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The Role of Soil Beneficial Bacteria in Wheat Production: A Review

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Abstract

Free-living plant growth-promoting rhizobacteria (PGPR) have favourable effect on plant growth, tolerance against stresses and are considered as a promising alternative to inorganic fertilizer for promoting plant growth, yield and quality. PGPR colonize at the plant root, increase germination rates, promote root growth, yield, leaf area, chlorophyll content, nitrogen content, protein content, tolerance to drought, shoot and root weight, and delayed leaf senescence. Several important bacterial characteristics, such as biological nitrogen fixation, solubilization of inorganic phosphate and mineralization of organic phosphate, nutrient uptake, 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity and production of siderophores and phytohormones, can be assessed as plant growth promotion traits. By efficient use, PGPR is expected to contribute to agronomic efficiency, chiefly by decreasing costs and environmental pollution, by eliminating harmful chemicals. This review discusses various bacteria acting as PGPR, their genetic diversity, screening strategies, working principles, applications for wheat and future aspects in terms of efficiency, mechanisms and the desirable properties. The elucidation of the diverse mechanisms will enable microorganisms developing agriculture further.

Keywords: PGPR, wheat, abiotic stress, enzymes, nitrogen fixation

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the three major cereals (together with maize and rice), major source of energy, renewable resource for food, feed and industrial raw material, protein and fibre source in human diet, staple food crop for more than one-third of the world population [1], grown both as a spring and winter crop.

Plant growth-promoting bacteria (PGPR), typically colonizing at the rhizosphere, is known to increase the yield and help alleviating the effects of biotic or abiotic stresses [2]. The practice of PGPRs is promising in reducing the use of chemical fertilisers, at the same time maintaining yields at commercially viable levels and/or maintaining grain protein content [3]. As such, PGPR contributes to the improvement of both local and global environments, reducing dependence on non-renewable resources while still being economically competitive (both price and quality aspect) [4–6].

Several beneficial free-living rhizobacteria have been termed as PGPR, including, but not limited to, *Acinetobacter*, *Acetobacter*, *Alcaligenes*, *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Beijerinckia*, *Enterobacter*, *Flavobacterium*, *Methylobacterium*, *Pseudomonas*, *Rhizobium*, *Paenibacillus* and *Pantoea* [7–10]. These bacteria enhance growth through numerous mechanisms [2, 11–15]. A short list of mechanisms cover:

- The biological nitrogen fixation (BNF) and phosphate solubilization
- Secretion of hormones, for example, auxins, indole acetic acid (IAA), cytokinins, gibberellins and ethylene
- Facilitating the uptake of essential nutrients (N, P, Fe, Zn, etc.) from the atmospheric air and soil
- Zinc and iron solubilization and organic matter mineralization
- Secretion of certain volatiles and lowering of plant ethylene level
- Induction of systemic resistance
- Production of 1-aminocyclopropane-1-carboxylate deaminase (ACC)
- Quorum sensing (QS) signal interference and inhibition of biofilm formation
- Promoting beneficial plant-microbe symbioses
- Exhibiting antifungal activity, exhibition of antagonistic activity against phytopathogenic microorganisms by producing siderophores, b-1,3-glucanase, chitinases and antibiotics
- Interference with pathogen toxin production.

A non-exhaustive list of Plant Growth Promoting Rhizobacteria (PGPR)s used to alleviate various stresses is given in **Table 1**, and the various other uses of these bacteria are listed in **Table 2**. Two important mechanisms employed by PGPR are the production of different phytohormones,

Stress type	Bacterial inoculate	Properties of the crop	Reference
Drought/water	<i>Azospirillum brasilense</i> Sp245	Wheat, growth rate of coleoptiles	[132]
Drought	<i>Azospirillum brasilense</i> INTA Az-39 wheat roots	Wheat (<i>T. aestivum</i>)	[133]
Drought	<i>Azospirillum lipoferum</i>	Wheat (<i>T. aestivum</i> L.)	[134]
Drought	<i>Burkholderia phytofirmans</i>	Wheat (<i>T. aestivum</i>) Grain yield, photosynthetic rate, water use efficiency, chlorophyll content	[135]
Drought	<i>Bacillus safensis</i> , <i>Ochrobactrum pseudoregionense</i>	Wheat (<i>T. aestivum</i>)	[137]
Heavy metal-stressed	<i>Bacillus</i> sp	Wheat (<i>T. aestivum</i>) Indole-3-acetic acid Antioxidant defence system SOD shoots and roots Shoot POD and CAT	[198]
Heavy metal	<i>Bacillus thuringiensis</i> , <i>Azotobacter chroococcum</i> , <i>Paenibacillus ehimensis</i> , <i>Pseudomonas pseudoalcaligenes</i>	Higher heavy metal resistance Siderophore,, indole acetic acid, HCN, P solubilization	[151]
Osmotic stress	<i>Azospirillum</i>	Wheat (<i>T. aestivum</i>)	[199]
Osmotic stress	<i>Azospirillum brasilense</i> sp. 245	Wheat (<i>T. aestivum</i>)	[200]
Cold	<i>Pseudomonas</i> spp.	IAA, P solubilization, rhamnolipids, siderophores	[201]
Cold	<i>Bacillus megaterium</i> M3, <i>Bacillus subtilis</i> OSU142, <i>Azospirillum brasilense</i> Sp245, <i>Raoultella terrigena</i>	Root and shoot dry weight, leaf total chlorophyll content, stomatal conductance, leaf relative water content	[171]
Temperature	<i>Bacillus amyloliquefaciens</i> and <i>Azospirillum brasilense</i>	Wheat (<i>T. aestivum</i>)	[202]
Heat stress	<i>Pseudomonas putida</i> AKMP7	Wheat (<i>Triticum</i> spp)	[98]
Temperature	<i>Pseudomonas fluorescens</i> , <i>Pantoea agglomerans</i> , <i>Mycobacterium</i> sp	Wheat (<i>T. aestivum</i>)	[203]
Salinity	<i>Azospirillum</i>	Wheat (<i>T. aestivum</i>)	[62]
Salinity	<i>Pseudomonas putida</i> , <i>Pseudomonas extremorientalis</i> , <i>Pseudomonas chlororaphis</i> and <i>Pseudomonas aurantiaca</i> .	Wheat (<i>T. aestivum</i> cv. Turon) wheat root tip coloniser, tolerated salt	[125]
Salinity	<i>Pseudomonas fluorescens</i> 153, 169, <i>Pseudomonas putida</i> 108	Wheat (<i>Triticum aestivum</i>) grain yield, 1000 grain weight, grain yield	[143]
Salinity	<i>Pseudomonas putida</i> N21, <i>Pseudomonas aeruginosa</i> N39 and <i>Serratia proteamaculans</i> M35	Wheat (<i>Triticum aestivum</i> L.)	[142]
Salinity	<i>Azospirillum</i> sp	Durum wheat (<i>Triticum durum</i>)	[128]

Stress type	Bacterial inoculate	Properties of the crop	Reference
Salinity	<i>Pseudomonas putida</i> , <i>Enterobacter cloacae</i> , <i>Serratia ficaria</i> , and <i>Pseudomonas fluorescens</i>	Wheat	[204]
	<i>Bacillus</i> , <i>Burkholderia</i> , <i>Enterobacter</i> , <i>Microbacterium</i> , <i>Paenibacillus</i>	Wheat (<i>T. aestivum</i>)	[46]
Salinity	<i>Bacillus pumilus</i> , <i>Pseudomonas mendocina</i> , <i>Arthrobacter</i> sp., <i>Halomonas</i> sp., and <i>Nitrincola laticapensis</i>	P solubilization, indole acetic acid (IAA), siderophore, ammonia, proline accumulation, salt tolerance, choline oxidase activity	[140]
	<i>Streptomyces</i> sp	Wheat (<i>T. aestivum</i>)	[85]
Salinity	<i>B. subtilis</i> , <i>Arthrobacter</i> sp.	Wheat (<i>T. aestivum</i>)	[97]
	<i>Azospirillum</i> sp.	Wheat (<i>T. aestivum</i>)	[95]
Salinity	<i>Pseudomonas putida</i> , <i>Enterobacter cloacae</i> , <i>Serratia ficaria</i> and <i>P. fluorescens</i>	Wheat (<i>T. aestivum</i>) Germination rate percentage and index and improved nutrient status	[205]
Salinity	<i>Hallobacillus</i> sp. SL3 and <i>Bacillus halodenitrificans</i> PU62	Root length, root elongation, dry weight	[1]
Salinity	<i>Enterobacter asburiae</i> , <i>Moraxella plurinimalium</i> , <i>Pseudomonas stutzeri</i>	Number of tillers, grain weight, growth and yield	[138]

Table 1. PGPB-mediated IST against abiotic stress.

PGPR	Source	Plant growth regulation	Results of addition of bacteria to plants	References
<i>Azospirillum</i> sp.	Wheat rhizospheric	N ₂ fixation	Grain yield, dry matter, N content	[32]
<i>Azospirillum brasilense</i>	Mutant	Indole-3-acetic acid (IAA)	Number and length of lateral roots, distribution of root hairs.	[206]
<i>Cyanobacteria</i>	Rhizospheric	N ₂ fixation	Root dry weight, N content root and hoot	[207]
<i>Azorhizobium caulinodans</i>	Wheat	N ₂ fixation	Dry weight, nitrogen content	[192]
<i>Azotobacter chroococcum</i>	Wheat Rhizospheric	P solubilization, N ₂ fixation, IAA	Seed emergence radicle and plumule length	[114]
<i>Azotobacter</i> sp. <i>Azotobacter chroococcum</i>	Wheat Rhizospheric	N ₂ fixation	Growth	[73]
<i>Paenibacillus polymyxa</i>	Wheat	Cytokinin, N ₂ fixation	Plant growth	[208]
<i>Azospirillum brasilense</i> Sp7	<i>Digitaria decumbens</i>	Lectins, N ₂ fixation	Activities of a-glucosidase, b-glucosidase and b-galactosidase in wheat-seedling	[209]
<i>Azospirillum brasilense</i> 75, 80 and Sp245	Non-sterilised and surface-sterilised wheat roots	N ₂ fixation	Root-hair deformation colonization	[99]

PGPR	Source	Plant growth regulation	Results of addition of bacteria to plants	References
<i>Azospirillum brasilense</i>	Wheat rhizospheric	N ₂ fixation	Plant growth, N accumulation and content, biomass, grain yield and protein concentration	[164]
<i>Klebsiella pneumoniae</i> 342	Maize	N ₂ fixation	Dry weight of roots and shoots, total N per plant colonized the interior of wheat roots	[26]
<i>Pseudomonas denitrificans</i> <i>Pseudomonas rathonis</i>		Auxin	Plant growth	[210]
<i>Bacillus simplex</i> BS BNM-10, <i>Bacillus firmus</i> BF BNM-4	Wheat roots,		Biomass number of ears nitrogen accumulation, N content	[172]
<i>Azotobacter chroococcum</i> <i>Pantoea agglomerans</i>	Geographically and climatically diverse locations	Gibberellic acid (GA), IAA	Increase in number root hairs, thickening of roots, root and shoot biomass	[11]
<i>Pseudomonas</i> spp	Rhizosphere of wheat	P solubilization, siderophore Indole acetic acid ACC deaminase, diacetyl-phloroglucinol	Protein content, yield and grain quality	[162]
<i>Bacillus</i> RC01, <i>Bacillus</i> RC03	Rhizosphere of wheat	P solubilization, N ₂ fixation	Root and shoot weight, total biomass	[111]
<i>Azotobacter chroococcum</i>	Various sources	N ₂ fixation	Grain and straw yield, N content in grain and straw	[211]
<i>Rhizobium leguminismarum</i> Thal-8/ SK8), <i>Pseudomonas</i> sp. 54RB	Rice	N ₂ fixation P solubilization	Root and shoot weight, plant height, spike length, grain yield, seed P content, leaf protein and sugar content	[185]
<i>Pseudomonas putida</i> , <i>P. extremorientalis</i> , <i>P. chlororaphis</i> , <i>P. aurantiaca</i>	Rhizosphere of wheat grown in saline soil	Hydrogen cyanide (HCN), IAA, ACC deaminase, protease, cellulases competitive colonisers, tolerated salt	Shoot and root length, shoot, root and dry matter of wheat	[125]
<i>Acinetobacter calcoaceticus</i>	Rhizospheres of wheat.	P solubilization, siderophore IAA	Wheat growth, increase in the rate of germination, in the root length and dry weight	[106]
<i>Azospirillum brasilense</i>		N ₂ fixation	uptake of several macro and micronutrients	[5]
<i>Acinetobacter calcoaceticus</i> , <i>A. baumannii</i> , <i>A. lwoffii</i>		N ₂ fixation, siderophores, P solubilization	Root growth Root length	[45]
<i>Bacillus simplex</i> KBS1F-3, <i>Bacillus megaterium</i> NAS7-L, <i>Bacillus cereus</i> KFP9-F, <i>Paenibacillus alvei</i> NAS6G-6	Grass	IAA, siderophores P solubilization	Shoot and root Weight colonisation	[212]

PGPR	Source	Plant growth regulation	Results of addition of bacteria to plants	References
<i>Pseudomonas</i> sp.	Wheat	P solubilization, ACC deaminase, siderophores, IAA	Increased soil enzyme activities, total productivity, and nutrient uptake, nutrient assimilation	[102]
<i>Pseudomonas jessenii</i> R62; <i>Pseudomonas synxantha</i> R81 and arbuscular mycorrhizal fungi (AMF)	Wheat roots	P solubilization, IAA, siderophores, ACC deaminase, diacetyl-phloroglucinol	Grain yield Protein and mineral nutrient concentration (P, K, Cu, Fe, Zn, Mn) alkaline and acid phosphatase, urease, dehydrogenase.	[163]
<i>Pseudomonas putida</i> AKMP7	sorghum	Phytohormones (IAA, GA), HCN, ammonia, Siderophore, P-solubilization	Increased root, shoot length, dry biomass, chlorophyll content	[98]
<i>Bacillus</i> sp. (AW1), <i>Providencia</i> sp. (AW5), <i>Brevundimonas diminuta</i> (AW7)	Rhizosphere of wheat	P-solubilization, N ₂ fixation, ACC deaminase siderophore, ammonia, HCN	Seedling length, germination, plant height, panicle weight, root weight	[40]
<i>Pseudomonas fluorescens</i> 153 and 169, <i>P. putida</i> 4 and 108		ACC deaminase, IAA-like products, P solubilization	Height, tillers, number of grains/spike, grain and straw yield, N, P and K uptake	[54]
<i>Pseudomonas lurida</i>	Radish	P solubilization IAA, HCN, siderophores	Growth and nutrient uptake parameters	[64]
<i>Providencia</i> sp. PW5	Wheat rhizosphere	Ammonia siderophore, HCN, IAA, P solubilization Zn solubilization	N uptake in wheat grain. protein content grain Fe, Zn, Mn, and Cu content	[161]
<i>Pseudomonas fluorescens</i> MKB37	Barley	Siderophore ACC deaminase. Protease phytate	Grain number, weight and yield	[23]
<i>Azospirillum</i> sp., <i>Azotobacter</i> sp. <i>Bacillus megaterium</i>	Wheat	N ₂ fixation, P solubilization	Plant height, number spikes, grain yield, protein content	[213]
<i>Azospirillum brasilense</i>	Wheat	N ₂ fixation	Agronomic performance and yield of wheat	[35]
<i>P. fluorescens</i> and <i>Serratia</i> sp.	Rubus and wheat	P solubilization	Shoot length, root and shoot dry weight, P uptake	[214]
<i>Hallobacillus</i> sp. SL3, <i>Bacillus halodenitrificans</i> PU62	Naturally saline habitats	ACC deaminase, IAA, HCN, siderophores, P solubilization,	Seed germination, root length, root elongation, dry weight root biomass	[1]
<i>A. chroococcum</i> (W5), <i>Mesorhizobium ciceri</i> (F 75), <i>P. striata</i> (P27), <i>S. marcescens</i> (L11) <i>A. torulosa</i>		N ₂ fixation P solubilization,	Nutrient status of soil and plants, plant biomass, N and P uptake	[177]

PGPR	Source	Plant growth regulation	Results of addition of bacteria to plants	References
<i>Bacillus</i> OSU-142, <i>Bacillus</i> M3, <i>A. brasilense</i> sp. 245, <i>B. megaterium</i> RC07, <i>P. polymyxa</i> RC05, <i>B. licheniformis</i> RC08, <i>R. terrigena</i> , <i>B. cepacia</i> FS Tur		N ₂ fixation P solubilization	Grain and straw N content, root and shoot weight, grain and total biomass yield, protein content, grain weight per spike	[3]
<i>Bacillus</i> spp.	Rhizospheres of wheat and tomato	IAA, lipase, protease, siderophore, P solubilization salt tolerant	Germination, root length, root weight, panicle weight	[52]
<i>B. subtilis</i> IB-22 <i>B. subtilis</i> IB-21		Zeatin type cytokinins	Shoot concentrations of zeatin, total chlorophyll and nitrogen contents of wheat leaves	[90]
<i>Streptomyces</i> spp.	Wheat roots	P solubilization, phytase, chitinase, IAA, siderophore	Growth, biomass, Fe, Mn and P content antifungal activity	[43]
<i>P. brassicacearum</i> subsp. <i>brassicacearum</i> RZ310 <i>Pseudomonas</i> sp. PO283, <i>Pseudomonas</i> sp. PO366	Rhizosphere of wheat	IAA, ACC deaminase	Both coleoptiles and root elongation, root length, wheat seedling growth, growth and biomass of Wheat coleoptiles	[215]
<i>S.liquefaciens</i> , <i>S.</i> <i>marcescens</i> , <i>B.</i> <i>thuringiensis</i>	Wheat rhizosphere	Zn solubilizing	Enhance grain yield and Zn content of wheat	[160]
<i>Bacillus</i> sp., <i>Pseudomonas</i> , sp., <i>Arthrobacter</i> sp.	Wheat rhizosphere	P solubilization	Plant biomass P, K, Mg, Zn and Mn contents at harvest	[216]

Table 2. Examples of plant growth-promoting substances released by some commonly employed PGPR.

including auxins, cytokinins and gibberellins, and the synthesis of several enzymes, such as phosphatase and catalase, modulating plant growth and development as well as strengthening their immune system [16, 17]. In a review, Palacios et al. compiled many molecules facilitating interactions of PGPR with plants [18]. The list includes plant hormones, hydrolytic enzymes, antibiotics, flavonoids, other signal molecules, toxic molecules, siderophores, exopolysaccharide, volatiles, polyamines, lectins and vitamins. The PGPR efficiency, in turn, depends upon a number of factors like soil mineral content, type of crop and its genotype, specific PGPR strain and its combination with the plant, competition with indigenous strains, environmental conditions and the growth parameters evaluated, as illustrated in greenhouse and field trials [3] and other studies [19–22].

Despite the promising features from agronomic efficiency and crop yield perspective, the key bottleneck for the commercial use of PGPRs is their varying performance under field conditions: the results obtained in a field are not always similar to those of laboratory [23], which calls for immediate further research on the agricultural use of these PGPRs.

2. Mechanisms of plant growth promotion

2.1. Biological nitrogen fixation

PGPR improve plant growth by multiple mechanisms. A well-established mechanism is the biological nitrogen fixation (BNF), as described in extensive literature available on diazotrophic association in wheat and subsequent addition of nitrogen to the ecosystem [24], contributing to the total N_2 requirement of wheat [25–27]. Nitrogen fixation is considered to be a direct plant growth-promoting trait and the nitrogen-fixing rhizobacteria provide an alternative source to inorganic nitrogen fertilizers.

Azospirillum is a kind of nitrogen-fixing bacterium that lives in close association with plants in the rhizosphere. Its beneficial effects on wheat yields in both greenhouse and field conditions have been reported [28, 29]. Balandreau found that *Azospirillum lipoferum* inoculation increased yield around 1.8 t/ha and wheat grain by up to 30% [30, 31]; Okon and Labandera-Gonzalez by inoculation with *Azospirillum brasilense* [31]. In an earlier study, Boddey et al. were unable to observe fixed N in wheat from similar organisms [32]. Further, Ruppel and Merbach investigated the dinitrogen-fixing ability strain of *Pantoea agglomerans* and *Azospirillum* spp. and in hydroponic experiments with wheat found that bacterial strain inoculation affected plant growth, by nitrogen uptake and the amount of biologically fixed dinitrogen. In this sense, when *Azospirillum brasilense* is inoculated using seed inoculation, it increases the productivity of wheat [33–35]. *P. agglomerans*, as a diazotroph, is able to fix molecular N_2 with wheat [36]. Ruppel et al. reported *P. agglomerans* to be superior strain for winter wheat, reporting a grain yield increase for different wheat cultivars ([37], also in Ref. [38]). Moreover, a nitrogen-fixing *P. agglomerans* Lma2 was isolated from wheat rhizosphere, it was found to have the ability to produce IAA, siderophores and solubilize P, and growth performance of plant was significantly better in the presence of salt [39].

Acinetobacter strains also possessed BNF properties, siderophore and ammonia production as well as mineral solubilization. Rana et al. reported a positive correlation of BNF potential of *Providencia* spp. AW4 and *Brevundimonas diminuta* AW7 strains with panicle weight and plant height in wheat, indicating the enhancing plant growth role of BNF [40].

2.2. Phosphate solubilization and mineralization

Soil stores several structures and forms of phosphate, both organic and inorganic. Phosphorus plays a key role in photosynthesis, respiration, root development, signal transduction, energy transfer, macromolecular biosynthesis and the resistance ability of plants to diseases and adverse conditions. However, majority of soil phosphorus is insoluble that is not available to plants. The secondary significant contributing factor to promoted growth is the availability of phosphorous in the rhizospheric region, as a result of phosphate solubilization by the PGPR [41].

PGPRs serve as phosphate (and zinc) solubilizer (PSB). This is due to the decreased pH of the medium, indicating the possible involvement of organic acids such as gluconic acid. Plant growth promotion can be achieved through solubilization of inorganic phosphates by these

organic acids. de Werra et al. showed that this happens with not only gluconate but also malate [42, 43]. These results were consistent with earlier report on the P and Zn solubilizing properties of *Acinetobacter* sp. [44]. Nearly all the *Acinetobacter* species isolated from rhizosphere soil of the three wheat varieties in the present study were efficient phosphate and zinc solubilizers and produced iron chelating siderophores [45]. Phosphate solubilizing bacteria (PSB) belong largely to the genera pseudomonads, bacilli and rhizobia [46].

Phosphorus-solubilizing *Bacillus* strains have been reported to increase the plant biomass and yield of wheat as well as uptake of nutrients [47]. Similar results have been reported by Afzal et al. when a combination of nitrogen-fixing *Rhizobium leguminosarum* with P-solubilizing *Pseudomonas* sp. strain 54RB have been used [48]. Similarly, several *Pseudomonas* spp. strains have been tested in the field for their efficacy to increase growth and yield of wheat [49]. Four P solubilizer (*Arthrobacter* WP-2, *Bacillus* MP5, *Rhodococcus* M28 and *Serratia* 5D) and one phytohormone producer (*Azospirillum* WS1) strains tested as single-strain inocula resulted in improved growth of wheat plants [50]. Some *Bacillus* species can improve phosphate solubilization of the soil [51, 52]. On the other hand, Baig et al. reported a positive correlation between P-concentration in soil, P-solubilization activity of the *Bacillus* strains and P uptake by wheat plants [53]. Along the same line, improvement of growth and yield of wheat was observed and reported upon inoculation with P-solubilizing microorganisms. Both PGPR (*Bacillus* and *Pseudomonas* spp.) are similar in effectively solubilizing phosphate. A short list of phosphate-solubilizing bacteria (PSB) includes *P. fluorescens* 153, *P. fluorescens* 169, *P. putida* 4 and *P. putida* 108 together with their capability in natural soil ecosystem to synthesize ACC deaminase and IAA-like products [54].

Combined application of PSB with conventional fertilizer (50% PSB, 25 kg/ha P_2O_5) improves plant growth. Similarly, a combination of PGPRs are more effective when compared with isolated applications as reported by Hassan et al. for wheat crops and by Baig et al. for wheat yield and P uptake [53, 55].

2.2.1. Mineralization

Mineralization of most organic phosphorous compounds is carried out by means of phosphatase enzymes. The conversion of insoluble inorganic P to a form accessible by plants is achieved by PSB via organic acids, chelation and exchange reactions [56]. However, organic P forms, particularly phytates, are predominant in most soils (10–50% of total P) and must be mineralized by phytases (myo-inositol hexakisphosphate phosphohydrolases) to be available P for plants [57, 58]. Previous research has shown that *Bacillus* sp., *Providencia* sp., *Brevundimonas* and *Alcaligenes* were recorded positive for P solubilization [40, 59].

Singh et al. reported that phytase-producing bacteria from Himalayan soils showed ability to solubilize inorganic phosphate, producing phytase, siderophores, ammonia and IAA and increased availability of P, IAA and ammonia leading to increased plant growth [57]. The role of PGPR in production of phosphatases, β -glucanase, dehydrogenase, antibiotic, solubilization of phosphates and other nutrients, stabilization of soil aggregates, improved soil structure and organic matter contents has been recognized.

2.3. Production of plant hormones and other beneficial plant metabolite

There are five groups of plant hormones of well-known PGRs, namely auxins, gibberellins, cytokinins, ethylene and abscisic acid [60]. Direct plant growth promotion includes symbiotic and non-symbiotic PGPR, which functions through production of these plant hormones [11, 61–63]. Much attention has been given on the role of phytohormone auxin. Production of indole-3-ethanol or indole-3-acetic acid (IAA), the compounds belonging to auxins, which is known to stimulate in cell elongation, division and differentiation responses in plants, has been reported for several bacterial genera [12, 17, 64]. PGPR promote root growth by increasing root surface area, which, in turn, promotes nutrient uptake, thereby indirectly stimulating plant growth positively [52, 65]. Khalid et al. reported a correlation between *in vitro* auxin production and increase in early growth parameters of inoculated wheat seeds [66].

Inoculation with *A. brasilense* Cd and the application of pure IAA to the roots both increased root length, number of lateral roots and number of root hairs in wheat as observed by earlier workers [67, 68]. IAA-producing *Azospirillum* sp. also promoted alterations in the growth and development of wheat (*Triticum aestivum* L.) plants [69–72]. Bacteria of the *Azotobacter* genus synthesize auxins, cytokinins and GA-like substances, and these growth materials are the primary substances controlling the enhanced growth [73]. These hormonal substances, which originate from the rhizosphere or root surface, affect the growth of the closely associated higher plants. The highest concentration of IAA is produced by bacterial strain *P. fluorescens* and *Kocuria* varians [74]. Specifically for wheat, the positive effect of PGPR via IAA has been reported [75–78].

When applied in optimum concentrations, bacterial indole-3-acetic acid (IAA), synthesized by gram-positive and -negative, photosynthetic, methylotrophic and cyanobacteria, is reported to stimulate root hair formation, at the same time increasing the length and the number of primary and lateral roots [66, 72, 79]. IAA synthesis by these bacteria is reported to be affected by tryptophan, vitamins, salt and oxygen levels, as well as pH, temperature, carbon and nitrogen source. For example, IAA from *Azospirillum brasilense* Sp245 stimulates early plant development and increases significantly the plants and roots yield (in dry weight) and the N-uptake efficiency of wheat [71, 80]. The ability to synthesize ABA, particularly under stressful conditions, for example, salinity, and to affect the ABA level in plants was detected in PGPR from the genera *Azospirillum*, *Bacillus*, *Pseudomonas*, *Brevibacterium* and *Lysinibacillus* [15, 81, 82]. Both plants and bacteria can be synthesized via several pathways, including the indole-3-pyruvic acid (IPA), indole-3-acetamide (IAM) and indole-3-acetonitrile (IAN) pathways, which are often regulated by tryptophan, carbon and nitrogen availability, a reduction in growth rate and abiotic factors such as temperature, pH and oxygen [79].

As a PGPR application to wheat seedlings, Sachdev et al. reported that IAA producing *Klebsiella* strains significantly increased the root length and shoot height, when compared with the control, in pot experiments [83, 84]. Similarly, Khalid et al. reported up to 28% higher grain yields in wheat grown in field as a result of seed inoculation in peats with high auxin-producing rhizobacteria [66]. The capability of auxin synthesis detected in many bacterial strains from the genera *Azospirillum*, *Pseudomonas*, *Bacillus*, etc., is thought to underlie the activation of plant root growth by these microorganisms [81]. Sadeghi et al. demonstrated

that a *Streptomyces* isolate increased plant growth in wheat and produced indole acetic acid and auxin in presence of salt [85]. Phytohormone-producing *Bacillus* sp. and *B. subtilis* have potential at field level to improve wheat productivity and may be helpful in formulation of an effective biofertilizer for wheat [52, 79, 86–89]. A complete understanding of the IAA system can further mediate the efficient use of these PGPRs for biofertilizer.

Cytokinins can be produced by representative strains of *Bacillus*, *Rhizobium*, *Arthrobacter*, *Azotobacter*, *Azospirillum* and *Pseudomonas*. The plants inoculated with cytokinin-producing bacteria *B. subtilis* showed the increased chlorophyll content and cytokinin accumulation, which led to the increase in weight of shoots and roots [90, 91]. On the other hand, treatment of plant with a substance obtained from cytokinin-producing microorganisms, typically colonizing in wheat roots [92, 93], increased chlorophyll content in leaf; in this case, the level of chlorophyll was comparable to that observed in the plants treated with a synthetic cytokinin benzyladenine. Cytokinins can promote stomatal opening, stimulate shoot growth and decrease root growth.

2.3.1. Accumulation of osmolytes

Proline is a known osmoprotectant, promoting the protection of the plant from drought, salt and other stresses [94]. Alternative to proline accumulation, another defence strategy is to increase total soluble sugar level in plants under salinity stress. PGPRs have been demonstrated to enhance wheat stress tolerance via osmolyte accumulation as reported in Refs. [95–97]. Ali et al. used *P. putida* AKMP7 resulting in significant increase in proline levels in heat-stressed wheat plants [98].

Yegorenkova et al. suggested that lectin-carbohydrate interactions are involved in the initial stages of bacterial-plant root attachment [99]. Additionally, PGPR producing extracellular polymeric substance are reported to enhance greatly the soil volume macropores and the rhizosphere aggregation of soil, which results in increased water and fertiliser availability to plants [46].

2.4. Siderophore and exopolysaccharide production by PGPR

With its unique physico-chemical properties, iron (Fe) has a key role in plant growth, taking part in several metabolic pathways including TCA cycle, nitrogen fixation, respiration and ETC, oxidative phosphorylation and photosynthesis, biosynthetic regulation (chlorophyll, toxin, vitamins, antibiotic, cytochrome and pigment) and as cofactor for numerous enzymes [100]. Following this, iron deficiency (typically caused by low iron bioavailability) is frequently seen at elevated pH, alkali soils in dry regions, as well as in case of excessive fertilizer and pesticides application.

Siderophores are small iron carriers, chemically high-affinity iron chelating compounds secreted by PGPRs and are among the strongest soluble Fe³⁺ binding agents known. Comprehensive information on the role of siderophores in increasing iron oxide solubility and promoting dissolution in soils requires the consideration of the rates of various processes such as siderophore exudation, the uptake, and the degradation rates [101]. In BNF, siderophores are expected to play significant role, since in its very essence, nitrogenase requires Fe [102], also supported by a high correlation between N and Fe uptake.

Siderophore productions promote the crop growth, or protect the plant against pathogens. Produced by microorganisms, these are found in soil solutions and influence Fe nutrition of plants [103]. The role of siderophores has been reported as signalling molecules and as such, their use points to avenues for novel agricultural applications [54].

The wheat seed inoculation was tested for their effect on wheat in terms of healthier germination and productivity. The organisms used were siderophoregenic pyoverdinin-producing *Pseudomonas putida* and *Pseudomonas aeruginosa* strains from two diverse habitats. Inoculation with siderophoregenic PGPR increased percentage germination, shoot height, shoot and root length, weight of spikelets, chlorophyll content, grain yield and iron content [100, 104, 105]. Inoculated wheat plants showed increase in total iron uptake and physiologically available iron contents. *Acinetobacter calcoaceticus* obtained from wheat rhizosphere produces catechol type of siderophores during exponential phase, which is influenced by iron content of medium [106]. Ca, Cd and Mg ions and succinic acid stimulated the synthesis of the siderophore examined, whereas Zn and Pb ions partially decreased its level.

Some PGPR strains may also protect plants from salt and drought stress by producing exopolysaccharides (EPS), binding, in turn, Na⁺ or by biofilm formation [107]. Resultingly, reduced Na⁺ results in lower Na⁺ uptake and high K⁺/Na⁺ ratio, promoting survival in salt-stressed conditions [107, 108]. Another example is the wheat seedling inoculation by EPS producing strain of *Pantoea agglomerans* (NAS206) isolated from the wheat rhizosphere, growing in a Moroccan vertisol. It had a positive effect on aggregation and stabilization of root-adhering soil, by increased mean aggregate diameter and macroporosity [109].

2.5. PGPR and plant nutrient uptake

Seed inoculation with the bacterium has been found to improve the growth and nutrient uptake of wheat seedlings via promotion of the plant growth and increased root surface area or the general root architecture [110]. With enlarged root hairs, nutrient uptake is promoted [21, 71, 77, 111].

The PGPR effects also increase N and P uptake in field trials [112], presumably, by stimulating greater plant root growth. Both *A. chroococcum* and *P. agglomerans* were found to increase plant growth, plant dry matter, as well as N and P uptake [25, 113]. *Azospirillum*-inoculated plants under drought conditions had increased Mg, K and Ca contents compared to non-inoculated plants [62, 114–117]. The increase in nutrient accumulation/uptake due to biofertilizers/PGPR was previously reported in wheat [118–120]. Sharma et al. reported that the majority of 13 tested *Pseudomonas* spp. strains increased the macro (N, P, K and S) and micronutrients uptake (Cu, Fe, Zn and Mn) in wheat [102, 121].

Inoculation of efficient plant-growth-promoting actinobacterial *Streptomyces* species significantly improved the Fe, Mn and P content of wheat plants when compared with an uninoculated control [43, 105]. Yasin et al. investigated the effects of selenate fertilization and bacterial inoculation on Se uptake and plant growth [122]. They found that *Bacillus pichinotyi* enhanced wheat growth, dry weight, shoot length and spike length, Se and Fe concentration in wheat kernels and stems. Selenium (Se) is an essential trace element for humans [123], and

they reported that inoculation with rhizospheric microorganisms significantly enhanced wheat Se content.

2.6. Alleviation of abiotic stress in wheat by PGPR

Abiotic stress is the major cause of decreasing crop productivity worldwide. The application of the combination of PGPR and mycorrhizal fungi alleviates the stress conditions, as reported by Nadeem et al., via the regulation of hormones, nutrition uptake and growth [124]. Similar outcomes have been reported by Cakmakci et al. for wheat and spinach plants [77]. Enzymatic activities in the leaves of these plants such as glucose-6-phosphate dehydrogenase, 6-phosphogluconate dehydrogenase, glutathione reductase and glutathione S-transferase have been observed.

Additionally, numerous studies suggested that both IAA and ACC deaminase-producing bacteria protect plants most effectively, against a wide range of different stresses [125]. Notable reports among those are *Azospirillum* strains helping to cope with salt stress [126–128] and *Bacillus* and *Azospirillum* leading to improve heat tolerance in wheat [129].

2.6.1. Drought

Drought stress, exhibited as limited water supply, usually causes a severe loss in plant yield, where the combination of severity and duration are critical factors for plant survival [130]. The application of PGPR can counteract damaging effects of moisture stress, and therefore boost crop yields. Creus et al. reported that growing *Azospirillum brasilense* Sp245-primed wheat under drought stress conditions resulted in large increase in water content and potential, and apoplastic water function in both shoots and roots compared to the non-primed plants [62].

Moreover, Pereyra et al. reported that *Azospirillum* inoculation provided a better water status in wheat seedlings under osmotic stress due to morphological modifications of the coleoptile xylem architecture [131]. *Azospirillum*-inoculated wheat seedlings subjected to osmotic stress developed significant higher coleoptiles, with higher fresh weight and better water status than non-inoculated seedlings [132]. In this regard, ABA-producing bacteria *Azospirillum* promoted resistance of *Arabidopsis*, maize and wheat plants to soil drought [81]. *Azospirillum brasilense* INTA Az-39-inoculated wheat plants under typical dry land farming conditions exhibited better growth and increased vegetative growth, shoot and root dry matter accumulation, grain number and grain yield [133]. According to Arzanesh et al. results, inoculation of wheat with *Azospirillum* spp. can alleviate drought stress on plant growth and yield through adjusting plant water characters [134].

Inoculation of wheat with *Burkholderia phytofirmans* PsJN significantly diluted the adverse effects of drought on relative water contents and CO₂ assimilation rate, thus improving the photosynthetic rate, water use efficiency and chlorophyll content over the uninoculated control [135]. In a similar study conducted on wheat under water stress environment showed that mycorrhizal inoculation enhanced the activities of antioxidant enzymes such as peroxidase and catalase compared to those in uninoculated control plants [136]. Several other studies report similar outcomes [137].

2.6.2. Salinity

Salinity decreases the yield of many crops because salt inhibits plant photosynthesis, protein synthesis and lipid metabolism. Nutrient contents decrease in the roots and shoots with increasing NaCl concentration in the growth medium. PGPR counteract osmotic stress and help plant growth. Investigations on interaction of PGPR with other microbes and their effect on the physiological response of crop plants under different soil salinity regimes are still in incipient stage.

Rhizobacteria that are residing within the rhizosphere of plants growing in saline habitats may have already been adapted to salt stress that may be a valuable resource to develop crop inoculants. Raheem and Ali isolated rhizobacteria that were producing beneficial plant growth-promoting metabolites such as IAA and ACC-deaminase activity [138]. The isolation of indigenous microorganisms from the stress-affected soils and screening on the basis of their stress tolerance and PGP traits may be useful in the rapid selection of efficient strains that could be used as bio-inoculants for stressed crops [139, 140]. For several durum cultivars, PGPR efficacy in mitigating salt stress in tetraploid wheat is salt level and bacterial strain-specific [128, 141, 142]. There are some instances of ameliorating salt-stricken cereal crops by PGPR's. Salinity stress in the wheat was alleviated by inoculations with four strains of PGPR, *Pseudomonas fluorescens* 153, 169, *Pseudomonas putida* 108 and 4 [143]. Upadhyay et al. considered the impact of PGPR inoculation on the growth and antioxidant of wheat under saline conditions [46]. In a follow-up study, Upadhyay et al. investigated the effects of two salt-tolerant PGPR (*B. subtilis* and *Arthobacter* sp.) on wheat plants under different salinity regimes and the results obtained demonstrated alleviation of the salinity stress effects on plants treated with bacteria [97]. Similar outcome has been reported by Nia et al. for *Azospirillum* strains on wheat plants [144]. Several PGPR of the genus *Pseudomonas* contain ACC-deaminase enzyme, and when inoculated into plant roots may sustain plant growth under salinity [125, 142].

2.6.3. Mitigation of cold stress in wheat by PGPR

The over-wintering ability of PGPR is fundamental when considering uses in colder climates. De Freitas and Germida reported that *Pseudomonas* species are able to over-winter in sufficient quantities on the roots of winter wheat [145]. It has also been argued that antifreeze protein activity of many bacterial species may contribute to their survival in colder climates [146–148].

The effect of inoculation with 12 psychrotolerant *Pseudomona* strains on cold alleviation and growth of wheat seedling at cold temperature was investigated in Ref. [105]. Psychrotolerant PGPR inoculation improved metabolite levels, such as chlorophyll, anthocyanin, free proline, total phenolics, starch content, physiologically available iron, proteins and amino acids that are sign of alleviation of cold stress in wheat plants.

Higher chlorophyll content in leaves of cold acclimated winter wheat over control plants was also reported [105]. Proline is a dominant amino acid that accumulates in many organisms upon exposure to environmental stress and plays multiple roles in plant adaptation to stress. Also increased proline content in wheat plant at low temperature with the bacterial inoculation is an indication to chilling tolerance [105].

Turan et al. conducted greenhouse experiments in wheat and barley under cold stress conditions to determine the growth, freezing injury, antioxidant enzyme activity effect of four different rhizobacteria and boron [149]. The authors showed that boron+PGPR treatments have positive effect on root and shoot growth, H_2O_2 , and SOD, POD and CAT antioxidant enzyme activities of wheat and barley plants under cold and control conditions. This suggests that the PGPR application can ameliorate the deleterious effects of cold stress by increasing chlorophyll content, photosynthetic activity and relative water content, altering mineral uptake, and decreasing membrane damage, increasing cold tolerance in wheat and barley.

2.6.4. Metal stress tolerance in wheat

Plant growth-promoting bacteria are able to also grow in heavy metal-contaminated environment and protect plants against heavy metals toxicity in contaminated soils [150, 151]. Hasnain and Sabri reported that upon *Pseudomonas* sp. inoculation of wheat in Pakistan, growth was stimulated, less toxic ions were taken up and increased auxin content was observed [152].

Under Cr stress conditions, Shahzadi et al. reported root length, shoot length, root dry weight and shoot dry weight, respectively, as compared to uninoculated control plants upon inoculation of wheat seeds with *Pseudomonas fluorescens* Q14 and *Bacillus thuringiensis* KAP5 [153]. In this context, ACC-deaminase producing PGPR could play vital role in improving the plant growth under metal-stress condition and they may enhance bioremediation process in Cr-contaminated environment. Similarly, Jamali et al. studied the relationship of bacterial Cr mobilization in soil with total Cr accumulation in wheat [154]. Hassan et al. reported that inoculation with PGPR decreased the deleterious effects of cadmium pollution by chelating and influencing its bioavailability and increased the wheat growth [155]. Singh et al. found that PGPR having ACC-deaminase activity were resistant against Cd, Cr, Pb and Cu toxicity, and increased the wheat and pigeon pea growth [156]. Consequently, uses of rhizospheric microorganisms are generally considered as safe, cost effective and reliable technique for elimination of heavy metals from environmental compartments [150, 157, 158]. Govindasamy et al. observed that growth-promoting ability of rhizobacteria containing ACC deaminase in wheat seedlings through modulation of stress ethylene synthesis enhanced root elongation significantly and minimized ethylene synthesis in wheat seedlings under induced cadmium stress condition [159].

2.7. Improve yield and quality of wheat

Beneficial rhizobacteria associated with cereals has increased recently and several studies clearly demonstrated the positive and beneficial effects of PGPR on growth and yield of wheat at different environment under variable ecological conditions (Turan et al., 2010).

Zn solubilizing rhizobacteria significantly influenced the growth, yield and Zn concentration of wheat grain over uninoculated control and Zn fertilizer [160, 161]. Similarly, increased nutrient concentrations in wheat due to inoculation were reported in Refs. [5, 118, 162–165]. It is pointed out by Mäder et al. that microbial inoculants have been shown to be a valid option for sustainable high quality wheat production in low-input areas, promising to improve the nutritional status and health of the rural population [163]. In a survey of 20 years of experiments, Okon

and Labandera-Gonzalez reported that 60–70% of the experiments showed yield increases due to inoculation, with statistically significant increases in yield from 5 to 30% [31].

Pseudomonas strains significantly increased grain yield of wheat [23, 49, 143, 166]. Similarly, Shaharoon et al. reported that N use efficiency increased in response to inoculation with *Pseudomonas fluorescens* at all fertilizer levels in wheat [167]. PGPR isolates significantly increased shoot and root length, shoot and root dry weight, grain weight per spike, shoot and root N content and also enhanced the N contents of inoculated wheat seedlings [168]. Barneix et al. reported that inoculation of wheat with *Bacillus simplex* and *Bacillus firmis* resulted in consistent increase in dry matter and wheat grain quality. A number of other *Bacillus* spp. isolated from wheat rhizosphere have also been investigated for their growth-promoting property in wheat having similar effects on dry weight [10, 40, 169], the latter focusing on isolating and characterizing PGPRs. Trials with rhizosphere-associated plant growth-promoting N₂-fixing and P-solubilising *Bacillus* and other species indicated yield increases in many crops such as wheat [43, 51, 170, 171]. In wheat, several rhizobacteria have been reported as improving grain yield, grain protein concentration or both [3, 135, 140, 164, 172].

3. Co-inoculation of multiple PGPRs

Inoculation with mixed different strains could be an alternative to inoculation with individual strains, likely reflecting the different mechanisms used by each strain in the consortium [173]. Combined inoculation with N₂-fixing and phosphate solubilizing bacteria were more effective than a single microorganism for providing a more balanced nutrition for plants [19, 174]. There are numerous examples in wheat whereby synergistic effects of multiple PGPRs are observed [97, 175, 176]. Among those, notable is the combined inoculation of mixtures and biofilmed bio-inoculants (*Anabaena torulosa* + *Pseudomonas striata* and/or *Anabaena torulosa* + *Azotobacter chroococcum*) were superior over single inoculation and chemical fertilizer control in term of plant growth and nutrient uptake [177]. The benefits can be on nutrient uptake, but also in root physiology as exemplified by Manjunath et al. as co-inoculation of wheat with two proteobacterial (*Providencia* sp. and *Alcaligenes* sp.) and two cyanobacterial (*Anabaena oscillarioides* and *Anabaena torulosa*) inoculants, similarly in Ref. [178, 179].

Seed bacterization with both strains, *P. fluorescens* BAM-4 and *B. cepacia* BAM-12 single or combined significantly enhanced growth and yield, but increase in bacterial population, spike length, P content of shoots and grain yield was more in co-inoculation treatment than single. The best among the bioinoculation treatments was *B. cepacia* BAM-12 + TCP and *B. cepacia* BAM-12 + *P. fluorescens* BAM-4 + TCP for P content with free and immobilized cells [180].

Several authors conducted experiments on wheat either under pot and field conditions to examine the effect of co-inoculations of PGPR on the growth and yield of wheat. Kumar et al. found that *B. megaterium*, *A. chlorophenolicus* and *Enterobacter* significantly increased plant height, grain yield and straw yield [181]; Baris et al. concluded that *Bacillus megaterium* M3 and Mixed (*Bacillus subtilis* 05U142, *B. megaterium* M3, *Azospirillum brasilense* Sp245) inoculation provided greater plant nutrient element concentrations than mineral fertilizer application

[182]. Similar outcomes also compared with chemically fertilized soils are reported in Refs. [53, 183–185].

Nowadays, there is a greater awareness to use biological components such as PGPR and mycorrhizal fungi as a component of integrated nutrient management strategies to obtain higher input use efficiency, to maintain the desired productivity through optimization of the benefits from all possible sources, to cope with increasing fertilizer costs and their long-term adverse effects on agricultural ecosystems such as increased nutritional imbalances, declining productivity, adverse conditions prevailing in this ecosystem, and or a combination of these factors, as reported in Refs. [113, 177]. Note that some PGPR inoculants may adversely affect mutualistic associations between plants and indigenous soil microorganisms and suggest a possible reason as to why spring wheat growth was not consistently enhanced by these *pseudomonad* PGPR [186]. Co-inoculation of *Azotobacter* and *Mycorrhiza* increased grain yield and yield components of wheat [187].

Wheat rhizobacterial community structure is highly dynamic and influenced by different factors such as wheat cultivar line ages, plant's age, growth stage, distance from the soil to the root, root exudation pattern, multiple soil properties and agronomic practises [162, 188, 189]. Roesti et al. employed a consortia formed by a PGPR *Pseudomonas* spp. and an indigenous AMF to study their effect on the bacterial community structure and wheat growth [162].

All in all, greater attention should be paid to new combinations of different types and properties organisms such as N₂-fixing and P-solubilizing bacteria for improvement of biofertilizers efficiency [19].

4. PGPR reduce chemical fertilization

Due to high cost of chemical fertilizers and negative environmental effects, the use of PGPR as biofertilizer is advantageous for development of sustainable agriculture, increasing agronomic efficiency, once the use of chemical fertilizers can be reduced or eliminated if the inoculants are efficient [6]. The use of bio-fertilizers with a good management can decrease the leaching loss of nitrate and phosphate from the agricultural land and improve the ground water quality [190]. Also, the use of PGPR with low-fertilizer rate is also an environment friendly step and would be a viable supplementary strategy for further increasing crop yields [71, 78, 191].

Trials conducted under greenhouse conditions showed that most of PGPR in the absence of any fertilizer application achieved increases in root and shoot weight [3], corresponding to nitrogen treatment at the rate of 40 and 80 kg N ha⁻¹ in wheat. Furthermore, co-inoculation of N₂-fixing and P-solubilizing bacteria always gave equal or higher grain yield than conventional application of nitrogen.

Rosas et al. studied the promotion effect of *Pseudomonas aurantiaca* SR1 on maize and wheat in field treatments that included phosphorus and nitrogen fertilization [166]. Both crops, when inoculated with the SR1 strain, presented significant promoting effect in growth parameters and higher yields with lower fertilization doses than conventionally applied. Additionally,

PGPR are also important with respect to an efficient use of resources such as P and N, as illustrated by a 95% increased P use efficiency of wheat grains [163].

It could be concluded that application of PGPR with low-fertilizer rates could be a viable supplementary strategy for maximum benefits and should be employed with appropriate doses of fertilizers to get maximum benefit in terms of fertilizer savings and better growth in any yield of crops. Experiments as field trials with dry land areas, the co-inoculations of PGPR strains for wheat, maize and barley with chemical fertilizers gave improved response [3, 183, 192–197].

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References

- [1] Ramadoss D, Lakkineni VK, Bose P, Ali S, Annapurna K. Mitigation of salt stress in wheat seedlings by halotolerant bacteria isolated from saline habitats. SpringerPlus. 2013;2(1):1.
- [2] Chauhan A, Shirkot C, Kaushal R, Rao D. Plant Growth-Promoting Rhizobacteria of Medicinal Plants in NW Himalayas: Current Status and Future Prospects. Plant-Growth-Promoting Rhizobacteria (PGPR) and Medicinal Plants: Chapter 19. Soil Biology, Springer International Publishing Switzerland ; 2015. pp. 381–412.

- [3] Cakmakci R, Turan M, Gulluce M, Sahin F. Rhizobacteria for reduced fertilizer inputs in wheat (*Triticum aestivum* spp. vulgare) and barley (*Hordeum vulgare*) on Aridisols in Turkey. *International Journal of Plant Production*. 2014;8(2):163-182.
- [4] Adesemoye A, Torbert H, Kloepper J. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. *Microbial Ecology*. 2009;58(4):921–9.
- [5] Hungria M, Campo RJ, Souza EM, Pedrosa FO. Inoculation with selected strains of *Azospirillum brasilense* and *A. lipoferum* improves yields of maize and wheat in Brazil. *Plant and Soil*. 2010;331(1–2):413–25.
- [6] Souza Rd, Ambrosini A, Passaglia LM. Plant growth-promoting bacteria as inoculants in agricultural soils. *Genetics and Molecular Biology*. 2015;8(4):401-419.
- [7] Kloepper J, Schroth M, Miller T. Effects of rhizosphere colonization by plant growth-promoting rhizobacteria on potato plant development and yield. *Phytopathology*. 1980;70(11):1078–82.
- [8] Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*. 2003;255(2):571–86.
- [9] Sharma MP, Srivastava K, Sharma SK. Biochemical characterization and metabolic diversity of soybean rhizobia isolated from Malwa region of Central India. *Plant Soil and Environment*. 2010;56(8):375–83.
- [10] Chanway C, Nelson L, Holl F. Cultivar-specific growth promotion of spring wheat (*Triticum aestivum* L.) by coexistent *Bacillus* species. *Canadian Journal of Microbiology*. 1988;34(7):925–9.
- [11] Narula N, Deubel A, Gans W, Behl R, Merbach W. Paranodules and colonization of wheat roots by phytohormone producing bacteria in soil. *Plant Soil and Environment*. 2006;52(3):119.
- [12] Hayat R, Ali S, Amara U, Khalid R, Ahmed I. Soil beneficial bacteria and their role in plant growth promotion: a review. *Annals of Microbiology*. 2010;60(4):579–98.
- [13] Bhattacharyya P, Jha D. Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. *World Journal of Microbiology and Biotechnology*. 2012;28(4):1327–50.
- [14] Pérez-Montaña F, Alías-Villegas C, Bellogín R, Del Cerro P, Espuny M, Jiménez-Guerrero I, et al. Plant growth promotion in cereal and leguminous agricultural important plants: from microorganism capacities to crop production. *Microbiological Research*. 2014;169(5):325–36.
- [15] Maksimov I, Veselova S, Nuzhnaya T, Sarvarova E, Khairullin R. Plant growth-promoting bacteria in regulation of plant resistance to stress factors. *Russian Journal of Plant Physiology*. 2015;62(6):715–26.
- [16] Glick BR. Plant growth-promoting bacteria: mechanisms and applications. *Hindawi Publishing Corporation Scientifica*. 2012, 1-15, Article ID 963401.

- [17] Frankenberger J, Arshad M. Microbial synthesis of auxins. *Phytohormones in soils*. Marcel Dekker, New York. 1995. pp. 35–71.
- [18] Palacios OA, Bashan Y, de-Bashan LE. Proven and potential involvement of vitamins in interactions of plants with plant growth-promoting bacteria—an overview. *Biology and Fertility of Soils*. 2014;50(3):415–32.
- [19] Şahin F, Çakmakçı R, Kantar F. Sugar beet and barley yields in relation to inoculation with N₂-fixing and phosphate solubilizing bacteria. *Plant and Soil*. 2004;265(1–2):123–9.
- [20] Çakmakçı R, Dönmez F, Aydın A, Şahin F. Growth promotion of plants by plant growth-promoting rhizobacteria under greenhouse and two different field soil conditions. *Soil Biology and Biochemistry*. 2006;38(6):1482–7.
- [21] Çakmakçı R, Dönmez MF, Erdoğan Ü. The effect of plant growth promoting rhizobacteria on barley seedling growth, nutrient uptake, some soil properties, and bacterial counts. *Turkish Journal of Agriculture and Forestry*. 2007;31(3):189–99.
- [22] Çakmakçı R, Dönmez MF, Ertürk Y, Erat M, Haznedar A, Sekban R. Diversity and metabolic potential of culturable bacteria from the rhizosphere of Turkish tea grown in acidic soils. *Plant and Soil*. 2010;332(1–2):299–318.
- [23] Smyth E, McCarthy J, Nevin R, Khan M, Dow J, O’Gara F, et al. In vitro analyses are not reliable predictors of the plant growth promotion capability of bacteria; a *Pseudomonas fluorescens* strain that promotes the growth and yield of wheat. *Journal of Applied Microbiology*. 2011;111(3):683–92.
- [24] Döbereiner J, editor *Biological N₂ fixation by endophytic diazotrophs in non-leguminous crops in the tropics*. Abstr 7th Int Symp BNF with Non-legumes; 1996.
- [25] Islam N, Rao C, Kennedy I. Facilitating a N₂-fixing symbiosis between diazotrophs and wheat. *Biofertilisers in action*. Rural Industries Research and Development Corporation, Canberra. 2002. pp. 84–93.
- [26] Iniguez AL, Dong Y, Triplett EW. Nitrogen fixation in wheat provided by *Klebsiella pneumoniae* 342. *Molecular Plant-Microbe Interactions*. 2004;17(10):1078–85.
- [27] Venieraki A, Dimou M, Pergalis P, Kefalogianni I, Chatzipavlidis I, Katinakis P. The genetic diversity of culturable nitrogen-fixing bacteria in the rhizosphere of wheat. *Microbial Ecology*. 2011;61(2):277–85.
- [28] Hegazi N, Fayez M, Amin G, Hamza M, Abbas M, Youssef H, et al. *Diazotrophs associated with non-legumes grown in sandy soils. Nitrogen fixation with non-legumes*: Springer; 1998. pp. 209–22.
- [29] Ganguly T, Jana A, Moitra D. An evaluation of agronomic potential of *Azospirillum brasilense* and *Bacillus megaterium* in fibre-legume-cereal system in an Aeric Haplaquept. *Indian Journal of Agricultural Research*. 1999;33(1):35–9.

- [30] Balandreau J. The spermosphere model to select for plant growth promoting rhizobacteria. Biofertilisers in Action Rural Industries Research and Development Corporation, Canberra. 2002. pp. 55–63.
- [31] Okon Y, Labandera-Gonzalez CA. Agronomic applications of Azospirillum: an evaluation of 20 years worldwide field inoculation. Soil Biology and Biochemistry. 1994;26(12):1591–601.
- [32] Boddey RM, Baldani VL, Baldani JL, Döbereiner J. Effect of inoculation of Azospirillum spp. on nitrogen accumulation by field-grown wheat. Plant and Soil. 1986;95(1):109–21.
- [33] Santa O, Santa H, Fernández R, Michela G, Ronzelli P, Soccol C. Influence of Azospirillum sp. inoculation in wheat, barley and oats Rev Setor Ciênc Agrárias Ambientais. 2008;4(2):197–207.
- [34] Piccinin GG, Dan LGdM, de LE Braccini A. Agronomic Efficiency of Azospirillum brasilense in physiological parameters and yield components in wheat crop. Journal of Agronomy. 2011;10(4):132–5.
- [35] Piccinin GG, Braccini AL, Dan LG, Scapim CA, Ricci TT, Bazo GL. Efficiency of seed inoculation with Azospirillum brasilense on agronomic characteristics and yield of wheat. Industrial Crops and Products. 2013;43:393–7.
- [36] Merbach W, Ruppel S, Schulze J. Dinitrogen fixation of microbe-plant associations as affected by nitrate and ammonium supply. Isotopes in Environmental and Health Studies. 1998;34(1–2):67–73.
- [37] Ruppel S, Hecht-Buchholz C, Remus R, Ortmann U, Schmelzer R. Settlement of the diazotrophic, phytoeffective bacterial strain Pantoea agglomerans on and within winter wheat: an investigation using ELISA and transmission electron microscopy. Plant and Soil. 1992;145(2):261–73.
- [38] Remus R, Ruppel S, Jacob H-J, Hecht-Buchholz C, Merbach W. Colonization behaviour of two enterobacterial strains on cereals. Biology and Fertility of Soils. 2000;30(5–6):550–7.
- [39] Silini-Cherif H, Silini A, Ghoul M, Yadav S. Isolation and characterization of plant growth promoting traits of a rhizobacteria: Pantoea agglomerans lma2. Pakistan Journal of Biological Sciences. 2012;15(6):267.
- [40] Rana A, Saharan B, Joshi M, Prasanna R, Kumar K, Nain L. Identification of multi-trait PGPR isolates and evaluating their potential as inoculants for wheat. Annals of Microbiology. 2011;61(4):893–900.
- [41] Jones DL, Darrah PR. Role of root derived organic acids in the mobilization of nutrients from the rhizosphere. Plant and Soil. 1994;166(2):247–57.
- [42] de Werra P, Péchy-Tarr M, Keel C, Maurhofer M. Role of gluconic acid production in the regulation of biocontrol traits of *Pseudomonas fluorescens* CHA0. Applied and Environmental Microbiology. 2009;75(12):4162–74.

- [43] Jog R, Pandya M, Nareshkumar G, Rajkumar S. Mechanism of phosphate solubilization and antifungal activity of *Streptomyces* spp. isolated from wheat roots and rhizosphere and their application in improving plant growth. *Microbiology*. 2014;160(4):778–88.
- [44] Indiragandhi P, Anandham R, Madhaiyan M, Sa T. Characterization of plant growth-promoting traits of bacteria isolated from larval guts of diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae). *Current Microbiology*. 2008;56(4):327–33.
- [45] Sachdev D, Nema P, Dhakephalkar P, Zinjarde S, Chopade B. Assessment of 16S rRNA gene-based phylogenetic diversity and promising plant growth-promoting traits of *Acinetobacter* community from the rhizosphere of wheat. *Microbiological Research*. 2010;165(8):627–38.
- [46] Upadhyay S, Singh J, Singh D. Exopolysaccharide-producing plant growth-promoting rhizobacteria under salinity condition. *Pedosphere*. 2011;21(2):214–22.
- [47] Chen Y, Rekha P, Arun A, Shen F, Lai W-A, Young C. Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. *Applied Soil Ecology*. 2006;34(1):33–41.
- [48] Afzal A, Ashraf M, Asad SA, Farooq M. Effect of phosphate solubilizing microorganisms on phosphorus uptake, yield and yield traits of wheat (*Triticum aestivum* L.) in rainfed area. *International Journal of Agriculture and Biology*. 2005;7:207–9.
- [49] Shaharoona B, Jamro G, Zahir Z, Arshad M, Memon K. Effectiveness of various *Pseudomonas* spp. and *Burkholderia caryophylli* containing ACC-Deaminase for improving growth and yield of wheat (*Triticum aestivum* L.). *Journal of Microbiology and Biotechnology*. 2007;17(8):1300.
- [50] Basheer A, Zaheer A, Qaisrani MM, Rasul G, Yasmin S, Mirza MS. Development of DNA markers for detection of inoculated bacteria in the rhizosphere of wheat (*Triticum aestivum* L.). *Pakistan Journal of Agriculture Science*. 2016;53(1):135–42.
- [51] Turan M, Gulluce M, von Wirén N, Sahin F. Yield promotion and phosphorus solubilization by plant growth-promoting rhizobacteria in extensive wheat production in Turkey. *Journal of Plant Nutrition and Soil Science*. 2012;175(6):818–26.
- [52] Baghaee Ravari S, Heidarzadeh N. Isolation and characterization of rhizosphere auxin producing *Bacilli* and evaluation of their potency on wheat growth improvement. *Archives of Agronomy and Soil Science*. 2014;60(7):895–905.
- [53] Baig KS, Arshad M, Shaharoona B, Khalid A, Ahmed I. Comparative effectiveness of *Bacillus* spp. possessing either dual or single growth-promoting traits for improving phosphorus uptake, growth and yield of wheat (*Triticum aestivum* L.). *Annals of Microbiology*. 2012;62(3):1109–19.
- [54] Zabihi H, Savaghebi G, Khavazi K, Ganjali A, Miransari M. *Pseudomonas* bacteria and phosphorous fertilization, affecting wheat (*Triticum aestivum* L.) yield and P uptake under greenhouse and field conditions. *Acta Physiologiae Plantarum*. 2011;33(1):145–52.

- [55] Hassan TU, Bano A. Role of carrier-based biofertilizer in reclamation of saline soil and wheat growth. *Archives of Agronomy and Soil Science*. 2015;61(12):1719–31.
- [56] Pandey A, Trivedi P, Kumar B, Palni LMS. Characterization of a phosphate solubilizing and antagonistic strain of *Pseudomonas putida* (B0) isolated from a sub-alpine location in the Indian Central Himalaya. *Current Microbiology*. 2006;53(2):102–7.
- [57] Singh P, Kumar V, Agrawal S. Evaluation of phytase producing bacteria for their plant growth promoting activities. *International Journal of Microbiology*. 2014.
- [58] Richardson A, Hadobas P, Hayes J, O'hara C, Simpson R. Utilization of phosphorus by pasture plants supplied with myo-inositol hexaphosphate is enhanced by the presence of soil micro-organisms. *Plant and Soil*. 2001;229(1):47–56.
- [59] Forchetti G, Masciarelli O, Alemano S, Alvarez D, Abdala G. Endophytic bacteria in sunflower (*Helianthus annuus* L.): isolation, characterization, and production of jasmonates and abscisic acid in culture medium. *Applied Microbiology and Biotechnology*. 2007;76(5):1145–52.
- [60] Zahir ZA, Arshad M, Frankenberger WT. Plant growth promoting rhizobacteria: applications and perspectives in agriculture. *Advances in Agronomy*. 2003;81:97–168.
- [61] Dobbelaere S, Vanderleyden J, Okon Y. Plant growth-promoting effects of diazotrophs in the rhizosphere. *Critical Reviews in Plant Sciences*. 2003;22(2):107–49.
- [62] Creus CM, Sueldo RJ, Barassi CA. Water relations and yield in *Azospirillum*-inoculated wheat exposed to drought in the field. *Canadian Journal of Botany*. 2004;82(2):273–81.
- [63] Etesami H, Alikhani HA, Jadidi M, Aliakbari A. Effect of superior IAA producing rhizobia on N, P, K uptake by wheat grown under greenhouse condition. *World Applied Sciences Journal*. 2009;6:1629–33.
- [64] Selvakumar G, Joshi P, Suyal P, Mishra PK, Joshi GK, Bisht JK, et al. *Pseudomonas lurida* M2RH3 (MTCC 9245), a psychrotolerant bacterium from the Uttarakhand Himalayas, solubilizes phosphate and promotes wheat seedling growth. *World Journal of Microbiology and Biotechnology*. 2011;27(5):1129–35.
- [65] Egorshina A, Khairullin R, Sakhabutdinova A, Luk'yantsev M. Involvement of phytohormones in the development of interaction between wheat seedlings and endophytic *Bacillus subtilis* strain 11BM. *Russian Journal of Plant Physiology*. 2012;59(1):134–40.
- [66] Khalid A, Arshad M, Zahir Z. Screening plant growth-promoting rhizobacteria for improving growth and yield of wheat. *Journal of Applied Microbiology*. 2004;96(3):473–80.
- [67] Harari A, Kigel J, Okon Y. Involvement of IAA in the interaction between *Azospirillum brasilense* and *Panicum miliaceum* roots. *Nitrogen fixation with non-legumes*: Springer; 1989. pp. 227–34.
- [68] Martin P, Glatzle A, Kolb W, Omay H, Schmidt W. N₂-fixing bacteria in the rhizosphere: Quantification and hormonal effects on root development. *Zeitschrift für Pflanzenernährung und Bodenkunde*. 1989;152(2):237–45.

- [69] Dobbelaere S, Croonenborghs A, Thys A, Broek AV, Vanderleyden J. Phytostimulatory effect of *Azospirillum brasilense* wild type and mutant strains altered in IAA production on wheat. *Plant and Soil*. 1999;212(2):153–62.
- [70] Akbari GA, Arab SM, Alikhani H, Allakdadi I, Arzanesh M. Isolation and selection of indigenous *Azospirillum* spp. and the IAA of superior strains effects on wheat roots. *World Journal of Agricultural Sciences*. 2007;3(4):523–9.
- [71] Spaepen S, Dobbelaere S, Croonenborghs A, Vanderleyden J. Effects of *Azospirillum brasilense* indole-3-acetic acid production on inoculated wheat plants. *Plant and Soil*. 2008;312(1-2):15–23.
- [72] Baudoin E, Lerner A, Mirza MS, El Zemrany H, Prigent-Combaret C, Jurkevich E, et al. Effects of *Azospirillum brasilense* with genetically modified auxin biosynthesis gene *ipdC* upon the diversity of the indigenous microbiota of the wheat rhizosphere. *Research in Microbiology*. 2010;161(3):219–26.
- [73] Mrkovacki N, Milic V. Use of *Azotobacter chroococcum* as potentially useful in agricultural application. *Annals of Microbiology*. 2001;51(2):145–58.
- [74] Egamberdieva D. Plant growth promoting properties of rhizobacteria isolated from wheat and pea grown in loamy sand soil. *Turkish Journal of Biology*. 2008;32(1):9–15.
- [75] Leinhos V, Vacek O. Biosynthesis of auxins by phosphate-solubilizing rhizobacteria from wheat (*Triticum aestivum* and rye (*Secale cereale*). *Microbiological Research*. 1994;149(1):31–5.
- [76] Hafeez FY, Yasmin S, Ariani D, Zafar Y, Malik KA. Plant growth-promoting bacteria as biofertilizer. *Agronomy for Sustainable Development*. 2006;26(2):143–50.
- [77] Çakmakçı R, Erat M, Erdoğan Ü, Dönmez MF. The influence of plant growth-promoting rhizobacteria on growth and enzyme activities in wheat and spinach plants. *Journal of Plant Nutrition and Soil Science*. 2007;170(2):288–95.
- [78] Abbasi M, Sharif S, Kazmi M, Sultan T, Aslam M. Isolation of plant growth promoting rhizobacteria from wheat rhizosphere and their effect on improving growth, yield and nutrient uptake of plants. *Plant Biosystems*. 2011;145(1):159–68.
- [79] Duca D, Lorv J, Patten CL, Rose D, Glick BR. Indole-3-acetic acid in plant-microbe interactions. *Antonie Van Leeuwenhoek*. 2014;106(1):85–125.
- [80] Kucey R. Alteration of size of wheat root systems and nitrogen fixation by associative nitrogen-fixing bacteria measured under field conditions. *Canadian Journal of Microbiology*. 1988;34(6):735–9.
- [81] Dodd I, Zinovkina N, Safronova V, Belimov A. Rhizobacterial mediation of plant hormone status. *Annals of Applied Biology*. 2010;157(3):361–79.
- [82] Belimov AA, Dodd IC, Safronova VI, Dumova VA, Shaposhnikov AI, Ladatko AG, et al. Absciscic acid metabolizing rhizobacteria decrease ABA concentrations in planta and alter plant growth. *Plant Physiology and Biochemistry*. 2014;74:84–91.

- [83] Sachdev DP, Chaudhari HG, Kasture VM, Dhavale DD, Chopade BA. Isolation and characterization of indole acetic acid (IAA) producing *Klebsiella pneumoniae* strains from rhizosphere of wheat (*Triticum aestivum*) and their effect on plant growth. *Indian Journal of Experimental Biology*. 2009;47(12):993.
- [84] Bothe H, Körsgen H, Lehmacher T, Hundeshagen B. Differential effects of Azospirillum, auxin and combined nitrogen on the growth of the roots of wheat. *Symbiosis*. 1992;13(1-3):167–79.
- [85] Sadeghi A, Karimi E, Dahaji PA, Javid MG, Dalvand Y, Askari H. Plant growth promoting activity of an auxin and siderophore producing isolate of *Streptomyces* under saline soil conditions. *World Journal of Microbiology and Biotechnology*. 2012;28(4):1503–9.
- [86] Ahemad M, Kibret M. Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. *Journal of King Saud University-Science*. 2014;26(1):1–20.
- [87] Selvakumar G, Kundu S, Gupta AD, Shouche YS, Gupta HS. Isolation and characterization of nonrhizobial plant growth promoting bacteria from nodules of Kudzu (*Pueraria thunbergiana*) and their effect on wheat seedling growth. *Current microbiology*. 2008;56(2):134–9.
- [88] Fatima Z, Saleemi M, Zia M, Sultan T, Aslam M, Rehman R, et al. Antifungal activity of plant growth-promoting rhizobacteria isolates against *Rhizoctonia solani* in wheat. *African Journal of Biotechnology*. 2009;8(2).
- [89] Ali B, Sabri AN, Hasnain S. Rhizobacterial potential to alter auxin content and growth of *Vigna radiata* (L.). *World Journal of Microbiology and Biotechnology*. 2010;26(8):1379–84.
- [90] Kudoyarova GR, Melentiev AI, Martynenko EV, Timergalina LN, Arkhipova TN, Shendel GV, et al. Cytokinin producing bacteria stimulate amino acid deposition by wheat roots. *Plant Physiology and Biochemistry*. 2014;83:285–91.
- [91] Arkhipova T, Prinsen E, Veselov S, Martinenko E, Melentiev A, Kudoyarova G. Cytokinin producing bacteria enhance plant growth in drying soil. *Plant and Soil*. 2007;292(1–2):305–15.
- [92] Arkhipova T, Veselov S, Melentiev A, Martynenko E, Kudoyarova G. Ability of bacterium *Bacillus subtilis* to produce cytokinins and to influence the growth and endogenous hormone content of lettuce plants. *Plant and Soil*. 2005;272(1–2):201–9.
- [93] Kuz'mina LY, Melent'ev A. The effect of seed bacterization by *Bacillus Cohn* bacteria on their colonization of the spring wheat rhizosphere. *Microbiology*. 2003;72(2):230–5.
- [94] Peng YL, Gao ZW, Gao Y, Liu GF, Sheng LX, Wang DL. Eco-physiological characteristics of Alfalfa seedlings in response to various mixed salt-alkaline stresses. *Journal of Integrative Plant Biology*. 2008;50(1):29–39.
- [95] Zarea M, Hajinia S, Karimi N, Goltapeh EM, Rejali F, Varma A. Effect of *Piriformospora indica* and *Azospirillum* strains from saline or non-saline soil on mitigation of the effects of NaCl. *Soil Biology and Biochemistry*. 2012;45:139–46.

- [96] Bashan Y. Interactions of *Azospirillum* spp. in soils: a review. *Biology and Fertility of Soils*. 1999;29(3):246–56.
- [97] Upadhyay SK, Singh JS, Saxena AK, Singh DP. Impact of PGPR inoculation on growth and antioxidant status of wheat under saline conditions. *Plant Biology*. 2012;14(4):605–11.
- [98] Ali SZ, Sandhya V, Grover M, Linga VR, Bandi V. Effect of inoculation with a thermotolerant plant growth promoting *Pseudomonas putida* strain AKMP7 on growth of wheat (*Triticum* spp.) under heat stress. *Journal of Plant Interactions*. 2011;6(4):239–46.
- [99] Yegorenkova I, Konnova S, Sachuk V, Ignatov V. *Azospirillum brasilense* colonisation of wheat roots and the role of lectin–carbohydrate interactions in bacterial adsorption and root-hair deformation. *Plant and Soil*. 2001;231(2):275–82.
- [100] Sarode P, Rane M, Kadam M, Chincholkar S. Role of Microbial Siderophores in Improving Crop Productivity in Wheat. *Bacteria in Agrobiolgy: Crop Productivity*: Springer; 2013. pp. 287–308.
- [101] Scavino AF, Pedraza RO. The role of siderophores in plant growth-promoting bacteria. *Bacteria in Agrobiolgy: Crop Productivity*: Springer; 2013. pp. 265–85.
- [102] Sharma SK, Johri BN, Ramesh A, Joshi OP, Prasad SS. Selection of plant growth-promoting *Pseudomonas* spp. that enhanced productivity of soybean-wheat cropping system in central India. *Journal of Microbiology and Biotechnology*. 2011;21:1127–42.
- [103] Rroço E, Kosegarten H, Harizaj F, Imani J, Mengel K. The importance of soil microbial activity for the supply of iron to sorghum and rape. *European Journal of Agronomy*. 2003;19(4):487–93.
- [104] Jankiewicz U. Synthesis of siderophores by soil bacteria of the genus *Pseudomonas* under various culture conditions. *Acta Scientiarum Polonorum Agricultura*. 2006;5(2).
- [105] Mishra PK, Bisht SC, Ruwari P, Selvakumar G, Joshi GK, Bisht JK, et al. Alleviation of cold stress in inoculated wheat (*Triticum aestivum* L.) seedlings with psychrotolerant *Pseudomonads* from NW Himalayas. *Archives of Microbiology*. 2011;193(7):497–513.
- [106] Sarode Prashant D, Rane Makarand R, Chaudhari Bhushan L, Chincholkar Sudhir B. Siderophoregenic *Acinetobacter calcoaceticus* isolated from wheat rhizosphere with strong PGPR activity. *Malaysian Journal of Microbiology*. 2009;5(1):6–12.
- [107] Khodair T, Galal GF, El-Tayeb T. Effect of inoculating wheat seedlings with exopolysaccharide-producing bacteria in saline soil. *Journal of Applied Sciences Research*. 2008;4:2065–70.
- [108] Sandhya V, Grover M, Reddy G, Venkateswarlu B. Alleviation of drought stress effects in sunflower seedlings by the exopolysaccharides producing *Pseudomonas putida* strain GAP-P45. *Biology and Fertility of Soils*. 2009;46(1):17–26.
- [109] Amellal N, Bartoli F, Villemain G, Talouizte A, Heulin T. Effects of inoculation of EPS-producing *Pantoea agglomerans* on wheat rhizosphere aggregation. *Plant and Soil*. 1999;211(1):93–101.

- [110] Lucy M, Reed E, Glick BR. Applications of free living plant growth-promoting rhizobacteria. *Antonie van Leeuwenhoek*. 2004;86(1):1–25.
- [111] Canbolat MY, Bilen S, Çakmakçı R, Şahin F, Aydın A. Effect of plant growth-promoting bacteria and soil compaction on barley seedling growth, nutrient uptake, soil properties and rhizosphere microflora. *Biology and Fertility of Soils*. 2006;42(4):350–7.
- [112] Panwar J, Singh O. Response of *Azospirillum* and *Bacillus* on growth and yield of wheat under field conditions. *Indian Journal of Plant Physiology*. 2000;5(1):108–10.
- [113] Narula N, Remus R, Deubel A, Granse A, Dudeja S, Behl R, et al. Comparison of the effectiveness of wheat roots colonization by *Azotobacter chroococcum* and *Pantoea agglomerans* using serological techniques. *Plant Soil and Environment*. 2007;53(4):167.
- [114] Kumar V, Narula N. Solubilization of inorganic phosphates and growth emergence of wheat as affected by *Azotobacter chroococcum* mutants. *Biology and Fertility of Soils*. 1999;28(3):301–5.
- [115] Kumar V, Behl RK, Narula N. Establishment of phosphate-solubilizing strains of *Azotobacter chroococcum* in the rhizosphere and their effect on wheat cultivars under green house conditions. *Microbiological Research*. 2001;156(1):87–93.
- [116] Narula N, Kumar V, Behl RK, Deubel A, Gransee A, Merbach W. Effect of P-solubilizing *Azotobacter chroococcum* on N, P, K uptake in P-responsive wheat genotypes grown under greenhouse conditions. *Journal of Plant Nutrition and Soil Science*. 2000;163(4):393–8.
- [117] Singh R, Behl R, Jain P, Narula N, Singh K. Performance and gene effects for root characters and micronutrient uptake in wheat inoculated with arbuscular mycorrhizal fungi and *Azotobacter chroococcum*. *Acta Agronomica Hungarica*. 2007;55(3):325–30.
- [118] Khan MS, Zaidi A. Synergistic effects of the inoculation with plant growth-promoting rhizobacteria and an arbuscular mycorrhizal fungus on the performance of wheat. *Turkish Journal of Agriculture and Forestry*. 2007;31(6):355–62.
- [119] Zaidi A, Khan S. Interactive effect of rhizotrophic microorganisms on growth, yield, and nutrient uptake of wheat. *Journal of Plant Nutrition*. 2005;28(12):2079–92.
- [120] Abbasi M, Yousra M. Synergistic effects of biofertilizer with organic and chemical N sources in improving soil nutrient status and increasing growth and yield of wheat grown under greenhouse conditions. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*. 2012;146(sup1):181–9.
- [121] Oliveira Ad, Urquiaga S, Döbereiner J, Baldani J, Omar M, Hamouda A, et al. Evaluating the efficiency of inoculating some diazotrophs on yield and protein content of 3 wheat cultivars under graded levels of nitrogen fertilization. *Plant and Soil*. 2002;242(2):205–15.
- [122] Yasin M, El-Mehdawi AF, Anwar A, Pilon-Smits EA, Faisal M. Microbial-enhanced selenium and iron biofortification of wheat (*Triticum aestivum* L.)-applications in phytoremediation and biofortification. *International Journal of Phytoremediation*. 2015;17(4):341–7.

- [123] Cakmak I, Pfeiffer WH, McClafferty B. Review: biofortification of durum wheat with zinc and iron. *Cereal Chemistry*. 2010;87(1):10–20.
- [124] Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M. The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. *Biotechnology Advances*. 2014;32(2):429–48.
- [125] Egamberdieva D, Kucharova Z. Selection for root colonising bacteria stimulating wheat growth in saline soils. *Biology and Fertility of Soils*. 2009;45(6):563–71.
- [126] Bacilio M, Rodriguez H, Moreno M, Hernandez J-P, Bashan Y. Mitigation of salt stress in wheat seedlings by a gfp-tagged *Azospirillum lipoferum*. *Biology and Fertility of Soils*. 2004;40(3):188–93.
- [127] Choudhary DK, Kasotia A, Jain S, Vaishnav A, Kumari S, Sharma KP, et al. Bacterial-mediated tolerance and resistance to plants under abiotic and biotic stresses. *Journal of Plant Growth Regulation*. 2016;35(1):276–300.
- [128] Nabti E, Sahnoune M, Ghoul M, Fischer D, Hofmann A, Rothballer M, et al. Restoration of growth of durum wheat (*Triticum durum* var. waha) under saline conditions due to inoculation with the rhizosphere bacterium *Azospirillum brasilense* NH and extracts of the marine alga *Ulva lactuca*. *Journal of Plant Growth Regulation*. 2010;29(1):6–22.
- [129] El-Daim IAA, Bejai S, Meijer J. Improved heat stress tolerance of wheat seedlings by bacterial seed treatment. *Plant and Soil*. 2014;379(1–2):337–50.
- [130] Farooq M, Wahid A, Kobayashi N, Fujita D, Basra S. Plant drought stress: effects, mechanisms and management. *Sustainable agriculture*: Springer; 2009. pp. 153–88.
- [131] Pereyra M, Garcia P, Colabelli M, Barassi C, Creus C. A better water status in wheat seedlings induced by *Azospirillum* under osmotic stress is related to morphological changes in xylem vessels of the coleoptile. *Applied Soil Ecology*. 2012;53:94–7.
- [132] Alvarez M, Sueldo R, Barassi C. Effect of *Azospirillum* on coleoptile growth in wheat seedlings under water stress. *Cereal Research Communications*. 1996, 24 (1):101–107.
- [133] Díaz-Zorita M, Fernández-Canigia MV. Field performance of a liquid formulation of *Azospirillum brasilense* on dryland wheat productivity. *European Journal of Soil Biology*. 2009;45(1):3–11.
- [134] Arzanesh MH, Alikhani H, Khavazi K, Rahimian H, Miransari M. Wheat (*Triticum aestivum* L.) growth enhancement by *Azospirillum* sp. under drought stress. *World Journal of Microbiology and Biotechnology*. 2011;27(2):197–205.
- [135] Naveed M, Hussain MB, Zahir ZA, Mitter B, Sessitsch A. Drought stress amelioration in wheat through inoculation with *Burkholderia phytofirmans* strain PsJN. *Plant Growth Regulation*. 2014;73(2):121–31.
- [136] Khalafallah AA, Abo-Ghalia HH. Effect of arbuscular mycorrhizal fungi on the metabolic products and activity of antioxidant system in wheat plants subjected to short-term water stress, followed by recovery at different growth stages. *Journal of Applied Sciences Research*. 2008;4(5):559–69.

- [137] Chakraborty U, Chakraborty B, Chakraborty A, Dey P. Water stress amelioration and plant growth promotion in wheat plants by osmotic stress tolerant bacteria. *World Journal of Microbiology and Biotechnology*. 2013;29(5):789–803.
- [138] Raheem A, Ali B. Halotolerant rhizobacteria: beneficial plant metabolites and growth enhancement of *Triticum aestivum* L. in salt-amended soils. *Archives of Agronomy and Soil Science*. 2015;61(12):1691–705.
- [139] Shrivastava P, Kumar R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences*. 2015;22(2):123–31.
- [140] Tiwari S, Singh P, Tiwari R, Meena KK, Yandigeri M, Singh DP, et al. Salt-tolerant rhizobacteria-mediated induced tolerance in wheat (*Triticum aestivum*) and chemical diversity in rhizosphere enhance plant growth. *Biology and Fertility of Soils*. 2011;47(8):907–16.
- [141] Tabatabaei S, Ehsanzadeh P. Comparative response of a hulled and a free-threshing tetraploid wheat to plant growth promoting bacteria and saline irrigation water. *Acta Physiologiae Plantarum*. 2016;38(1):1–17.
- [142] Zahir ZA, Ghani U, Naveed M, Nadeem SM, Asghar HN. Comparative effectiveness of *Pseudomonas* and *Serratia* sp. containing ACC-deaminase for improving growth and yield of wheat (*Triticum aestivum* L.) under salt-stressed conditions. *Archives of Microbiology*. 2009;191(5):415–24.
- [143] Abbaspoor A, Zabihi HR, Movafegh S, Asl MA. The efficiency of plant growth promoting rhizobacteria (PGPR) on yield and yield components of two varieties of wheat in salinity condition. *American Eurasian Journal of Sustainable Agriculture*. 2009;3(4):824–8.
- [144] Nia SH, Zarea MJ, Rejali F, Varma A. Yield and yield components of wheat as affected by salinity and inoculation with *Azospirillum* strains from saline or non-saline soil. *Journal of the Saudi Society of Agricultural Sciences*. 2012;11(2):113–21.
- [145] Freitas JRd, Germida JJ. Plant growth promoting rhizobacteria for winter wheat. *Canadian Journal of Microbiology*. 1990;36(4):265–72.
- [146] Sun X, Griffith M, Pasternak J, Glick BR. Low temperature growth, freezing survival, and production of antifreeze protein by the plant growth promoting rhizobacterium *Pseudomonas putida* GR12-2. *Canadian Journal of Microbiology*. 1995;41(9):776–84.
- [147] Xu H, Griffith M, Patten CL, Glick BR. Isolation and characterization of an antifreeze protein with ice nucleation activity from the plant growth promoting rhizobacterium *Pseudomonas putida* GR12-2. *Canadian Journal of Microbiology*. 1998;44(1):64–73.
- [148] Mishra PK, Mishra S, Selvakumar G, Bisht SC, Bisht JK, Kundu S, et al. Characterisation of a psychrotolerant plant growth promoting *Pseudomonas* sp. strain PGERs17 (MTCC 9000) isolated from North Western Indian Himalayas. *Annals of Microbiology*. 2008;58(4):561–8.

- [149] Turan M, Güllüce M, Çakmak R, Şahin F. Effect of plant growth-promoting rhizobacteria strain on freezing injury and antioxidant enzyme activity of wheat and barley. *Journal of Plant Nutrition*. 2013;36(5):731–48.
- [150] Tica D, Udovic M, Lestan D. Immobilization of potentially toxic metals using different soil amendments. *Chemosphere*. 2011;85(4):577–83.
- [151] Kumar V, Singh S, Singh J, Upadhyay N. Potential of plant growth promoting traits by bacteria isolated from heavy metal contaminated soils. *Bulletin of Environmental Contamination and Toxicology*. 2015;94(6):807–14.
- [152] Hasnain S, Sabri AN. Growth stimulation of *Triticum aestivum* seedlings under Cr-stresses by non-rhizospheric pseudomonad strains. *Environmental Pollution*. 1997;97(3):265–73.
- [153] Shahzadi I, Khalid A, Mahmood S, Arshad M, Mahmood T, Aziz I. Effect of bacteria containing ACC deaminase on growth of wheat seedlings grown with chromium contaminated water. *Pakistan Journal of Botany*. 2013;45:487–94.
- [154] Jamali MK, Kazi TG, Arain MB, Afridi HI, Jalbani N, Kandhro GA, et al. Heavy metal accumulation in different varieties of wheat (*Triticum aestivum* L.) grown in soil amended with domestic sewage sludge. *Journal of Hazardous Materials*. 2009;164(2):1386–91.
- [155] Hassan W, Bashir S, Ali F, Ijaz M, Hussain M, David J. Role of ACC-deaminase and/or nitrogen fixing rhizobacteria in growth promotion of wheat (*Triticum aestivum* L.) under cadmium pollution. *Environmental Earth Sciences*. 2016;75(3):1–14.
- [156] Singh Y, Ramteke P, Shukla PK. Isolation and characterization of heavy metal resistant *Pseudomonas* spp. and their plant growth promoting activities. *Advances in Applied Sciences Research* 2013;4:269–72.
- [157] Barakat M. New trends in removing heavy metals from industrial wastewater. *Arabian Journal of Chemistry*. 2011;4(4):361–77.
- [158] Dell'Amico E, Cavalca L, Andreoni V. Improvement of Brassica napus growth under cadmium stress by cadmium-resistant rhizobacteria. *Soil Biology and Biochemistry*. 2008;40(1):74–84.
- [159] Govindasamy V, Senthilkumar M, Annapurna K. Effect of mustard rhizobacteria on wheat growth promotion under cadmium stress: characterization of *acdS* gene coding ACC deaminase. *Annals of Microbiology*. 2015;65(3):1679–87.
- [160] Abaid-Ullah M, Hassan MN, Jamil M, Brader G, Shah MKN, Sessitsch A, et al. Plant growth promoting rhizobacteria: an alternate way to improve yield and quality of wheat (*Triticum aestivum*). *International Journal of Agriculture and Biology*. 2015;17:51–60.
- [161] Rana A, Joshi M, Prasanna R, Shivay YS, Nain L. Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. *European Journal of Soil Biology*. 2012;50:118–26.

- [162] Roesti D, Gaur R, Johri B, Imfeld G, Sharma S, Kawaljeet K, et al. Plant growth stage, fertiliser management and bio-inoculation of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria affect the rhizobacterial community structure in rain-fed wheat fields. *Soil Biology and Biochemistry*. 2006;38(5):1111–20.
- [163] Mäder P, Kaiser F, Adholeya A, Singh R, Uppal HS, Sharma AK, et al. Inoculation of root microorganisms for sustainable wheat–rice and wheat–black gram rotations in India. *Soil Biology and Biochemistry*. 2011;43(3):609–19.
- [164] Saubidet MI, Fatta N, Barneix AJ. The effect of inoculation with *Azospirillum brasilense* on growth and nitrogen utilization by wheat plants. *Plant and Soil*. 2002;245(2):215–22.
- [165] Cáceres ER, Anta GG, Lopez J, Ciocco CD, Basurco JP, Parada J. Response of field-grown wheat to inoculation with *Azospirillum brasilense* and *Bacillus polymyxa* in the semiarid region of Argentina. *Arid Land Research and Management*. 1996;10(1):13–20.
- [166] Rosas SB, Avanzini G, Carlier E, Pasluosta C, Pastor N, Rovera M. Root colonization and growth promotion of wheat and maize by *Pseudomonas aurantiaca* SR1. *Soil Biology and Biochemistry*. 2009;41(9):1802–6.
- [167] Shaharoona B, Naveed M, Arshad M, Zahir ZA. Fertilizer-dependent efficiency of Pseudomonads for improving growth, yield, and nutrient use efficiency of wheat (*Triticum aestivum* L.). *Applied Microbiology and Biotechnology*. 2008;79(1):147–55.
- [168] Majeed A, Abbasi MK, Hameed S, Imran A, Rahim N. Isolation and characterization of plant growth-promoting rhizobacteria from wheat rhizosphere and their effect on plant growth promotion. *Frontiers in Microbiology*. 2015;6:198.
- [169] Mehboob I, Zahir ZA, Arshad M, Tanveer A, Azam F. Growth promoting activities of different *Rhizobium* spp. in wheat. *Pakistan Journal of Botany*. 2011;43(3):1643–50.
- [170] Ozturk A, Caglar O, Sahin F. Yield response of wheat and barley to inoculation of plant growth promoting rhizobacteria at various levels of nitrogen fertilization. *Journal of Plant Nutrition and Soil Science*. 2003;166(2):262–6.
- [171] Turan M, Gulluce M, Şahin F. Effects of plant-growth-promoting rhizobacteria on yield, growth, and some physiological characteristics of wheat and barley plants. *Communications in Soil Science and Plant Analysis*. 2012;43(12):1658–73.
- [172] Barneix A, Saubidet M, Fatta N, Kade M. Effect of rhizobacteria on growth and grain protein in wheat. *Agronomy for Sustainable Development*. 2005;25(4):505–11.
- [173] Trabelsi D, Mhamdi R. Microbial inoculants and their impact on soil microbial communities: a review. *BioMed Research International*. 2013.
- [174] Belimov A, Kojemiakov A, Chuvarliyeva Cn. Interaction between barley and mixed cultures of nitrogen fixing and phosphate-solubilizing bacteria. *Plant and Soil*. 1995;173(1):29–37.

- [175] Combes-Meynet E, Pothier JF, Moënne-Loccoz Y, Prigent-Combaret C. The *Pseudomonas* secondary metabolite 2, 4-diacetylphloroglucinol is a signal inducing rhizoplane expression of *Azospirillum* genes involved in plant-growth promotion. *Molecular Plant-Microbe Interactions*. 2011;24(2):271–84.
- [176] Galal Y, El-Ghandour I, El-Akel E. Stimulation of wheat growth and N fixation through *Azospirillum* and *Rhizobium* inoculation: a field trial with ¹⁵N techniques. *Plant Nutrition: Springer*; 2001. pp. 666–7.
- [177] Swarnalakshmi K, Prasanna R, Kumar A, Pattnaik S, Chakravarty K, Shivay YS, et al. Evaluating the influence of novel cyanobacterial biofilmed biofertilizers on soil fertility and plant nutrition in wheat. *European Journal of Soil Biology*. 2013;55:107–16.
- [178] Nain L, Rana A, Joshi M, Jadhav SD, Kumar D, Shivay Y, et al. Evaluation of synergistic effects of bacterial and cyanobacterial strains as biofertilizers for wheat. *Plant and Soil*. 2010;331(1–2):217–30.
- [179] Manjunath M, Prasanna R, Sharma P, Nain L, Singh R. Developing PGPR consortia using novel genera *Providencia* and *Alcaligenes* along with cyanobacteria for wheat. *Archives of Agronomy and Soil Science*. 2011;57(8):873–87.
- [180] Minaxi J, Chandra S, Nain L. Synergistic effect of phosphate solubilizing rhizobacteria and arbuscular mycorrhiza on growth and yield of wheat plants *Journal of Soil Science and Plant Nutrition*, 2013, 13 (2), 511–525.
- [181] Kumar A, Maurya B, Raghuwanshi R. Isolation and characterization of PGPR and their effect on growth, yield and nutrient content in wheat (*Triticum aestivum* L.). *Biocatalysis and Agricultural Biotechnology*. 2014;3(4):121–8.
- [182] Baris O, Sahin F, Turan M, Orhan F, Gulluce M. Use of plant-growth-promoting rhizobacteria (PGPR) seed inoculation as alternative fertilizer inputs in wheat and barley production. *Communications in Soil Science and Plant Analysis*. 2014;45(18):2457–67.
- [183] Afzal A, Saleem S, Iqbal Z, Jan G, Malik MFA, Asad SA. Interaction of *Rhizobium* and *Pseudomonas* with Wheat (*Triticum Aestivum* L.) in Potted Soil with or Without P₂O₅. *Journal of Plant Nutrition*. 2014;37(13):2144–56.
- [184] Bulut S. Evaluation of efficiency parameters of phosphorous-solubilizing and N-fixing bacteria inoculations in wheat (*Triticum aestivum* L.). *Turkish Journal of Agriculture and Forestry*. 2013;37(6):734–43.
- [185] Afzal A, Bano A. *Rhizobium* and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (*Triticum aestivum*). *International Journal of Agriculture and Biology*. 2008;10:85–8.
- [186] Germida J, Walley F. Plant growth-promoting rhizobacteria alter rooting patterns and arbuscular mycorrhizal fungi colonization of field-grown spring wheat. *Biology and Fertility of Soils*. 1996;23(2):113–20.

- [187] Bahrani A, Pourreza J, Joo MH. Response of Winter Wheat to Co-Inoculation with Azotobacter and Arbuscular Mycorrhizal Fungi (AMF) under different sources of nitrogen fertilizer. *American-Eurasian Journal of Agricultural & Environmental Sciences*. 2010;9(4):376–84.
- [188] Germida J, Siciliano S. Taxonomic diversity of bacteria associated with the roots of modern, recent and ancient wheat cultivars. *Biology and Fertility of Soils*. 2001;33(5):410–5.
- [189] Marschner P, Crowley D, Yang CH. Development of specific rhizosphere bacterial communities in relation to plant species, nutrition and soil type. *Plant and Soil*. 2004;261(1–2):199–208.
- [190] Kant C, Aydin A, Turan M, Huang YM. Mitigation of N and P leaching from irrigated wheat area as influence plant growth promoting rhizobacteria (PGPR). *Romanian Biotechnological Letters*. 2010;15(6):5754–63.
- [191] Fischer SE, Fischer SI, Magris S, Mori GB. Isolation and characterization of bacteria from the rhizosphere of wheat. *World Journal of Microbiology and Biotechnology*. 2007;23(7):895–903.
- [192] Sabry SR, Saleh SA, Batchelor CA, Jones J, Jotham J, Webster G, et al. Endophytic establishment of Azorhizobium caulinodans in wheat. *Proceedings of the Royal Society of London B: Biological Sciences*. 1997;264(1380):341–6.
- [193] Singh N, Chaudhary F, Patel D. Effectiveness of Azotobacter bio-inoculant for wheat grown under dryland condition. *Journal of Environmental Biology*. 2013;34(5):927.
- [194] Narula N, Kumar V, Singh B, Bhatia R, Lakshminarayana K. Impact of biofertilizers on grain yield in spring wheat under varying fertility conditions and wheat-cotton rotation. *Archives of Agronomy and Soil Science*. 2005;51(1):79–89.
- [195] Ali SM, Hamza MA, Amin G, Fayez M, El-Tahan M, Monib M, et al. Production of biofertilizers using baker's yeast effluent and their application to wheat and barley grown in north Sinai deserts: (Produktion von Biodüngern unter Verwendung von Backhefeabwasser und ihre Anwendung zu Weizen-und Gerstenanbau im Norden der Sinai-Wüste). *Archives of Agronomy and Soil Science*. 2005;51(6):589–604.
- [196] Mertens T, Hess D. Yield increases in spring wheat (*Triticum aestivum* L.) inoculated with *Azospirillum lipoferum* under greenhouse and field conditions of a temperate region. *Plant and Soil*. 1984;82(1):87–99.
- [197] Bashan Y, Holguin G, De-Bashan LE. Azospirillum-plant relationships: physiological, molecular, agricultural, and environmental advances (1997–2003). *Canadian Journal of Microbiology*. 2004;50(8):521–77.
- [198] Wang H, Xu R, You L, Zhong G. Characterization of Cu-tolerant bacteria and definition of their role in promotion of growth, Cu accumulation and reduction of Cu toxicity in *Triticum aestivum* L. *Ecotoxicology and Environmental Safety*. 2013;94:1–7.

- [199] Pereyra M, Zalazar C, Barassi C. Root phospholipids in *Azospirillum*-inoculated wheat seedlings exposed to water stress. *Plant Physiology and Biochemistry*. 2006;44(11):873–9.
- [200] Creus CM, Sueldo RJ, Barassi CA. Water relations in *Azospirillum*-inoculated wheat seedlings under osmotic stress. *Canadian Journal of Botany*. 1998;76(2):238–44.
- [201] Mishra PK, Mishra S, Bisht SC, Selvakumar G, Kundu S, Bisht J, et al. Isolation, molecular characterization and growth-promotion activities of a cold tolerant bacterium *Pseudomonas* sp. NARs9 (MTCC9002) from the Indian Himalayas. *Biological Research*. 2009;42(3):305–13.
- [202] Abd-Alla MH, El-Sayed E-SA, Rasmey A-HM. Indole-3-acetic acid (IAA) production by *Streptomyces atrovirens* isolated from rhizospheric soil in Egypt. *Journal of Biology and Earth Sciences*. 2013;3(2):B182–B93.
- [203] Egamberdiyeva D, Höflich G. Influence of growth-promoting bacteria on the growth of wheat in different soils and temperatures. *Soil Biology and Biochemistry*. 2003;35(7):973–8.
- [204] Nadeem SM, Zahir ZA, Naveed M, Asghar HN, Arshad M. Rhizobacteria capable of producing ACC-deaminase may mitigate salt stress in wheat. *Soil Science Society of America Journal*. 2010;74(2):533–42.
- [205] Nadeem SM, Zahir ZA, Naveed M, Nawaz S. Mitigation of salinity-induced negative impact on the growth and yield of wheat by plant growth-promoting rhizobacteria in naturally saline conditions. *Annals of Microbiology*. 2013;63(1):225–32.
- [206] Barbieri P, Galli E. Effect on wheat root development of inoculation with an *Azospirillum brasilense* mutant with altered indole-3-acetic acid production. *Research in Microbiology*. 1993;144(1):69–75.
- [207] Obreht Z, Kerby NW, Gantar M, Rowell P. Effects of root-associated N₂-fixing cyanobacteria on the growth and nitrogen content of wheat (*Triticum vulgare* L.) seedlings. *Biology and Fertility of Soils*. 1993;15(1):68–72.
- [208] Timmusk S, Nicander B, Granhall U, Tillberg E. Cytokinin production by *Paenibacillus polymyxa*. *Soil Biology and Biochemistry*. 1999;31(13):1847–52.
- [209] Alen'kina S, Payusova O, Nikitina V. Effect of *Azospirillum* lectins on the activities of wheat-root hydrolytic enzymes. *Plant and Soil*. 2006;283(1–2):147–51.
- [210] Egamberdiyeva D. Plant-growth-promoting rhizobacteria isolated from a Calcisol in a semi-arid region of Uzbekistan: biochemical characterization and effectiveness. *Journal of Plant Nutrition and Soil Science*. 2005;168(1):94–9.
- [211] Kızılkaya R. Yield response and nitrogen concentrations of spring wheat (*Triticum aestivum*) inoculated with *Azotobacter chroococcum* strains. *Ecological Engineering*. 2008;33(2):150–6.

- [212] Hassen AI, Labuschagne N. Root colonization and growth enhancement in wheat and tomato by rhizobacteria isolated from the rhizoplane of grasses. *World Journal of Microbiology and Biotechnology*. 2010;26(10):1837–46.
- [213] El-Razek UA, El-Sheshtawy A. Response of some wheat varieties to bio and mineral nitrogen fertilizers. *Asian Journal of Crop Science*. 2013;5(2):200.
- [214] Schoebitz M, Ceballos C, Ciamp L. Effect of immobilized phosphate solubilizing bacteria on wheat growth and phosphate uptake. *Journal of Soil Science and Plant Nutrition*. 2013;13(1):1–10.
- [215] Magnucka EG, Pietr SJ. Various effects of fluorescent bacteria of the genus *Pseudomonas* containing ACC deaminase on wheat seedling growth. *Microbiological Research*. 2015;181:112–9.
- [216] Ogut M, Er F. Mineral composition of field grown winter wheat inoculated with phosphorus solubilizing bacteria at different plant growth stages. *Journal of Plant Nutrition*. 2016;39(4):479–90.