	Rubber wood	Sajitha and Dev (2016)
B. cepacia, *B. amyloliquefaciens*, *S. marcescens*, *S. marcescens*, *P. aeruginosa*	*Pythium myriotylum* (soft rot)	—	Ginger	Dinesh et al. (2015)
Burkholderia pyrrocinia 2327	*Rhizoctonia solani*, *Trichophyton*	Antibiotic production (pyrrolnitrin)	—	Kwak and Shin (2015)
Pseudomonas fluorescens	*Botrytis cinerea* (gray mold)	Phenazines, cyanogens, siderophores, proteases	*Medicago truncatula*	Hernández-león et al. (2015)
Arthrobacter, *Curtobacterium*, *Enterobacter*, *Microbacterium*, *Pseudomonas*	*Xanthomonas axonopodis* pv. *passiflorae*	Siderophore	Passion fruit	Halfeld-vieira et al. (2015)
B. amyloliquefaciens GB1	*Valsa mali* (apple valsa canker)	—	Apple	Zhang et al. (2015)
Pseudomonas sp., *Paenibacillus* sp.Pb28, *Enterobacter* sp. En38, *Serratia* sp. Se40	*Ralstonia solanacearum* (wilt)	Siderophore, HCN, protease production	Potato	Kheirandish and Harighi (2015)
Bacillus thuringiensis UM96	*Botrytis cinerea* (gray mold)	Chitinase	*Medicago truncatula*	Martínez-Absaló et al. 2014
Bacillus amyloliquefaciens S20	*F. oxysporum*, *R.solanacearum* (Wilt)	Iturins A	Eggplant	Chen et al. (2014)
Pseudomonas fluorescens	*Athelia rolfsii* (southern blight)	VOCs, dimethyl disulfide	*Atractylodes*	Zhou et al. (2014)
Pseudomonas fluorescens MGR12	*Fusarium proliferatum* (head blight)	VOCs	Cereals	Cordero et al. (2014)
Bacillus subtilis NCD-2	*Rhizoctonia solani* (damping-off)	Fengycin	Cotton	Guo et al. (2014)
Pseudomonas sp. LBUM223	*Streptomyces scabies* (potato scab)	PCA	Potato	Arseneault et al. (2014)
Bacillus licheniformis, *Pseudomonas fluorescens*	*Botrytis cinerea*	—	Grape	Salomon et al. (2014)

(continued)

Table 11.2 (continued)

Biological control agents	Phytopathogens	Mechanism	Plant species	References
Bacillus amyloliquefacien CM-2 and T-5	*Ralstonia solanacearum* (vascular wilt)	—	Tomato	Tan et al. (2013)
Pseudomonas putida PP3WT, *Bacillus cereus* SC1AW	*Ralstonia solanacearum* (wilt)	—	Tomato	Kurabachew and Wydra (2013)
Pseudomonas chlororaphis subsp. *aurantiaca* StFRB508	*Fusarium oxysporum* f. sp. *conglutinans*	PCA	Potato	Morohoshi et al. (2013)
Bacillus amylolequifaciens	*Polymyxa betae* (Rhizomania disease)	ISR	Sugar beet	Desoignies et al. (2013)
Acinetobacter lwoffii, *B. subtilis*, *Pantoea agglomeran*, *P. fluorescens*	*Botrytis cinerea*	ISR	Grapevine	Magnin-Robert et al. (2013)
Pseudomonas fluorescens	*P. syringae* pv. *tomato* (bacterial speck)	DAPG, ISR	*Arabidopsis*	Weller et al. (2012)
Pantoea agglomerans	*Erwinia amylovora* (fire blight)	Pantocin A, herbicolins, microcins, phenazines	Pome fruits	Braun-Kiewnick et al. (2012)
Pseudomonas brassicacearum J12	*Ralstonia solanacearum* (wilt)	DAPG, HCN, siderophore, protease	Tomato	Zhou et al. (2012)
Chryseobacterium wanjuense KJ9C8	*Phytophthora capsici* (blight)	Proteinase and HCN production	Pepper	Kim et al. 2012
Pseudomonas fluorescens	*P. syringae* pv. *tomato* (speck)	DAPG, ISR	*Arabidopsis*	Weller et al. (2012)
Pseudomonas brassicacearum J12	*Ralstonia solanacearum* (wilt)	DAPG, HCN, siderophore, protease	Tomato	Zhou et al. (2012)
Bacillus sp., *Stenotrophomonas maltophilia* 2JW6	*Ralstonia solanacearum*	—	Ginger	Yang et al. (2012)
Pseudomonas sp., *Bacillus* sp.	*Ralstonia solanacearum* (bacterial wilt)	—	Eggplant	Ramesh and Phadke (2012)
Pseudomonas fluorescens Psd	*Fusarium oxysporum*	PCA, pyrrolnitrin	Tomato	Upadhya, Srivastava 2011

Pseudomonas protegens	—	DAPG, pyoluteorin	—	Ramette et al. (2011)
Bacillus subtilis CAS15	*Fusarium oxysporum* (wilt)	2,3-dihydroxybenzoate and 2,3 dihydroxybenzoyl glycine	Pepper	Yu et al. (2011)
Bacillus cereus AR156	*Pseudomonas syringae* pv. *tomato* DC3000	ISR–SA, jasmonic acid and ethylene	*Arabidopsis*	Niu et al. (2011)
Fungus				
Aspergillus terreus JF27	*Pseudomonas syringae* pathovar (pv.) *tomato* DC3000 (speck)	ISR	Tomato	Yoo et al. (2018)
T. asperellum CWD CHF 78	*Fusarium oxysporum* f. sp. *lycopersici* (wilt)	Chitinases, proteases, siderophores	Tomato	Li et al. (2018)
Clonostachys rosea	*Rhizoctonia solani* AG-3 (black scurf)	—	Potato	Salamone et al. (2018)
T. harzianum Ths97	*Fusarium solani* (root rot)	Mycoparasitism	Olive trees	Amira et al. (2017)
T. harzianum ThHP-3	*F. oxysporum*, *C. capsici*, *C. truncatum*, *Gloesercospora sorghi*	Mycoparasitism	—	Sharma et al. (2017a, b, c)
T. harzianum T1A	*Guignardia citricarpa* (citrus black spot)	Mycoparasitism	—	de Lima et al. (2017)
T. harzianum	*Fusarium oxysporum*	ISR	Soybean	Zhang et al. (2017)
P. simplicissimum, *Leptosphaeria* sp., *Talaromyces flavus*, *Acremonium* sp.	*V. dahliae* Kleb. (Verticillium wilt)	ISR	Cotton	Yuan et al. (2017)
Trichoderma M10	*Uncinula necator* (powdery mildew)	Secondary metabolites, SIR	*Vitis vinifera*	Pascale et al. (2017)
Trichoderma atroviridae	*Fusarium solani* (root rot, damping off)	Mycoparasitism, secretion of toxic secondary metabolites, competition	Common bean	Toghueo et al. (2016)

(continued)

Table 11.2 (continued)

Biological control agents	Phytopathogens	Mechanism	Plant species	References
Trichoderma harzianum T-aloe	*Sclerotinia sclerotiorum* (stem rot)	Hyphal parasitism, 1,3-β-glucanase, chitinase	Soybean	Zhang et al. (2016)
T. asperellum CCTCC-RW0014	*Fusarium oxysporum* f. sp. *cucumerinum*	CWD enzymes (chitinase, protease, glucanase)	Cucumber	Saravanakumar et al. (2016)
T. polysporum	*Fusarium oxysporum* f. sp. *melonis* (melon wilt)	Competition, antibiosis, mycoparasitism	Water melon	Gava and Pinto (2016)
Trichoderma sp.	*Sclerotinia sclerotiorum* (white mold)	CWD enzymes, parasitism	Beans	Geraldine et al. (2013)
Chaetomium globosum	*Fusarium sulphureum*, *A. alternate*, *C. sorghi*, *F. oxysporum* f. sp. *vasinfectum*, *Botrytis cinerea*, *F. graminearum*	Antibiotic production (gliotoxin)	Ginkgo biloba	Li et al. (2011)
T. viride	*Fusarium oxysporum* f. sp. *adzuki* and *Pythium arrhenomanes*,	Mycoparasitism	Soybean	John et al. (2010)
Actinomycetes				
Streptomyces sp. CB-75	*Colletotrichum musae*, *C. gloeosporioides*	Type I polyketide synthase, nonribosomal peptide synthetase	Banana	Chen et al. (2018)
Streptomyces sp.	*Sclerotium rolfsii* (collar rot)	Host defense enzymes/genes and accumulation of phenolic compounds	Chickpea	Singh and Gaur (2017)
Streptomyces sp.	*Magnaporthe oryzae* (blast)	—	Rice	Law et al. (2017)
Streptomyces PM5	*Pectobacterium carotovorum subsp. brasiliensis* (soft rot)	Lipase and VOCs	Tomato	Dias et al. (2017)
Streptomyces UPMRS4	*Pyricularia oryzae* (blast)	Chitinase, glucanase and PR1	Rice	Awla et al. (2017)
Streptomyces sp.	*Phytophthora capsici*, *Sclerotium rolfsii*	Hydrolytic enzymes (amylases, proteases, lipases, cellulases)	Black pepper	Thampi and Bhai (2017)
S. corchorusii UCR3-16	Several pathogens	Antifungal metabolites, VOCs, siderophores, CWD enzymes	Rice	Tamreihao et al. (2016)

S. plicatus isolate B4-7	*Phytophthora capsici* (damping off, root rot, leaf blight)	Antibiotic (borrelidin)	Bell pepper	Chen et al. (2016)
Streptomyces sp.	*Sclerotium rolfsii* (stem rot)	—	Groundnut	Adhilakshmi et al. (2014)
Streptomyces sp. NSP (1–6)	*Fusarium oxysporum* f.sp. *capsici* (wilt)	Chitinase	Chili plants	Saengnak et al. (2013)
Streptomyces sp.	*Fusarium oxysporum* f.sp. *zingiberi* (rhizome rot)	—	Ginger	Manasa et al. (2013)
Streptomyces sp.	*Xanthomonas oryzae* pv. *oryzae (Xoo)*, (leaf blight)	Chitinase, phosphatase, and siderophore	Rice	Hastuti et al. (2012)
Streptomyces sp.	*Rhizoctonia solani* AG-2, *Fusarium solani*, *Phytophthora drechsleri* (root rot)	Protease, chitinase, α-amylase activity	Sugar beet	Karimi et al. (2012)
S. toxytricini vh6, *S. flavotricini* vh8, *S. toxytricini* vh22, *S. avidinii* vh32, *S. tricolor* vh85	*Rhizoctonia solani* (root rot)	ISR (antimicrobial phenolics and SA)	Tomato	Patil et al. (2011)

CWD enzymes cell wall-degrading enzymes, *DAPG* 2,4-diacetylphloroglucinol, *HCN* hydrocyanic acid, *ISR* induced systemic resistance, *PCA* phenazine-1-carboxylic acid, *SA* salicylic acid, *VOCs* volatile organic compounds

Table 11.3 Recent studies reporting biocontrol activities of PGPR, PGPF, and other microbes against different pests are summarized

Biological control agents	Pest	PGP traits	Plant species	References
Bacteria				
Pseudomonas, *Bacillus* sp.	*Meloidogyne javanica*, *Ditylenchus* sp	Production of phytohormones, antibiotic production	Garlic, soybean	Turatto et al. (2018)
Bacillus cereus, *B. licheniformis*, *Lysinibacillus sphaericus*, *P. fluorescens*, *P. brassicacearum*	*Meloidogyne incognita*	–	Tomato	Colagiero et al. (2018)
Bacillus sp., *Pseudomonas* sp.	Aphid	Yield enhancement	Wheat	Naeem et al. (2018)
Pseudomonas fluorescens, *Bacillus subtilis*	*Plutella xylostella*	–	Chinese kale	Rahardjo and Tarno (2018)
Serratia proteamaculans	*Meloidogyne incognita*	Increase in root and shoot growth	Tomato	Zhao et al. (2018)
Pseudomonas putida strain, BG2 and *Bacillus cereus* BC1	*Meloidogyne incognita*	Increase in plant growth and essential oil	Patchouli	Borah et al. (2018)
Kosakonia radicincitans	*Brevicoryne brassicae* and *Myzus persicae*	–	*Arabidopsis*	Brock et al. (2018)
Bacillus velezensis, *B. mojavensis*, *B. safensis*	*Heterodera glycine* (cyst nematode)	Increased in plant height, plant biomass and yield	Soybean	Xiang et al. (2017)
Bacillus sp. BC27 and BC29	*Meloidogyne javanica*	Increase in shoot weight	Soybean	Chinheya et al. (2017)
Pseudomonas putida and *Rothia sp.*	*Spodoptera litura*	Increase in plant biomass and yield	Tomato	Bano and Muqarab (2017)
Bacillus methylotrophicus strain R2-2	*Meloidogyne incognita*	Yield enhancement	Tomato	Zhou et al. (2016)
Lysobacter antibioticus strain 13-6				
Bacillus subtilis isolates Sb4–23, Mc5-Re2, and Mc2-Re2,	*Meloidogyne incognita*	–	Tomato	Adam et al. (2014)

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Table 11.3 (continued)

Biological control agents	Pest	PGP traits	Plant species	References
Fungus				
Beauveria bassiana	*Spodoptera littoralisn*	Boosted spike production	Wheat	Sánchez-Rodríguez et al. (2018)
Purpureocillium lilacinum	*Meloidogyne javanica*, *Meloidogyne incognita*	Increase in yield	Tomato	Kepenekci et al. (2018)
Beauveria bassiana GHA	–	Enhance the root sett	Sugarcane	Donga et al. (2018)
Metarhizium brunneum CB15	–	Biomass, leaf area, nitrogen and phosphorus contents were enhanced	Potato	Krell et al. (2018)
Beauveria bassiana, *Isaria fumosorosea*, and *Metarhizium brunneum*	–	Positive effect on survival, growth, health, length, and dry weight of cabbage	Cabbage	Dara et al. (2017)
Syncephalastrum racemosum, *Paecilomyces lilacinus*	*Meloidogyne incognita*	Stimulated root length, shoot length and increased the cucumber yield	Cucumber	Huang et al. (2016)
Beauveria bassiana and *Metarhizium brunneum*	–	Plant growth enhancement	*Vicia faba*	Jaber and Enkerli (2016)
Beauveria bassiana and *Purpureocillium lilacinum*	*Helicoverpa zea* (cotton bollworm)	Plant growth enhancement	Cotton	Lopez and Sword (2015)
Metarhizium robertsii	Several insects	Induced root hair proliferation and plant root growth	Switchgrass, haricot beans	Sasan and Bidochka (2012)
Metarhizium anisopliae LHL07	–	Higher shoot length, shoot fresh and dry biomass, chlorophyll contents, transpiration rate, photosynthetic rate and leaf area	Soybean	Khan et al. (2012)
Metarhizium anisopliae	–	Increased plant height, root length, shoot and root dry weigh	Tomato	Elena et al. (2011)
Actinomycetes				
S. rubrogriseus HDZ-9-47	*Meloidogyne incognita*	Increase in yield	Tomato	Jin et al. (2017a, b)
S. galilaeus strain KPS-C004	*Meloidogyne incognita*	Increase in plant biomass, shoot-root length	Chili	Nimnoi et al. (2017)

11.2 Plant Growth-Promoting Rhizobacteria (PGPR)

The term “PGPR” was first used for soil-borne bacteria supporting PGP activity by root colonization in plants (Kloepper and Schroth 1978). The PGPR comprises the heterogeneous group of nonpathogenic, root-colonizing bacteria that ameliorate plant growth. This group of rhizobacteria found in the narrow region of soil around plant root, known as the rhizosphere, primarily influenced by the plant root system. Lorenz Hiltner was the first to use term “rhizosphere,” a word primarily originating from the Greek word “rhiza” (Hiltner 1904). The rhizosphere is a highly competitive microenvironment for diverse groups of microbes to obtain nutrients and proliferative growth that helps plants in development and PGP activity.

The growth promotion by PGPR occurs by the modification of the rhizospheric microbial community. Generally, PGPR affect plant growth by exhibiting a variety of direct and indirect mechanisms. The direct PGP activity entails either facilitating the resource acquisition (essential minerals and nutrients) from the surrounding environment or by providing synthesized compounds. The indirect mechanisms are related to reduce the harmful effects of phytopathogens by synthesis of antibiotics, lytic enzymes (chitinases, cellulases, 1,3-glucanases, proteases, and lipases), and chelation of available iron in the plant-root interface.

11.2.1 Categories of PGPRs

The PGPR are categorized into extracellular (ePGPR-symbiotics) and intracellular (iPGPR-free-living) PGPR depending on their habitat in plant compartment (Gray and Smith 2005). The ePGPR exists among the spaces in the root cortex cells, rhizosphere and rhizoplane, whereas iPGPRs reside in the nodular structures of root cells (Figueiredo et al. 2010). The ePGPR include different bacterial genera such as *Erwinia*, *Flavobacterium*, *Arthrobacter*, *Agrobacterium*, *Azotobacter*, *Azospirillum*, *Burkholderia*, *Bacillus*, *Caulobacter*, *Chromobacterium*, *Micrococcous*, *Pseudomonas*, and *Serratia* (Ahemad and Kibret 2014). The iPGPR includes the members of Rhizobiaceae family (such as *Rhizobium*, *Bradyrhizobium*, *Allorhizobium*, *Mesorhizobium*), *Frankia* species, and endophytes (Bhattacharyya and Jha 2012).

The PGPR can be also classified on the bases of their functional activities. This classification includes biofertilizer (enhances the availability of primary nutrients and growth of host plant), biopesticide (suppress or control diseases, mainly by antifungal metabolites and antibiotic production), phytostimulators (the ability to produce phytohormones like IAA, GAs, etc.), and rhizoremediators (degrading organic pollutants) (Bhardwaj et al. 2014). The PGPRs employ number of mechanisms to interact with their host plants either simultaneously or separately under different time and conditions.

11.3 Plant Growth-Promoting Fungi (PGPF)

Most of the previous studies have focused on PGPR and their association with phytopathogens whereas little is known about the PGPF. The PGPF are nonpathogenic saprophytes that exert advantageous effects on plants. They are known to enhance plant growth, suppress plant diseases, and induce ISR. Some PGPFs species reported to suppress the bacterial and fungal diseases of some crop plants. The well-known nonpathogenic fungal genera include *Aspergillus*, *Piriformospora*, *Fusarium*, *Penicillium*, *Phoma*, *Rhizoctonia*, and *Trichoderma* and stimulate different plant traits helpful for higher yields (Jaber and Enkerli 2017; Lopez and Sword 2015).

Some examples of PGPF with BCA activity include endophytes, ectomycorrhizas (EcM), arbuscular mycorrhizae (AMF), yeasts, *Trichoderma* sp., and certain avirulent strains of phytopathogens like *Fusarium oxysporum*, *Cryphonectria parasitica*, and *Muscodor albus* (Waghunde et al. 2017). These beneficial fungi have been produced in large quantities and widely applied for management of plant diseases (Ghorbanpour et al. 2017). The PGPF and plant root association has shown to modulate plant growth, mineral nutrient uptake, increased biomass, and yield of crop plants (Deshmukh et al. 2006). Plant beneficial microorganisms are of great interest for applications in agriculture as biofertilizers and biopesticides and for phytoremediation (Berg 2009; Weyens et al. 2009; Shelake et al. 2018).

11.4 Biological Control by PGPR and PGPF

The term "biological control" was first coined to describe the use of natural enemies (introduced or manipulated) to control insect pests by Harry Scott Smith (1919). Later, Paul H. DeBach and Hagen (1964), an entomologist, redefined "natural control" from "biological control." The natural control includes biotic (such as food availability and competition) and abiotic (like weather and soil) factors, and also the natural enemies (like predators, parasites, and pathogens) mediated effects. The natural enemies are affecting or regulating the pest populations. The biological control or biocontrol is a part of the natural control and described as the use of natural or living organisms to inhibit pathogen and suppress plant diseases. The chief mode of action of biocontrol in PGPR/PGPF implicates competition for nutrients, SAR/ISR induction, niche exclusion, and production of antifungal/antibacterial metabolites like antibiotics, bacteriocins, and lytic enzymes (Salomon et al. 2017). The biological control is generally separated into three types: classical biological control (CBC), conservation, and augmentation. Each of these approaches can be used separately or in combination with each other in the biological control program.

11.4.1 Classical Biological Control

The importation of natural enemies to control an introduced or "exotic" pest is known as CBC. The initial step in CBC involves the determination of the pest origin, and then an exploration for its natural enemies in its habitat. The potential BCAs then introduced to the new pest location and released for its establishment. For example, in the late 1800s, the cottony cushion scale, a pest which is native to Australia devastated California citrus industry. The Vedalia beetle (predatory insect) was then introduced from Australia, and the pest control achieved in short time. Three exotic encyrtid parasitoids (*Anagyrus loecki*, *Acerophagus papayae*, and *P. Mexicana*) were introduced in Southern state of India (Tamil Nadu) against a papaya mealybug *Paracoccus marginatus*, causing damage to mulberry fields (Sakthivel 2010).

11.4.2 Conservation

Conservation involves the practices that protect, maintain, and enhance the existing natural enemies. Conservation practices include either reducing or eliminating the factors which interfere with or destroy the natural enemies, for example, use of selective chemical pesticides or providing resources that natural enemies need in their environment.

11.4.3 Augmentation

Augmentation involves the mass culture and release of natural enemies. It consists of two types: inoculative and inundative. The inoculative involves the release of few natural enemies seasonally and suppresses pest outbreaks whereas inundative involves the release of enormous numbers of natural enemies to outcompete the pest population completely. In inundative release, immediate control of pest population is achieved by massive release of their natural enemies.

11.5 PGPR and PGPF as Biological Control Agents (BCAs)

The term BCA generally used in broader sense that includes naturally occurring materials (biochemical pesticides), microbes (microbial pesticides), and plants-produced materials consisting genetic material or plant-incorporated protectants (US EPA 2012). The biochemical pesticides include organic acids, plant and insect growth regulators, plant extracts, pheromones, minerals, and other substances. The Association of Southeast Asian Nations (ASEAN) Sustainable Agrifood Systems (Biocontrol) Project (ABC) classified BCA into four product categories to accommodate living and nonliving active agents: microbial control agents (microbial), macroorganisms (macrobials), semiochemicals, and natural products. Microbial control agents often called as “biopesticides” include a variety of microbes, viz., bacteria, fungi, protozoa, nematodes, and viruses. Among these, bacteria and fungi dominate the commercial BCA formulations including PGPR/PGPF.

The macrobials agents include the mites and insects. Their mode of deployment includes the conservation and CBC. A more recent example includes the release of the *Anagyrus lopezi* (wasp) from Benin to control *Phenacossus manihoti* (mealybug) of pink cassava in Thailand (Winotai et al. 2012). The semiochemcials refers to the biochemical molecules or mixtures that carry specific messages between individuals of the same or different species. These semiochemicals often used as insect attractants (pheromones) and repellents in extremely low dosage. The last one includes the natural plant extracts or "botanicals" which cover diverse natural substances like azadirachtin, pyrethrum, ginseng extract, etc. with different biological activity (Regnault-Roger et al. 2005). In this work, microbials that include PGPR/PGPF are discussed in detail and other BCA categories.

11.6 Mechanisms of Biological Control by PGPR and PGPF

Prediction of disease epidemiology in plants is determined by the associations among the constituents of disease triangle, i.e., pathogen, susceptible host and environment. The interactions among these three components show the severity and occurrence of the disease. The BCAs interact with all the three components of the disease triangle. The BCAs-pathogens interactions studies have revealed the multiple mechanisms of biological control (Table 11.1). The BCAs act on phytopathogens through one or more multifarious mechanisms resulting in plant growth inhibition and spread of phytopathogens (summarized in Tables 11.2 and 11.3). The various mechanisms employed in controlling the plant diseases can broadly classified into direct, indirect, and mixed path antagonism.

11.6.1 Direct Antagonism

11.6.1.1 Parasitism and Hyperparasitism

Parasitism is a type of interaction between two phylogenetically unrelated organisms in which one organism, the parasite, is usually benefitted and the other called the "host" is harmed. For example, *Trichoderma* spp. have a parasitic activity toward a wide variety of phytopathogens such as *Botrytis cinerea*, *Rhizoctonia solani*, *Pythium* spp., *Sclerotium rolfsii*, *Sclerotinia sclerotiorum*, and *Fusarium* spp. (summarized in Waghunde et al. 2016). The *Rhizoctonia solani* cause several plant diseases like rice blight and black scurf of potato and *Trichoderma* spp. is being used as a potential BCA for all these diseases (Jia et al. 2013; Rahman et al. 2014).

The terms mycoparasitism and hyperparasitism have been used for fungal species parasitic on another fungus. The involved pathogen is known as hyperparasite or mycoparasite, or parasite. The mycoparasitism involves the chemotropic growth of the BCA toward the pathogen, recognition through the host lectins and carbohydrate receptors present on the biocontrol fungus. The next step involves the coiling and making of cell wall-degrading (CWD) enzymes and penetration. Some examples include the powdery mildew pathogen parasitized by multiple hyperparasites like *Ampelomyces quisqualis*, *Acrodontium crateriforme*, *A. alternatum*, *Cladosporium oxysporum*, and *Gliocladium virens* (Kiss 2003; Heydari and Pessarakli 2010). An additional case is the virus causing hypovirulence on *Cryphonectria parasitica*, an ascomycete causing chestnut blight (Tjamos et al. 2010).

11.6.1.2 Commensalism

Commensalism is a type of symbiotic interaction benefiting one partner while the other is neither harmed nor benefited. The benefited organism is known as commensal and obtains its nutrients and shelter from its host species. A good example of commensals comprises rhizobacteria. The rhizobacteria such as PGPR control soilborne phytopathogens through antibiotic production, nutrient competition thereby helping plants to survive from phytopathogens.

11.6.2 Indirect Antagonism

11.6.2.1 Competition

Competition is an indirect mechanism and plays a significant role in the biocontrol of pathogens. Biocontrol by competition occurs when nonpathogenic microbes compete for organic nutrients with pathogens to proliferate and survive in host plant. Predominantly, the BCAs have more competent nutrient uptake system than phytopathogens. One of the examples includes control of *Fusarium* wilt due to carbon competition between pathogenic and nonpathogenic strains of *F. oxysporum* (Alabouvette et al. 2009). Fire blight, a contagious disease caused by *Erwinia amylovora* is suppressed by its closely related saprophytic species *E. herbicola* due to nutrient competition on the leaf surface.

11.6.2.2 Systemic Acquired Resistance (SAR)

During the biotic or abiotic stress, the plant produces chemical signals like glutamate thereby activating the plant defense pathways (Toyota et al. 2018). In order to tackle abiotic and biotic stresses plants express a variety of active defense system. The PGPR and PGPF produce chemical stimuli which can induce a persistent variation in plants increasing its capacity to tolerate pathogenic infection and induce systemic host defense against wide-ranging pathogens, known as induced resistance. The induced resistance is of two different forms: the SAR and ISR represent the plant defense response active against phytopathogens. The SAR is the inherent resistance capacity of a plant which activates after being exposed to chemical elicitors from nonpathogenic, virulent, or avirulent microbes or artificial chemical stimuli (Gozzo and Faoro 2013). It remains active against broad-spectrum pathogens for a prolonged time. The SAR induction is mediated by the buildup of accumulated chemical stimuli like salicylic acid (SA) generally secreted after pathogen attack. The SA is the first chemical signal inducing the production of pathogenesis-related (PR) proteins, for example, chitinase, β-1, 3 glucanse. The PR genes code for chitinases and β-1, 3-glucanases which play a significant role in reducing or preventing the pathogen colonization (Sudisha et al. 2012). The SAR has been showed against some pathogens and pests, including *Uromyces viciae-fabae*, *Ascochyta fabae*, *M. incognita*, and *R. solanacearum* (Pradhanang et al. 2005; Molinari and Baser 2010; Sillero et al. 2012).

11.6.2.3 Induced Systemic Resistance (ISR)

The ISR naturally exists in plants and is generally associated to stimulation by nonpathogenic plant-associated rhizobacteria (Pieterse and Van Wees 2015). The ISR is independent of the SA-mediated pathway, and PR proteins are not involved. It is plant specific and depends upon the plant genotype. The applications of nonpathogenic PGPR/PGPF induce ISR facilitated by phytohormones production (viz., jasmonic acid and ethylene). The PGPRs induces ISR in several plants against numerous environmental stressors. The plant defense system produces an enormous number of enzymes involved in plant defense, like polyphenol oxidase, β-1, 3-glucanase, chitinase, phenylalanine ammonia lyase, peroxidase, etc. Even though ISR is not precisely against a specific pathogen, it plays a major role in control of a range of diseases in plant (Kamal et al. 2014). For example, the ISR activity induced by application of *Trichoderma* strains in the leaves was found effective against several diseases in tomato plants (Saksirirat et al. 2009). Rice plant treated with *Bacillus* sp. showed resistance against bacterial leaf blight (Udayashankar et al. 2011).

11.6.3 Mixed Path Antagonism

11.6.3.1 Antibiosis

Antibiosis is defined as the interactions involving a low-molecular-weight compound or an antibiotic that is detrimental to another microorganism. Antibiosis plays a significant role in the suppression of plant diseases and pathogens (Nikolić et al. 2018; Kumari et al. 2018). The PGPR like *Bacillus* sp. and *Pseudomonas* sp., produces a diverse range of antibiotics against different phytopathogens and is significantly more efficient biocontrol mechanism over the past decade (Ulloa-Ogaz et al. 2015). The antibiotics such as phenazine-1-carboxylic acid (PCA), phenazine-1-carboxamide, *N*-butylbenzene sulfonamide, pyrrolnitrin, pyoluteorin, rhamnolipids, oomycin A, cepaciamide A, 2,4-diacetylphloroglucinol, ecomycins, viscosinamide, butyrolactones, pyocyanin (antifungal), azomycin, pseudomonic acid, cepafungins, and Karalicine are produced by *Pseudomonas* sp. (Ramadan et al. 2016). *Bacillus* sp. also produces subtilintas A, subtilosin A, bacillaene, sublancin, difficidin, mycobacillin, chlorotetain bacilysin, rhizocticins, iturins, surfactin, and bacillomycin (Wang et al. 2015). The antibiotic 2,4-diacetyl phloroglucinol produced by *Pseudomonas* sp. is reported to inhibit *Pythium* sp. Similarly, iturin is reported to suppress *B. cinerea* and *R. solani* (Padaria et al. 2016).

11.6.3.2 Siderophores

In addition to water, carbon dioxide, and oxygen, all living plants need total 14 essential elements that include iron (Shelake et al. 2018). The PGPR produces low-molecular-weight (500–1500 Da) organic compounds called siderophores to competitively capture ferric ion under iron-lacking conditions. Siderophore-producing PGPRs gain more attention because of their distinctive property to extract iron from their surrounding (Saha et al. 2016). They sequester iron from their micro-environment, forming a ferric-siderophore complex that progress through diffusion and reverted to the cell surface (Andrews et al. 2003). The bacterial siderophores are of four classes depending on their iron coordinating functional groups: hydroxamates, carboxylate, pyoverdines and phenol catecholates (Crowley 2006).

The PGPRs exert their antagonism to several phytopathogens using secreted siderophores (Tables 11.2 and 11.3). They function by sequestering iron in the root zone, making it unavailable to phytopathogens and inhibiting their growth. Also, PGPR-secreted siderophores augment plant uptake of iron that can distinguish the bacterial ferric-siderophore complex (Katiyar and Goel 2004; Dimkpa et al. 2009). Siderophores produced by *Pesudomonas* group suppress several fungal pathogens and also enhanced growth of numerous crops (Bensidhoum et al. 2016; Sharma et al. 2017a, b, c; Tabli et al. 2018).

11.6.3.3 Volatile Substances

Soil microbes including PGPR produce and release various organic and inorganic volatile compounds (Audrain et al. 2015). The volatile compounds synthesized by PGPR suppressed diverse kind of phytopathogens, indicating their role in biocontrol of soil-borne pathogens (Karimi et al. 2016; Gotor-Vila et al. 2017; Rath et al. 2018). The volatile compounds from PGPR, for instance, *Pseudomonas*, *Bacillus*, and *Arthrobacter*, directly or indirectly facilitate enhanced resistance against diseases, tolerance against abiotic stress, and higher biomass production. The *Bacillus* sp. produces acetoin and 2, 3-butanediol, effective against fungal pathogens (Santoro et al. 2016). *Bacillus megaterium* was found to produce ammonia which inhibits *Fusarium oxysporum* (Shobha and Kumudini 2012). Several other studies on *Pseudomonas* sp. reported the production of ammonia and hydrocyanic acid serving PGP and biocontrol activity (Verma et al. 2016; Sharma et al. 2017a, b, c).

11.6.3.4 Lytic Enzyme Production

The PGPR/PGPF can suppress the growth and activities of phytopathogens by secreting lytic enzymes. The PGPR produces a diverse number of enzymes like ACC-deaminase, cellulases, chitinase, lipases, proteases, β-1,3-glucanase which are involved in the lysis of fungal cell wall (Goswami et al. 2016). The fungal cell wall primarily consists of chitin, glucans, and polysaccharides; hence β-1,3-glucanase- and chitinase-producing bacteria are effective to suppress their growth. The expression of lytic enzymes by PGPR can enhance the suppression of phytopathogens. For instance, chitinase produced by *S. plymuthica* strain C48 inhibits germ-tube elongation and spore germination in *Botrytis cinerea* (Frankowski et al. 2001). Chitinase secreted by *Paenibacillus* sp., *Streptomyces* sp., and *Serratia marcescens* was found to constrain the growth of *Botrytis cinerea*, *Sclerotium rolfsii*, and *Fusarium oxysporum* f. sp. *cucumerinum*. *Lysobacter* produces enzyme glucanase which inhibits *Bipolaris* and *Pythium* sp. (Palumbo et al. 2005). *Micromonospora chalcea* and

Actinoplanes philippinensis inhibit *Pythium aphanidermatum* in cucumber through the secretion of β-1, 3-glucanase (El-Tarabily 2006).

11.7 Advantages of PGPR and PGPF as BCAs

The agrochemicals and genetic approaches used as tools to control plant diseases, but they are not always effective. Moreover, several agrochemicals are nonbiodegradable and exert a harmful effect on the environment. The excessive usage of pesticides for plant disease management has increased pathogen-resistant strains (Burketova et al. 2015). In this regard, PGPR have been seen as an attractive strategy and a sustainable means of controlling soil-borne pathogens and diseases. The application of PGPR and PGPF in sustainable agriculture has been increased in several regions. The PGPR with biocontrol efficacy often provides long-term protection against soil-borne phytopathogens because of their rhizosphere competency, i.e., capacity to rapidly colonize the rhizosphere.

The PGPR/PGPF utilizes the plant's rhizodeposits as a chief carbon source for their development (Denef et al. 2007). The PGPF protect plants from harmful microbes by producing antibiotics while some act as a parasite and some compete for space and food with pathogens (described in earlier sections). They also protect plants by ISR against pathogenic bacteria (Yoshioka et al. 2012; Hossain and Sultana 2015), fungi (Murali et al. 2013; Tohid and Taheri 2015, Nassimi and Taheri 2017), viruses (Elsharkawy et al. 2013), and nematodes (Vu et al. 2006). The arbuscular mycorrhiza fungi (AMF) also help plants in resource acquisition, suppression of diseases, and tolerance to soil pollution and development (Wani et al. 2017). Many studies suggested AMF as an efficient BCAs against phytopathogens and nematodes (Veresoglou and Rillig 2012; Vos et al. 2012, 2013; Akhtar and Panwar 2013). The use of PGPR/PGPF as BCAs reduces the burden of agrochemicals (fertilizers and pesticides) in agricultural ecosystem thus preventing environmental pollution. The BCAs have several other advantages as compared to pesticides mentioned as follows:

1. The PGPR enhances growth and protects plants against phytopathogens.
2. The PGPR can act as a biofertilizer, biopesticide, phytostimulators, and rhizoremediators.
3. The PGPR multiply in soil, leaving no residual problem.
4. A single PGPR can protect against multiple plant pathogens.
5. The PGPR possess multifarious mechanisms including antibiosis, CWD enzymes and siderophore production and also induce SAR/ISR in plants.
6. They are nontoxic to plants and humans.
7. They are ecofriendly and easy to manufacture.
8. BCAs are cheaper as compared to the agrochemicals.
9. The PGPR can be handled easily and applied in the field.
10. The use of PGPR is sustainable in long-term.

11.8 Global Status of Biopesticides

The biopesticides have attracted more interest of global research community due to the harmful effects of chemical pesticides on human health through produced food and environmental safety. Consequently, the global crop protection chemical and conventional pesticide market have experienced major variations over the recent years (Pelaez and Mizukawa 2017). At present, biopesticides comprise only 5% of the total global crop protection market, with 3 billion dollars in revenue worldwide (Damalas and Koutroubas 2018). In the market of the United States, there are more than 200 products registered for use in comparison with 60 similar products in the market of European Union (EU). The global consumption of biopesticides is rising at a rate of 10% every year and is projected to increase further in the future (Kumar and Singh 2015).

The biopesticide development has prompted to replace the chemical pesticide for crop protection. The PGPR/PGPF seems effective in small amounts and much more specific to their target as compared to the conventional pesticides. A large number of biopesticides have already been registered and released in the market. Recently, novel substances have been formulated and reported for use as a biopesticides, like the products derived from plants (*Clitoria ternatea*), fungus (*Talaromyces flavus* SAY-Y-94-01, *Trichoderma harzianum*), bacteria (*Bacillus thuringiensis* var. *tenebrionis* strain Xd3, *Lactobacillus casei* LPT-111), oxymatrine (an alkaloid) (Damalas and Koutroubas 2018). It is anticipated that between the middle of 2040s and 2050s, biopesticide market will equalize with synthetic pesticides and major uncertainties will be due to its uptake in African and Southeast Asian countries (Olson 2015).

The biopesticide market development have improved the management practices and reduced the use of chemical pesticides. Various products have been certificated and commercialized for use in crop protection in different countries. However, in EU, there are very fewer biopesticides being registered as compared to Brazil, China, India, and the United States because of the complex and time-consuming registration processes. The main problem of the biopesticide industry is the lengthy submission process at the EU and other member state levels. The quicker implementation of registration procedures and time limits are essential if more new products have to be commercialized.

Furthermore, the high cost of registering a new BA or product is another limiting factor in its commercialization (Pavela 2014). Therefore, the regulatory authorities must try to ensure smooth and fast biopesticide registration processes and help to promote the safe technologies for product development. The small- and medium-sized firms should be developed to provide farmers with the reliable tools and products for pest management (Damalas and Koutroubas 2018).

11.9 Status of Biopesticide in India

In India, the organic pesticides market has generated total revenue of $102 million in 2016 and is projected to contribute $778 million by 2025. According to the market research report published by Inkwood research (2017) the market for biopesticides in India is anticipated to rise at a growth rate of 25.4% compounded annually during the 2017–2025 forecast period. The biopesticide industry in India represents only 4.2% of the entire pesticide market and is immensely driven by the sale of *Trichoderma viride*, *Pseudomonas fluorescens*, *Bacillus thuringinsis*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Verticillium lecanii*, *Paecilomyces lilacinus*. The Indian biopesticides market, to a high degree, is dominated by numerous unorganized and organized companies like Pest Control India (PCI) and International Panaacea Ltd. (2015). There are around 150 companies involved in biopesticide manufacturing and 12 different types of bioinsecticides registered under the Insecticides Act, 1968 (Gautam et al. 2018).

11.10 Conclusion and Future Perspectives

There has been a considerable rise in the crop yields over the last century, which is mainly attributed to the utilization of chemical pesticides and agrochemicals. Globally, these agrochemicals have become a significant component of agriculture systems. Because of public concern about the damage caused by the intensive use of agrochemicals, an alternative path to their usage in agriculture production system has to be developed. Over the past decade, the use of BCAs has significantly increased in agriculture and is being recommended as an alternative.

Understanding the stimulation of plant responses by PGPR, PGPF, and other microbials is crucial for developing novel methodologies to regulate plant diseases and growth. The exploitation of these microbials relates to their use in PGP activity and mode of action against a variety of pathogens. Future research needs to focus on attaining integrated management of microbial communities in the rhizospheric soil. The advances in biotechnological and molecular approaches will provide more understanding of the cellular processes and signaling pathways linked to growth and DP resistance, resulting from plant-microbe interactions. Recently, genome editing, a modern genetic tool was used to study different aspects of plant-microbe interactions in two species, *Bacillus subtilis* HS3 and *B. mycoides* EC18 (Yi et al. 2018). Such studies will help to understand molecular mechanisms that support plant growth and to identify the superior PGPR/PGPF species in the future. The new alternatives should be discovered to be used as bioinoculants for different crops such as fruits, vegetables, pulses, and flowers. The application of compatible PFPR and PGPF consortium over single strain could be an effective method for reducing plant diseases. Also, compatible combinations of PGP microbes with the agrochemicals or organic amendments needed in the near future.

Many agricultural companies are working in crop protection especially in BCA products. The PGPR, PGPF, and other microbials are already being used in different countries under a different name and are expecting to grow at enormous speed. Eventually, for effective use of these microbes as BCAs, practical techniques for its mass culturing, formulation development, and storage need to be addressed and established. Additionally, an effort is needed to educate the farmers about the BCAs. We advocate the application of multifarious PGP microbial singly or in consortia for development of ecofriendly sustainable agriculture.

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