Chapter 12
Endophytic Rhizobacteria for Mineral Nutrients Acquisition in Plants: Possible Functions and Ecological Advantages

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Abstract Nutrient-deficiency in agricultural soils is a major problem in many parts of the world, it is, therefore, artificial fertilizers are widely used to boost crop production. Unfortunately, these fertilizers are associated with a myriad of environmental problems hence, there is a need for viable alternatives. The realization that the plant microbiome can improve plant health, soil fertility, and crop productivity is one of the most fascinating scientific discoveries in the world. For several decades, rhizobacteria have been studied due to their various plant growth-promoting (PGP) traits. Endophytic rhizobacteria are unique plant microbiome that establish themselves within plant root tissues and exert beneficial functions to their hosts without harming them. A lot of emphases have been put on these bacteria as viable tools for sustainable agriculture and it is advanced that they could be better plant growth promoters than their external counterparts. However, this theory is not yet clearly understood. This chapter provides the current state of understanding of the putative functions of endophytic rhizobacteria and their future prospects for plant mineral nutrients acquisition. Their advantageous traits that largely advanced to facilitate these PGP functions are also discussed. Such informations can provide better opportunities for improved plant mineral nutrients acquisition and enhance the application of these microbes as viable strategies for sustainable agriculture.

Keywords Endophytes · Rhizobacteria · Sustainable agriculture · Plant growth promotion

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D. K. Maheshwari and S. Dheeman (eds.), *Endophytes: Mineral Nutrient Management, Volume 3*, Sustainable Development and Biodiversity 26,
https://doi.org/10.1007/978-3-030-65447-4_12

12.1 Introduction

Agricultural activities are quickly gaining momentum to feed the rapidly growing population across the globe. One of them is excessive use of chemicals established as an effective tool to increase crop productivity of different crops. However, conventional agricultural practices have a lot of undesirable outcomes as the chemical inputs have commonly been linked to land degradation, environmental pollution, global warming, climate change, etc. (Steffen et al. 2015; Di Benedetto et al. 2017). For many decades, researchers all over the world have focused on alternative crop fertilization mechanisms such as the use of plant growth-promoting bacteria (PGPB) to replace the contemporary fertilization practices (Smith et al. 2016). In fact, these are free-living bacteria with unique capabilities of stimulating plant growth, either directly or indirectly through different mechanisms (Archana et al. 2013; Ahemad and Kibret 2014; Kumar et al. 2014). Glick (2014) and later, Baliyan et al. (2018) described the exploitation of such organisms as a viable and environment friendly technology befitting for sustainable crop production in eco-safe ways.

Among them, endophytes are organisms that spend all or part of their lives in plant cells or tissues with different degrees of dependence without harming their hosts (Compant et al. 2010; Hardoim et al. 2015; Brader et al. 2017; Lata et al. 2019) and can be recovered from surface-sterilized plant tissues (Santoyo et al. 2016). As many plant species as exist on earth host bacterial endophytes (Ryan et al. 2008), and several endophytic bacteria like the Proteobacteria, Firmicutes Actinobacteria, and Bacteroidetes have putative PGP functions (Rosenblueth and Martinez-Romero 2006; Bulgarelli et al. 2013; Hardoim et al. 2015; Liu et al. 2017). Endophytic bacteria have been isolated from various plant parts including stems, roots, seeds, leaves, fruits, ovules, tubers, nodules, etc. (Benhizia et al. 2004; Pandey et al. 2018). Nevertheless, below ground potential i.e., plant roots harbor the greatest populations of these bacteria in comparison to aerial parts (Rosenblueth and Martinez-Romero 2006; Taghavi et al. 2010), at approximately 10^4–10^6 per g of root tissue (Compant et al. 2010; Bulgarelli et al. 2013).

Depsite occupying different ecological niches, endophytic bacterial populations employ PGP mechnaisms similar to those of free-living rhizosphere bacteria (Compant et al. 2005). The common PGP mechanisms can either be direct such as nitrogen-fixation, solubilization of nutrients, production of siderophores and phytohormones or indirect such as the suppression of plant pathogens and diseases (Suman et al. 2016; Lata et al. 2018). Diverse PGP bacterial endophytes have been explored and applied for crop yield enhancement under nutrient-poor conditions (Rosenblueth and Martinez-Romero 2006; Liu et al. 2017). Several studies demonstrate their positive effects in different food and cash crops such as the banana (*Musa* spp.) (Patel et al. 2017b), maize (*Zea mays*) (Alves et al. 2015), tomato (*Lycopersicon esculentum*) (Upreti and Thomas 2015), groundnut (*Arachis hypogaea*) (Dhole et al. 2016), and many more outlined by various workers (Hardoim et al. 2015; Pandey et al. 2018; Maheshwari 2018). Literature documents that endophyte-elicited PGP activities culminate into increased seed germination rates, biomass, chlorophyll, N and protein contents, root and shoot lengths, yield, and tolerance to abiotic stresses (Verma et al. 2013, 2015). The rhizobia which are the best-understood endophytes are critical for Nitrogen (N) nutrition in leguminous plants (Santoyo et al. 2016).

Although endophytic rhizobacteria have widely been investigated, their significance in improving plant mineral nutrient acquisition has emerged quite recently (Harman and Uphoff 2019), and literature propounds that they could be better plant growth promoters and possess certain advantageous traits that give them an edge over their external counterparts (Coutinho et al. 2015; Asaf et al. 2017). However, this theory is not yet clearly understood as both are similar to their facilitation of plant mineral nutrients acquisition. This chapter reviews the potential functions of endophytic rhizobacteria in the acquisition of certain plant mineral macronutrients such as N, P, K and micronutrients like Zn and Fe. The putative advantageous traits that facilitate these functions and make them suitable candidates for enhancing mineral nutrients acquisition in plants are also discussed. Such information will enrich our knowledge on these important plant endophytic microbiome and possibly pave the way for their complete understanding and utilization as biofertilizers for sustainable crop production.

12.2 Putative Functions of Endophytic PGPR for Mineral Nutrients Acquisition in Plants

Several studies demonstrate the diversity and functions of endophytic rhizobacteria toward plant mineral nutrients acquisition and general PGP activities. In this section, we outline some of these studies and functions to demonstrate the importance of these bacteria in plant mineral nutrition.

12.2.1 Endophytic Rhizobacteria and Nitrogen Acquisition in Plants

Nitrogen is the most important nutrient required for plant growth (Verma et al. 2019). Although the atmosphere contains about 78% N, most of this is present in inert form and inaccessible to plants, making it a major plant-limiting nutrient. Artificial N-fertilizers are commonly applied to supply N to plants. However, out of every 100 Tg of N applied in agricultural fields globally, only about 17 Tg are utilized by plants and the rest is either lost or accumulates in the environment with serious implications to the soil and environment (Erisman et al. 2008; Howarth 2008). The microorganisms can convert excess ammonium or nitrate in the soil into nitrous oxide (N_2O), a potent greenhouse gas (GHG) (Kandel et al. 2017), whose effects are reportedly much worse than that of CO_2 (Ramaswamy et al. 2001).

Endophytic N_2-fixing rhizobacteria are now emerging as one of the most efficient and environmentally sustainable approaches for increasing N acquisition for crops (Suman et al. 2016; Defez et al. 2017). Their potential has been illustrated in many studies, examples of which are provided in Table 12.1. It is proposed that endophytic N_2-fixers can enable plants to survive under N-limiting conditions better than their external rhizobacterial counterparts (Gupta et al. 2013). For instance, the N_2 fixation process requires energy to reduce the bonds in the N_2 molecules and the endophytic N_2-fixers can obtain the required energy from plant host tissues (Olivares et al. 2013). Similarly, their internal plant habitats offer favorable micro-aerobic environments that are more conducive to the nitrogenase enzyme complex that catalyzes the N_2 fixation process (Doty et al. 2016).

Although all diazotrophs are important for providing N to plants and enhancing their growth (Kumar et al. 2017), endophytic rhizobacteria not only provide the fixed N to their plant hosts more directly but also more efficiently (Suman et al. 2016; Lata et al. 2019). This is because the BNF process is largely mediated by the *nif* and *fix* genes whose transcriptions are primarily induced under low-oxygen conditions as in the interior plant tissues parts that host the endophytes (Bhagya and Rajkumar 2017). Literature suggests that the fixed N_2 is converted to NH_4^+ in the bacterial cytoplasm and subsequently excreted into the host cytoplasm (Mia and Shamsuddin 2010), where it is assimilated into glutamate and transported in the xylem from the plant roots to their shoots as the major source of organic N (Nawaz et al. 2017). Thus the endophytic diazotrophs can release NH_4 easily and directly into the plant host cell cytoplasm. Although some N_2-fixers can assimilate the produced NH_4 into organic compounds, most N_2-fixing strains have unique regulatory mechanisms to secrete the NH_4 outside their cells by diffusion instead of assimilating it (Day et al. 2001). This has a significant implication on the utilization of rhizobacteria as biofertilizers since the absence of this negative feedback mechanism can allow the nitrogenase enzyme complex to produce NH_3 continuously for plant uptake.

The symbiotic N_2-fixing rhizobia inhabiting in the cortial tissues of roots have been researched for several decades (Santoyo et al. 2016). The inoculation of crops and agricultural fields with such PGPR can help to maintain the N levels (Daman et al. 2016). For instance, about 1–2 kg N ha^{-1} day^{-1} can be obtained for all legumes by rhizobial N_2 fixation alone (Lesueur et al. 2016). Apart from legumes, rhizobia have also been found living endophytically with rice, sweet corn, cotton, maize, bean, barley, and wheat among others as outlined in the review by Bhagya and Rajkumar (2017). This shows that there is a great possibility that several rhizobial interactions can similarly enhance N acquisition with non-leguminous crops. For instance, the discovery of N_2-fixing endophytic rhizobacteria in sugarcane (Ohyama et al. 2014; Mus et al. 2016) and cereals (Annapurna et al. 2004; Suman et al. 2016) especially sparked a substantial interest. Rhizobia have also been found to infect *Brassica campestris* and enhance its growth by increasing its N content (Chandra et al. 2007). *Gluconacetobacter diazotrophicus* which is the main endophytic diazotroph in sugarcane can fix up to 150 kg N ha^{-1} $year^{-1}$ (Muthukumarasamy et al. 2005), and previous in vivo studies on this species also showed that it can promote the growth, germination, height, and nutrient uptake of sugarcane (Suman et al. 2008). Recently, a study

Table 12.1 Some important nitrogen-fixing endophytic rhizobacteria and their associated host plants

Source	Endophytic rhizobacteria	Reference
Banana (*Musa* spp.)	*Klebsiella sp., Bacillus sp., Microbacterium sp., Enterobacter sp.,*	Patel et al. (2017b)
	B. subtilis	Andrade et al. (2014)
Cassava (*Manihot esculenta*)	*Pantoea dispersa*	Chen et al. (2014)
Cowpea (*Vigna unguiculata*)	*Bradyrhizobium, Streptomyces griseoflavus*	Htwe et al. (2019)
Groundnut (*Arachis hypogaea*)	*Enterobacter ludwigii*	Dhole et al. (2016)
	Bradyrhiziobium	Taurian et al. (2013)
Maize (*Zea mays*)	*Pseudomonas aeruginosa, E. asburiae, Acinetobacter brumalii*	Sandhya et al. (2017)
	Klebsiella sp., *K. pneumoniae, B. pumilus Acinetobacter* sp., *B. subtilis*	Kuan et al. (2016)
	Bacillus sp., Enterobacter sp.	Szilagyi-Zecchin et al. (2014)
	P. pseudoalcaligenes, P. aeruginosa	Jha (2019)
Mungbean (*Vigna radiata*)	*Bradyrhizobium, Streptomyces griseoflavus*	Htwe et al. (2019)
Rice (*Oryza sativa*)	*Microbacterium, Bacillus, Klebsiella spp. Paenibacillus kribbensi, B. aryabhattai, K. pneumoniae, B. subtilis, M. trichotecenolyticum*	Ji et al. (2014)
	Rhizobium	Patel et al. (2017a)
	Burkholderia, Herbaspirillum, Azospirillum, Rhizobium leguminosarum	Choudhary and Kennedy (2004), Doty (2011)
	P. stutzeri	Pham et al. (2017)
	Lysinibacillus sphaericus	Shabanamol et al. (2018)
	Rhizobium sp., *Azospirillum* sp.	Sev et al. (2016)
Soybean (*Glycine max*)	*Bradyrhizobium, Streptomyces griseoflavus*	Htwe et al. (2019)
Sugarcane (*Saccharum officinarum* L)	*Gluconacetobacter diazotrophicus*	Suman et al. (2008)
	Pantoea agglomerans	Quecine et al. (2012)
	K. variicola DX120E	Wei et al. (2014)

(continued)

Table 12.1 (continued)

Source	Endophytic rhizobacteria	Reference
	G. diazotrophicus	Ahmed et al. (2016)
	Kosakania sp. *ICB117*	Kleingesinds et al. (2018)
Wheat (*Triticum aestivum*)	*Achromobacter insolitus, Azospirillum brasisilense*	Silveira et al. (2016)
	Stenotrophomonas maltophilia, Chryseobacterium, Flavobacterium, Pseudomonas mexicana	Youseif (2018)

involving other endophytes in a mixed inoculum also showed increased N uptake in sugarcane under N-limiting conditions (Marcos et al. 2016), an implication that there could be other beneficial diazotrophs in this plant. Ngamau et al. (2014), reviewed a number of endophytic banana rhizobacteria with BNF potential. As evidenced by these studies and many others, diazotrophic endophytes hold immense potential for enhancing N acquisition in various non-leguminous plants and further investigations in this regard are necessary.

12.2.2 *Endophytic Rhizobacteria and Potassium Acquisition in Plants*

Potassium is the third most important quality macronutrient required for plant metabolism and growth (Ahmad et al. 2016; Proença et al. 2017). However, over 90% of K occurs in soil in fixed forms and only about 2% is readily available for plant use (Tsegaye et al. 2017; Meena et al. 2018). The application of K-based/potash fertilizers is a contemporary practice in extensive and intensive agricultural systems worldwide (Dasan 2012; Yagedari et al. 2012; Zhang et al. 2013). However, these synthetic fertilizers decrease agricultural profitability (Mohammadi and Sohrabi 2012; Ahmad et al. 2016) and sustainable crop yield.

Potassium solubilizing bacteria (KSB) are an important source of the rhizosphere microbiome where they promote plant growth by solubilizing K-bearing minerals. Recent literature shows that KSB can be used to ameliorate K-deficient soils for crop production (Suman et al. 2016; Dhiman et al. 2019), and are quickly gaining momentum in the wake of calls for sustainable crop production (Ahmad et al. 2016). The burgeoning evidence of the large diversity of KSB associated with different plants shows that they have an immense potential for application in K-deficient soils (Meena et al. 2016; Velázquez et al. 2016). However, K solubilization abilities are less reported among endophytic rhizobacteria (Proença et al. 2017; Dhiman et al. 2019). For instance, in a study by Patel et al. (2017b), none of over 50 endophytic banana rhizobacteria were associated with K solubilization despite them showing other essential PGP functions including the solubilization abilities for other important plant nutrients. Nevertheless, there are studies that demonstrate the existence of K solubilizing endophytes.

Potassium solubilizing endophytic rhizobacteria have been identified from wheat (Verma et al. 2013, 2015), more recently, from pearl millet (Kushwaha et al. 2019), maize (Jha 2019), and other crops (Dhiman et al. 2019). Rhizobia are the best-studied endophytes and are widely known for symbiotic N_2 fixation in leguminous plants (Santoyo et al. 2016). However, of late, these novel rhizobacteria have also been shown to solubilize K in plant rhizospheres. For instance, K solubilization by rhizobia in rice has recently been reported by Patel et al. (2017a). Thirumal et al. (2017) demonstrated 5 rhizobial cultures associated with K solubilization in vitro. These new discoveries suggest that apart from enhancing N nutrition in plants, rhizobia can also be exploited for their K solubilizing abilities to enhance K availability in plant rhizosphere.

Indigenous KSB are currently in the limelight for sustainable cropping systems and environmental conservation and have emerged as one of the viable technologies for mitigating K-deficiency in soils (Meena et al. 2015). Potassium solubilization indeed holds a lot of potential for PGP and the K solubilizing abilities of endophytic rhizobacteria are worth exploring. According to Meena et al. (2018), KSB are precious bio-resources that can mitigate K-deficiency in agricultural soils but their experimental evidence at the field level is still inadequate. Such processes may need to be exploited in detail so as to increase their usability.

12.2.3 Endophytic Rhizobacteria and Phosphorus Acquisition in Plants

Phosphorus is the second most important plant nutrient after N (Goswami et al. 2016). Although soils contain P reserves, most of this is available in insoluble forms and inaccessible to plants (Verma et al. 2019).

This non-availability is recognized as a major plant growth-limiting factor in agricultural systems (Sharma et al. 2013). The P solubilization potential of soil microorganisms is one of the most essential traits of PGPR for enhancing P-nutrition acquisition in plants (Walia and Shirkot 2012; Ouattara et al. 2019). While P solubilizing rhizobacteria are widely investigated, recent literature maintains that only a few endophytic rhizobacteria possess this ability (Brigido et al. 2019).

Nevertheless, there is mounting evidence on the role of endophytes in P solubilization and mobilization compared to their widely reported rhizospheric counterparts (Ji et al. 2014; Oteino et al. 2015; Walitang et al. 2019). PSB can proliferate both in plant rhizospheres and endosphere (Hui et al. 2011), and according to Suman et al. (2016), P solubilization is a common trait among endophytic bacteria. However, the P solubilizing bacteria (PSB) still tend to be more abundant in plant rhizospheres in comparison to plant cells and tissues (Chen et al. 2006; Mwajita et al. 2013; Mehta et al. 2015; Walia et al. 2017). Generally, the population of endophytic PSB range between 10^2 and 10^4 bacteria/g of root tissue (Kumar et al. 2013; Saini et al. 2015). A number of endophytic rhizobacterial populations belonging to *Burkholderia, Enterobacter, Pantoea, Pseudomonas, Citrobacter, Azotobacte*r genera from wheat, rice, maize, legumes, and sunflower, respectively, are reported to solubilize mineral P in plate assays, and a vast number of P solubilizing PGPR are documented (Verma et al. 2013, 2015). In a recent study, Patel et al. (2017b), examined that 36% of over 50 endophytic rhizobacterial isolates belonging to genera *Bacillus, Klebsiella, Microbacterium*, and *Enterobacter* showed P solubilization. Further reports on P solubilizing endophytic rhizobacteria are depicted in Table 12.2.

The P solubilizing PGPR can greatly impact plant growth by increasing P availability in the rhizospheric soils but must maintain an intimate relationship with the host plants (Walia et al. 2017). Numerous studies have highlighted the importance and mechanisms of P solubilization by PSB (Chhabra and Dowling 2017; Varma et al. 2017; Walia et al. 2017; Shrivastava et al. 2018; Billah et al. 2019; Goswami et al. 2019; Rafi et al. 2019; Dheeman et al. 2020). The solubilization of P is purportedly mediated through acidification, chelation, or exchange reactions (Li et al. 2017). According to Rosenblueth and Martinez-Romero (2006), endophytic PSB are more competitive than free-living rhizobacteria since the plant-endophyte interactions are the result of complex evolutionary processes. Moreover, endophytic rhizobacteria can prevent the adsorption and fixation of P under P-limiting conditions by assimilating the solubilized P (Khan and Joergersen 2009; Shakeela et al. 2017).

12.2.4 Endophytic Rhizobacteria in Zinc Acquisition in Plants

Zinc is an important micronutrient required for primary and secondary metabolism in plants (Goteti et al. 2013; Bhatt and Maheshwari 2020). For instance, Zn is a cofactor in many enzymes (Hafeez et al. 2013) and it is critical for membrane function, photosynthesis, protein synthesis, and auxin metabolism in plants (Tavallali et al. 2010). Reports show that Zn deficiency is a common problem worldwide due to nutrient mining during crop harvesting and increased use of NPK fertilizers containing lesser amounts of Zn micronutrients (Sharifi and Paymozd 2016; Sindhu et al. 2019). Synthetic Zn fertilizers are often applied to overcome these deficiencies at rates of about 25 kg ha^{-1} ZnSO4 heptahydrate (equivalent to 5 kg ha^{-1} Zn). Nevertheless, these artificial fertilizers are not cost-effective and quickly get converted into insoluble forms that are inaccessible to plants (Bapiri et al. 2012; Sindhu et al. 2019).

Rhizobacterial Zn solubilization abilities are widely reported phenomenon (Mishra et al. 2013; Shaikh and Saraf 2017). Reports also exist on endophytic Zn solubilization. For instance, Zn solubilizing bacteria (ZSB) have been reported to enhance Zn uptake in soybean up to 21% (Sharma et al. 2014), various *G. diazotrophicus* strains showed solubilization potential for various Zn compounds (Suman et al. 2016)

Table 12.2 Studies demonstrating phosphate-solubilization by endophytic rhizobacteria in different crops

Source	Endophytic rhizobacteria	Reference
Bananas (Musa spp.)	*B. subtilis, Agrobacterium tumefaciens, Streptomyces* sp., *B. thuringiensis, B. amyloliquefaciens, Micrococcus luteus*	Matos et al. (2017)
	B. subtilis, Lysinibacillus sp.	Andrade et al. (2014)
Black pepper (*Piper nigrum*)	*Klebsiella* sp., *Enterbacter* sp.,	Jasim et al. (2013)
Cassava (*Manihot esculenta*)	*Pantoea dispersa*	Chen et al. (2014)
Chickpea (*Cicer arietinum*)	*B. subtilis, B. licheniformis*	Saini et al. (2015)
	Bacillus sp., *Klebsiella* sp., *Pseudomonas* sp.	Chhabra and Sharma (2019)
	P. agglomerans, B. cereus, B. sonorensis	Maheshwari et al. (2019a)
Cocoa (*Theobroma cacao*)	Not determined	Ouattara et al. (2019)
Common bean (*Phaseolus vulgaris*)	*Pseudomonas* sp.	Dinić et al. (2014)
Common pea (*Pisum sativum*)	*P. agglomerans, B. cereus, B. sonorensis*	Maheshwari et al. (2019a)
Tumeric (Curcuma longa L.*)*	*B. cereus, B. thuringiensis, B. pumilis, P. putida, Calvibacter michiganensis*	Kumar et al. (2016)
Faba bean (Vicia faba L.)	*Rhizobium nepotum, R. tibeticum*	Rfaki et al. (2015)
Ginseng (*Panax ginseng*)	*Lysinibacillus fusiformis, B. megaterium, B. cereus*	Vendan et al. (2010)
Maize (*Zea mays*)	*Bacillus* spp., *Klebsiella* sp., *E. ludwigii, Pantoea* spp.	de Abreu et al. (2017)
	P. aeruginosa, E. asburiae, Acinetobacter brumalii	Sandhya et al. (2017)
	Klebsiella sp., *K. pneumoniae, B. pumilus Acinetobacter* sp. and *B. subtilis*	Kuan et al. (2016)
	Non-identified species	Manzoor et al. (2017)
	P. pseudoalcaligenes, P. aeruginosa	Jha (2019)
Peach (*Prunus persica*)	*Brevundimonas diminuta, Agrobacterium tumefaciens, Stenotrophonomas rhizosphilia*	Liaqat and Eltem (2016)
Peanut (*Arachis hypogaea*)	*P. agglomerans*	Taurian et al. (2013)

(continued)

Table 12.2 (continued)

Source	Endophytic rhizobacteria	Reference
Pearl millet (*Pennisetum glaucum*)	*Bacillus* spp.	Ribeiro et al. (2018), Kushwaha et al. (2019)
Potato (Solanum tuberosum L.)	*Bacillus* spp., *Pseudomonas* spp., *Serratia* spp.	Abd El-Moaty et al. (2018)
Rice (*Oryza sativa*)	*Paenibacillus kribbensi, B. aryabhattai, K. pneumoniae, B. subtilis, Microbacterium trichotecenolyticum*	Ji et al. (2014)
	Serratia sp., *Pseudomonas* sp.	Yasmin et al. (2016)
Strawberry (*Fragaria ananassa*)	*B. subtilis, B. megaterium*	Dias et al. (2009)
Soybean (*Glycine max*)	*E. sakazakii, P. straminae, Acinetobacter calcoaceticus*	Kuklinsky-Sobral et al. (2004)
Sugarcane (*Saccharum officinarum* L)	*Herbaspirillum* spp., *Bacillus* spp.	Silva et al. (2015)
	Burkholderia mallei, B. cepacia, Proteus vulgaris, Pasteurella multocida, K. pneumoniae, K. oxytoca, E. cloacae, C. freundii	Awais et al. (2019)
	Gluconacetobacter diazotrophicus	Crespo et al. (2011)
Tea (*Camellia sinensis* L.)	*Bacillus, Brevibacterium, Paenibacillus, Lysinibacter*	Borah et al. (2019)
Tomato (*Solanum lycopersicum*)	*Lysinibacillus* spp.	Sahu et al. (2018)
Wheat (Triticum aestivum)	*Stenotrophomonas maltophilia, Chryseobacterium, Flavobacterium, P. mexicana*	Youseif (2018)
	Non-identified strains	Batool and Iqbal (2018)
Wild mint (Mentha arvensis)	*Bacillus sp.*	Prakash and Arora (2019)

and the endophytic *G. diazotrophicus* inhabiting sugarcane have shown to possess Zn solubilization abilities alongside other multifarious PGP activities (Saravanan et al. 2007; Natheer and Muthukkaruppan 2012).

Yaish et al. (2015), isolated endophytic bacteria from the date palm tree (*Phoenix dactylifera* L.), identified as *P. aeruginosa*, *P. monteilii*, *P. putida*, *Acitenobacter brumalii*, *E. asburiae*, *Sinorhizobium meliloti*, *P. thivervalensis*, *P. fulva*, and *P. lini* were capable of solubilizing Zn oxide (ZnO). The Gram-positive *B. aryabhattai* was also shown to improve the growth of soybean and wheat due to Zn solubilizing processes (Ramesh et al. 2014). Investigations on rhizobial and *Pseudomonas* cultures demonstrated the in vitro solubilization of different forms of insoluble Zn (Thirumal et al. 2017). The ability to solubilize various sources of insoluble Zn has been emphasized in the selection of potential endophytes for enhancement of Zn uptake in plants (Singh et al. 2018). Other endophytic ZSB include species of *Bacillus, Chryseobacterium, Paenibacillus, Rhodococcus, Staphylococcus, Achromobacter, Acinetobacter, Enterobacter, and Klebsiella* (Suman et al. 2016). Recently, Kushwaha et al. (2019) also observed that endophytic *Bacillus* strains from pearl millet exhibited Zn solubilization potential and had multiple roles in stress tolerance of the plant. The use of such ZSB can increase Zn uptake by filed crops, which would in turn lead to their improved growth and yield (Suman et al. 2016).

12.2.5 Endophytic Rhizobacteria and Iron Acquisition in Plants

Iron is the fourth most abundant element in soil and is an important micronutrient required by plants for many physiological processes (Saha et al. 2016). However, most agricultural soils are Fe-deficient because the element occurs in the insoluble ferric (Fe^{3+}) form that is unavailable for plant uptake (Rajkumar et al. 2010; Arora and Verma 2017; Singh et al. 2019). Some microorganisms have developed a special Fe acquisition mechanism under these Fe-limiting conditions by producing certain special metabolites known as siderophores (Maheshwari et al. 2019b).

Siderophores are secondary metabolites with high affinity for Fe^{3+} (Goswami et al. 2016; Arora and Verma 2017), and under Fe-limiting conditions, siderophores complex with Fe^{3+-}, a phenomenon which is important for enhancing Fe availability in the rhizosphere (Ferna´ndez-Scavino and Pedraza 2013; Boiteau et al. 2016; Chhabra and Dowling 2017). It is proposed that once the siderophores bind onto Fe^{3+}, the acquisition of the bound Fe by plants can occur by the degradation of the chelates or complexes (Rajkumar et al. 2009). According to Loaces et al. (2011), siderophore production is a common trait among the free-living PGPR (Souza et al. 2015) and is rarely reported for the endophytic rhizobacteria. Recent literature suggests that only a few endophytic bacterial isolates possess this trait (Brigido et al. 2019), investigated mainly as a bio-control agent against plant pathogens (Suman et al. 2016). In such cases, the siderophores chelate most of the Fe present in the rhizosphere and prevent the proliferation of pathogens due to its non-availability in the rhizosphere soil (Mitter et al. 2013; Olanrewaju et al. 2017). Nevertheless, endophytic rhizobacteria can also produce these metabolites under Fe-stress and aid in plant Fe acquisition (Ghavami et al. 2017; Perez-Rosales et al. 2017), and endophytic genera like *Pantoea, Bacillus*, *Burkholderia*, and *Pseudomonas* can increase the concentration of bioavailable Fe in plant tissues (Maheshwari et al. 2019a).

Endophytic siderophore producers that include *Brevundimonas diminuta, Leifsonia shinshuensis, Sphingomonas parapaucimobilis, Brevundimonas vesicularis*, and *Agrobacterium tumefaciens* have been identified from pear and peach roots (Liaqat and Eltem 2016). *Bacillus* sp., *Pseudomonas* sp., and *Stenotrophomonas* sp. are also recognized among the effective siderophore-producing endophytes (Jasim et al. 2014). *Serratia* sp. and *Pseudomonas* sp. from rice have been recently reported to produce siderophores by Yasmin et al. (2016). Siderophore-producing endophytic *P. agglomerans* from peanuts (Taurian et al. 2013), and in turmeric (Kumar et al. 2016) have also been reported. The endophytic *Bacillus* sp. and *P. putida* were also associated with siderophore production. Similar studies on pepper endophytic *Paenibacillis polymyxa* by Phi et al. (2010) also exhibited such abilities by Vendan et al. (2010). The endophytic bacteria such as *B. cereus, B. flexus, B. megaterium, Lysinibacillus fusiformis, L. sphaericus, Microbacterium phyllosphaerae*, *Micrococcus luteus* isolated from maize also showed excellent siderophore production. Investigations by Youseif (2018) also demonstrated siderophore production capabilities by wheat-root endophytic *Stenotrophomonas maltophilia, Chryseobacterium sp, Falvobacterium sp.*, and *Pseudoxanthomonas mexicana.* In another study, Maheshwari et al. (2019b), characterized siderophore-producing endophytic bacteria from chickpea (*Cicer arietinum*) and pea (*Pisum sativum*). Earlier, Wani and Khan (2010) stated that chickpea endophytic *Pseudomonas sp.* was one of the dominant siderophore-producing genera of the plant. Patel et al. (2017b), observed endophytic rhizobacterial isolates identified as *Bacillus, Klebsiella, Microbacterium*, and *Enterobacter* species which showed excellent siderophore production abilities. Similarly, siderophore-producing endophytes have also been isolated from maize and canola (Ghavami et al. 2017), corn (Szilagyi-Zecchin et al. 2014), banana, etc. (Ouma et al. 2014).

Siderophore-producing endophytes are important to crops not only directly by improving Fe availability for plant uptake but also indirectly by depriving Fe required to plant pathogens (Chhabra and Dowling 2017; Aloo et al. 2019b). The completed genome analyses of endophytic microbes like *Enterobacter* species have shown that they contain a large number of genes that code for siderophore transporter proteins (Taghavi et al. 2010). The production of siderophores is a classic example of how rhizobacteria can improve Fe availability in the plant rhizosphere and due to its indisputable role in plant nutrition, further investigations on siderophore-producing rhizobacteria are necessary (Aloo et al. 2019a).

12.3 Ecological Significance of Endophytes in Mineral Nutrients Acquisition by Plants

Endophytic rhizobacteria are considered as sub-sets of rhizosphere microbiome that have acquired the ability to colonize plant root tissues and exhibit specialized and unique lifestyles (Compant et al. 2010; Dheeman et al. 2017). Despite their special interaction with plants, endophytes share all the important PGP traits with other rhizobacteria (Compant et al. 2005). However, they possess characteristics that are distinct from rhizospheric bacteria, suggesting that not all rhizospheric bacteria can enter plants, and/or that once inside their hosts, they change their lifestyles to adapt to internal habitats within plants (Monteiro et al. 2012; Sessitsch et al.

2012). For instance, a study on plant colonization and the establishment of symbionts by Hardoim et al. (2015) showed the presence of significant putative properties in endophytes compared to other types of bacteria interacting with plants.

There is an increasing interest in harnessing the potential of endophytic microbes to develop sustainable crop production systems. Although endophytic rhizobacteria are considered a subset of the rhizospheric microflora, their endophytic lifestyle offers them a myriad of advantages over rhizospheric growth (Compant et al. 2010). For instance, they establish themselves in sheltered micro-environments within the plant root tissues (Castanheira et al. 2017), which are protective ecological niches that provide them with safe, consistent, and undisturbed environments as opposed to external rhizobacteria (Senthilkumar et al. 2011). Literature advances that endophytic microbes are relatively protected from external biotic and biotic environmental stresses, unlike their external counterparts whose survivability and colonizability are largely dependent on extrinsic soil factors (Rajkumar et al. 2009; Suman et al. 2016; Waghunde et al. 2017; Lata et al. 2019; Dubey et al. 2020).

Living endophytically allows these bacteria to maintain close contact with plant root tissues for the direct and constant supply of nutrients and their beneficial effects can be exerted onto the host plants more directly (Lata et al. 2019). The plant endosphere niche presents a unique habitat, and bacterial endophytes possibly have differential functions, specializations, adaptations, and competence (Compant et al. 2010). The diversity of endophytic communities also varies depending on host plant species and genotypes, location, developmental stages, and local environmental conditions (Shi et al. 2014). Nevertheless, the direct and intimate interactions that endophytic rhizobacteria form with plant root tissues makes them highly valuable tools and suitable candidates for improving mineral nutrient acquisition in plants more directly and efficiently (Sreejith et al. 2019).

12.4 Conclusions and Future Prospects

The need for eco-friendly crop fertilization alternatives is increasingly becoming urgent. However, endophytic rhizobacteria have not been fully understood and the prospects of finding unique and interesting bacteria are great. Identifying endophytic rhizobacterial strains with multiple PGP functions for specific plants can definitely pave way for more benefits in terms of plant mineral nutrients acquisition. As such, present and future research work should focus on the largely unexplored rhizobacterial endophytes and their potential uses for mineral nutrients acquisition in plants (Turner et al. 2013). Most plant-endophyte interactions have involved rhizobia and legumes and future research should explore fresh alternatives on their application for other agronomically important crops (Suman et al. 2016).

Although there is a wealth of information on culture-dependent and independent characterization of endophytic rhizobacterial diversity and their associated in vitro PGP mechanisms, reports on their practical applications as plant inoculants under field conditions are extremely scarce (Liu et al. 2017). Several endophytic rhizobacteria have been identified in laboratory studies but generally fail to give consistent results under field conditions and there is need to understand the complex dynamics that control plant-endophyte associations probably by identifying genes that govern these relationships at the molecular level. Although some studies have been conducted in this area, they remain limited and genomic analyses can decipher into the capabilities of endophytes and their roles in plant mineral acquisition. Our knowledge about the plant-microbe interactions can greatly be enhanced using metabolomic, genomic, and transcriptomic methods (Dubey et al. 2020). At the moment, only a limited number of genes that contribute to endophytic invasion and colonization have been identified. Perhaps whole-genome sequencing of these organisms will facilitate the identification of novel isolates and their successful exploitation for plant mineral nutrients acquisition. Further analysis of the sequenced genomes and characterization of the involved genes can also help to improve our understanding of their interaction with plants (Compant et al. 2010) for full exploitation. These efforts can also lead to the identification of some new genes required for endophytic lifestyle but there would be a need to separate the common genes for rhizosphere colonization from those involved in the endophytic lifestyle. Additionally, a more comprehensive understanding of whether these organisms are likely to establish themselves in plants if applied as biofertilizers is needed (Compant et al. 2010).

Numerous reports have revealed a range of beneficial features of the endophytic rhizobacteria for plant mineral nutrients acquisition. Nevertheless, there is still a great scope of further exploration and identification of more novel functions. For instance, research on N_2 fixation and P solubilization abilities by endophytic plant rhizobacteria continues to expand, but very little strides have been made regarding K solubilization yet K is the third major essential macronutrient for plant growth. Similarly, limited work has been carried out on S-oxidation (Dhiman et al. 2019). A combination of both traditional and modern biotechnological methods will help in advancements toward improved plant mineral nutrients acquisition and sustainable agriculture (Waghunde et al. 2017). Although a broad range of endophytes with traits for enhancing mineral nutrient acquisition in different plants have been described, only a few of these have conclusively been studied to demonstrate their significance in plants (Chhabra and Dowling 2017). Furthermore, the impact of endophytic colonization and enhanced nutrient uptake in plants can be varied depending on plant host species/cultivars, endophyte strains, and environmental conditions (Shi et al. 2014).

The successful manipulation of the plant microbiome can substantially contribute to sustainable agricultural production (Bakker et al. 2012; Tkacz et al. 2015), by reducing the need for chemical inputs (Adesemoye et al. 2009; Kandel et al. 2017) and GHG emissions (Singh et al. 2010). This chapter provides a comprehensive review of the putatie functions and ecological significance of endophytic PGPR for mineral nutrient acquisition in plants. Taking into consideration the intimate relationships they form with their plant hosts, these rhizobacteria present special tools for improving plant mineral nutrients acquisition and could be better plant growth promoters than their external counterparts (Lata et al. 2019). Endophytes are indeed fascinating life forms and there is no doubt that their intricate lifestyles and plant interactions still require better understanding to facilitate their application as viable alternatives to artificial fertilizers for agricultural sustainability.

References

Abd El-Moaty NM, Khalil HMA, Gomaa HH, Ismail MA, El-Dougdoug KA (2018) Isolation, characterization, and evaluation of multi-trait plant growth promoting rhizobacteria for their growth promoting. Middle East J Appl Sci 8:554–566

Adesemoye AO, Torbert H, Kloepper JW (2009) Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microb Ecol 58:921–929

Ahemad M, Kibret M (2014) Mechanisms and applications of plant growth promoting rhizobacteria: current perspective. J King Saud Univ-Sci 26:1–20. https://doi.org/10.1016/j.jksus.2013.05.001

Ahmad M, Nadeeem SM, Naveed M, Zahid ZA (2016) Potassium-solubilizing bacteria and their application in agriculture. In: Meena V, Maurya B, Verma J, Meena R (eds) Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi, pp 293–313

Ahmed HF, Badawy HH, Mahmoud SM, El-Dosouky MM (2016) Characterization of *Gluconacetobacter diazotrophicus* isolated from sugarcane (*Saccharum officinarum*) cultivated in Upper Egypt. Assiut J Agric Sci 47:569–582

Aloo BN, Mbega ER, Makumba BA (2019a) Rhizobacteria-based technology for sustainable cropping of potato (*Solanum tuberosum* L.). Potato Res: 1–21. https://doi.org/10.1007/s11540-019-09432-1

Aloo BN, Makumba BA, Mbega ER (2019b) The potential of Bacilli rhizobacteria for sustainable crop production and environmental sustainability. Microbiol Res 219:26–39. https://doi.org/10.1016/j.micres.2018.10.011

Alves GC, Videira SS, Urquiaga S, Reis VM (2015) Differential plant growth promotion and nitrogen fixation in two genotypes of maize by several *Herbaspirillum* inoculants. Plant Soil 387:307–321. https://doi.org/10.1007/s11104-014-2295-2

Andrade LF, de Souza GLOD, Nietsche S, Xavier AA, Costa MR, Cardoso AMS, Pereira MCT, Pereira DFGS (2014) Analysis of the abilities of endophytic bacteria associated with banana tree roots to promote plant growth. J Microbiol 52:27–34. https://doi.org/10.1007/s12275-014-3019-2

Annapurna J, Chowdary I, Lalitha G, Ramakrishna S, Iyengar D (2004) Phytochemical screening and in vitro bioactivity of *Cnidoscolus aconitifolius* (Euphorbiaceae). Pharm Biol 42:91–93

Archana DS, Nandish MS, Savalagi VP, Alagawadi AR (2013) Characterization of potassium solubilizing bacteria (KSB) from rhizosphere soil. Bioinfolet 10:248–257

Arora NK, Verma M (2017) Modified microplate method for rapid and efficient estimation of siderophore produced by bacteria. 3 Biotech 7:381. https://doi.org/10.1007/s13205-017-1008-y

Asaf S, Khan MA, Khan AL, Waqas M, Shahzad R, Kim AY, Kang SM, Lee IJ (2017) Bacterial endophytes from arid land plants regulate endogenous hormone content and promote growth in crop plants: an example of *Sphingomonas sp.* and *Serratia marcescens*. J Plant Interact 12:31–38

Awais M, Tariq M, Ali Q, Khan A, Ali A, Nasir IA, Husnain T (2019) Isolation, characterization and association among phosphate solubilizing bacteria from sugarcane rhizosphere. Cytol Genet 53:86–95. https://doi.org/10.3103/S0095452719010031

Bakker MG, Manter DK, Sheflin AM, Weir TL, Vivanco JM (2012) Harnessing the rhizosphere microbiome through plant breeding and agricultural management. Plant Soil 360:1–13

Baliyan N, Dheeman S, Maheshwari DK, Dubey RC, Vishnoi VK (2018) Rhizobacteria isolated under field first strategy improved chickpea growth and productivity. Environ Sustain 1:461–469

Bapiri A, Asgharzadeh A, Mujallali H, Khavazi K, Pazira E (2012) Evaluation of zinc solubilization potential by different strains of fluorescent Pseudomonads. J Appl Sci Environ Manag 16:295–298

Batool S, Iqbal A (2018) Phosphate solubilizing rhizobacteria as alternative of chemical fertilizer for growth and yield of *Triticum aestivum* (Var. Galaxy 2013). Saudi J Biol Sci. https://doi.org/10.1016/j.sjbs.2018.05.024

Benhizia Y, Benhizia H, Benguedouar A, Muresu R, Giacomini A, Squartini A (2004) Gamma proteobacteria can nodulate legumes of the genus *Hedysarum*. Syst Appl Microbiol 27:462–468

Bhagya I, Rajkumar S (2017) Host specificity and plant growth promotion by bacterial endophytes. Curr Res Microbiol Biotechnol 5:1018–1030

Bhatt K, Maheshwari DK (2020) Zinc solubilizing bacteria (*Bacillus megaterium*) with multifarious plant growth promoting activities alleviates growth in *Capsicum annuum* L. 3 Biotech 10:36. https://doi.org/10.1007/s13205-019-2033-9

Billah M, Khan M, Bano A, Hassan TU, Munir A, Gurmani AR (2019) Phosphorus and phosphate solubilizing bacteria: keys for sustainable agriculture. Geomicrobiol J 36:904–916. https://doi.org/10.1080/01490451.2019.1654043

Boiteau RM, Mende DR, Hawco NJ, Mcllvin MR, Fitzsimmons JN, Saito MA, Sedwick PN, DeLong EF, Repeta DJ (2016) Siderophore-based microbial adaptations to iron scarcity across the eastern Pacific Ocean. Proc Natl Acad Sci U S Am Natl Acad Sci US 113:14237–14242

Borah A, Das R, Mazumdar R, Thakur D (2019) Culturable endophytic bacteria of *Camellia* species endowed with plant growth promoting characteristics. J Appl Microbiol 127:825–844. https://doi.org/10.1111/jam.14356

Brader G, Compant S, Vescio K, Mitter B, Trognitz F, Ma LJ, Sessitsch A (2017) Ecology and genomic insights into plant-pathogenic and plant-non pathogenic endophytes. Annu Rev Phytopathol 55:61–83

Brigido C, Singh S, Menéndez E, Tavares MJ, Glick BR, Felix MR, Oliveira S, Carvalho M (2019) Diversity and functionality of culturable endophytic bacterial communities in chickpea plants. Plants 8:42

Bulgarelli D, Schlaeppi K, Spaepen S, van Thermaat EVL, Schulze-Lefert P (2013) Structure and functions of the bacterial microbiota of plants. Annu Rev Plant Biol: 807–838. https://doi.org/10.1146/annurev-arplant-050312-120106

Castanheira NL, Dourado AC, Pais I, Samedo J, Scotti-Campos P, Borges N, Fareleira P (2017) Colonization and beneficial effects on annual ryegrass by mixed inoculation with plant growth promoting bacteria. Microbiol Res 198:47–55

Chandra S, Choure K, Dubey RC, Maheshwari DK (2007) Rhizosphere competent *Mesorhizobium loti* MP6 induces root hair curling, inhibits *Sclerotinia sclerotiorum* and enhances growth of Indian mustard (*Brassica campestris*). Braz J Microbiol 38(1):124–130

Chen PY, Pekha PD, Arunshen AB, Lai WA, Young CC (2006) Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl Soil Ecol 34:33–41

Chen Y, Fan JB, Du L, Zhang QH, He YQ (2014) The application of phosphate solubilizing endophyte Pantoea dispersa triggers the microbial community in red acidic soil. Appl Soil Ecol 84:235–244

Chhabra S, Dowling DN (2017) Endophyte-promoted nutrient acquisition: phosphorus and iron. In: Doty SL (ed) Functional importance of the plant microbiome. Springer, Cham, pp 21–42

Chhabra S, Sharma P (2019) Non rhizobial endophytic bacteria from Chickpea (*Cicer arietinum* L.) tissues and their antagonistic traits. J Appl Nat Sci 11:346–351

Choudhary ATMA, Kennedy IR (2004) Prospects and potentials for systems of biological nitrogen fixation in sustainable rice production. Biol Fertil Soils 39:219–227

Compant S, Clement C, Sessitsch A (2010) Plant growth-promoting bacteria in the rhizo and endosphere of plants their role, organization, mechanisms involved and prospects for utilization. Soil Biol Biochem 42:669–678

Compant S, Duffy B, Nowak J, Clement C, Barka EA (2005) Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. Appl Environ Biol 71:4951–4959

Coutinho BG, Licastro D, Mendonca-Previato L, Cámara M, Venturi V (2015) Plant influenced gene expression in the rice endophyte *Burkholderia kururiensis* M130. Mol Plant Microbe Interact 28:10–21

Crespo JM, Boiardi JL, Luna MF (2011) Mineral phosphate solubilization activity of *Gluconacetobacter diazotrophicus* under P-limitation and plant root environment. Agric Sci 2:16–22

Daman M, Kaloori K, Gaddam B, Kausar R (2016) Plant growth promoting substances (phytohormones) produced by rhizobacterial strains isolated from the rhizosphere of medicinal plants. Int J Pharm Sci Rev Res 37:130–136

Dasan AS (2012) Compatibility of agrochemicals on the growth of phosphorous mobilizing bacteria *Bacillus megaterium* var. phosphaticum potassium mobilizing bacteria *Frateuria aurantia.* Appl Res Dev Inst J 6:118–134

Day DA, Poole PS, Tyermanc SD, Rosendahl L (2001) Ammonia and amino acid transport across symbiotic membranes in nitrogen fixing legume nodules. Cell Mol Life Sci 58:61–71

de Abreu CS, Figueiredo JEF, Oliveira CA, dos Santos VL, Gomes EA, Ribeiro VP, Lana UGP, Marriel IE (2017) Maize endophytic bacteria as mineral phosphate solubilizers. Genet Mol Res 16:1–13

Defez R, Anna Andreozzi A, Bianco C (2017) The overproduction of Indole-3-acetic acid (IAA) in endophytes upregulates nitrogen fixation in both bacterial cultures and inoculated rice plants. Microb Ecol 74:441–452

Dheeman S, Baliyan N, Dubey RC, Maheshwari DK, Kumar S, Chen L (2020) Combined effects of rhizo-competitive rhizosphere and non-rhizosphere *Bacillus* in plant growth promotion and yield improvement of *Eleusine coracana* (Ragi). Can J Microbiol 66(2):111–124

Dheeman S, Maheshwari DK, Baliyan N (2017) Bacterial endophytes for ecological intensification of agriculture. In: Maheshwari DK (ed) Endophytes: biology and biotechnology. Springer International Publishing, Cham, pp 193–231

Dhiman S, Dubey RC, Baliyan N, Kumar S, Maheshwari DK (2019a) Application of potassium-solubilising Proteus mirabilis MG738216 inhabiting cattle dung in improving nutrient use efficiency of *Foeniculum vulgare* Mill. Environ Sustain 2:401–409

Dhiman S, Dubey RC, Maheshwari DK, Kumar S (2019b) Sulfur-oxidizing buffalo dung bacteria enhance growth and yield of *Foeniculum vulgare* Mill. Can J Microbiol 65(5):377–386

Dhole A, Shelat H, Vyas P, Jhala Y, Bhange M (2016) Endophytic occupation of legume root nodules by nifH-positive non-rhizobial bacteria, and their efficacy in the groundnut (*Arachis hypogae*a). Ann Microbiol 66:1397–1407

Di Benedetto NA, Corbo MR, Campaniello D, Cataldi MP, Bevilacqua A, Sinigaglia M, Flagella Z (2017) The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: a focus on wheat. AIMS Microbiol 3:413–434

Dias ACF, Costa FEC, Andreote FD, Lacava PT, Teixeira MA, Assumpção LC, Araújo WL, Azevedo JL, Melo IS (2009) Isolation of micropropagated strawberry endophytic bacteria and assessment of their potential for plant growth promotion. World J Microbiol Biotechnol 25:189–195

Dinić Z, Ugrinović M, Bosnić P, Mijatović M, Zdravković J, Miladinović M, Jošić D (2014) Solubilization of inorganic phosphate by endophytic *Pseudomonas* sp. from French bean nodules. Ratar Povrt 51:100–105. https://doi.org/10.5937/ratpov51-6222

Doty SL (2011) Nitogen-fixing endophytic bacteria for improved plant growth. In: Maheshwari DK (ed) Bacteria in agrobiology: plant growth responses. Springer-Verlag, Berlin, Heidelberg, pp 183–199

Doty SL, Sher AW, Fleck ND, Khorosani M, Bumgarner RE, Khan Z, Ko AWK, Kim SH, Deluca TH (2016) Variable nitrogen fixation in wild populus. PLoS ONE 11:e0155979

Dubey RK, Tripathi V, Prabha R, Chaurasia R, Singh DP, Rao CS, El-Keblawy A, Abhilash PC (2020) Belowground microbial communities: key players for soil and environmental sustainability. In: Dubey RK, Tripathi V, Prabha R, Chaurasia R, Singh DP, Rao CS, El-Keblawy A, Abhilash PC (eds) Unravelling the soil microbiome: perspectives for environmental sustainability. Springer International Publishing, Cham, pp 5–22

Erisman JW, Sutton MA, Galloway JN, Klimont Z, Winiwarter W (2008) How a century of ammonia synthesis changed the world. Nat Geosci 1:636–639. https://doi.org/10.1038/ngeo325

Ferna´ndez-Scavino A, Pedraza RO (2013) The role of siderophores in plant growth-promoting bacteria. In: Maheshwari DK, Saraf M, Aeron A (eds) Bacteria in agribiology: crop productivity. Springer, Heidelberg, pp 265–285

Ghavami N, Alikhani HA, Pourbabei AA, Besharati H (2017) Effects of two new siderophore-producing rhizobacteria on growth and iron content of maize and canola plants. J Plant Nutr 40:736–746. https://doi.org/10.1080/01904167.2016.1262409

Glick BR (2014) Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiol Res 169:30–39

Goswami D, Thakker JN, Dhandhukia PC (2016) Portraying mechanics of plant growth promoting rhizobacteria (PGPR): a review. Congent Food Agric 2:1–9

Goswami SP, Maurya BR, Dubey AN, Singh NK (2019) Role of phosphorus solubilizing microorganisms and dissolution of insoluble phosphorus in soil. Int J Chem Stud 7:3905–3913

Goteti PK, Emmanuel LAE, Desai S, Shaik MHA (2013) Prospective zinc solubilising bacteria for enhanced nutrient uptake and growth promotion in maize (*Zea mays* L.). Int J Microbiol 2013:869697. https://doi.org/10.1155/2013/869697

Gupta G, Panwar J, Jha PN (2013) Natural occurrence of *Pseudomonas aeruginosa*, a dominant cultivable diazotrophic endophytic bacterium colonizing *Pennisetum glaucum* (L.) R. Br. Appl Soil Ecol 64:252–261

Hafeez B, Khanif YM, Saleem M (2013) Role of zinc in plant nutrition—a review. Am J Exp Agric 3:374–391

Hardoim PR, van Overbeek LS, Berg G, Pirttila AM, Compant S, Campisano A, Doring M, Sessitsch A (2015) The hidden world within plants: ecological and evolutionary considerations for defining functioning of microbial endophytes. Microbiol Mol Biol 79:293–320

Harman GE, Uphoff N (2019) Symbiotic root-endophytic soil microbes improve crop productivity and provide environmental benefits. Scientifica 9106395

Howarth RW (2008) Coastal nitrogen pollution: a review of sources and trends globally and regionally. Harmful Algae 8:14–20

Htwe AZ, Moh SM, Soe KM, Moe K, Yamakawa T (2019) Effects of Biofertilizer produced from *Bradyrhizobium* and *Streptomyces griseoflavus* on plant growth, nodulation, nitrogen fixation, nutrient uptake, and seed yield of Mung Bean, Cowpea, and Soybean. Agronomy 9:77. https://doi.org/10.3390/agronomy9020077

Hui L, Xiao QW, Jia-Hong R, Jian-Ren Y (2011) Isolation and identification of phosphobacteria in poplar rhizosphere from different regions of China. Pedosphere 21:90–97

Jasim B, Jimtha JC, Jyothis M, Radhakrishnan EK (2013) Plant growth promoting potential of endophytic bacteria isolated from Piper nigrum. Plant Growth Regul 71:1–11

Jasim B, Joseph AA, John CJ, Mathew J, Radhakrishnan EK (2014) Isolation and characterization of plant growth promoting endophytic bacteria from the rhizome of *Zingiber officinale*. 3 Biotech 4:197–204

Jha Y (2019) Endophytic bacteria as a modern tool for sustainable crop management under stress. In: Giri B, Prasad R, Wu QS, Varma A (eds) Biofertilizers for sustainable agriculture and environment. Springer International Publishing, Cham, pp 203–223

Ji SH, Gururani MA, Chun SC (2014) Isolation and characterization of plant growth promoting endophytic diazotrophic bacteria from Korean rice cultivars. Microbiol Res 169:83–98. https://doi.org/10.1016/j.micres.2013.06.003

Kandel SL, Joubert PM, Doty SL (2017) Bacterial endophyte colonization and distribution within plants. Microorganisms 5:77. https://doi.org/10.3390/microorganisms5040077

Khan KS, Joergersen RG (2009) Changes in microbial biomass and P fractions in biogenic household waste compost amended with inorganic P fertilizers. Bioresour Technol 100:303–309

Kleingesinds CK, de Santi Ferrara FI, Floh ELS, Aldar MPM, Barbosa HR (2018) Sugarcane growth promotion by *Kosakania* sp. ICB117 an endophytic and diazotrophic bacterium. Afr J Microbiol Res 12:105–114. https://doi.org/10.5897/AJMR2017.8738

Kuan KB, Othman R, Rahim KA, Shamsuddin ZH (2016) Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilization of maize under Greenhouse conditions. PLoS ONE 11:1–19

Kuklinsky-Sobral J, Araújo WL, Mendes R, Geraldi IO, Pizzirani-Kleiner AA, Azevedo JL (2004) Isolation and characterization of soybean associated bacteria and their potential for plant growth promotion. Environ Microbiol 6:1244–1251

Kumar A, Maurya BR, Raghuwanshi R (2014) Isolation and characterization of PGPR and their effect on growth, yield and nutrient content in wheat (*Triticum aestivum* L.). Biocatal Agric Biotechnol 3:121–128

Kumar A, Singh R, Yadav A, Giri DD, Singh KP, Pandey KD (2016) Isolation and characterization of bacterial endophytes of Curcuma longa L. 3 Biotech 6:60

Kumar SS, Ram KR, Kumar DR, Panwar S, Prasad CS (2013) Biocontrol by plant growth promoting rhizobacteria against black scurf and stem canker disease of potato caused by R. Solani. Arch Phytopathol Plant Prot 46:487–502

Kumar U, Paneerselvam P, Govindasamy V, Vithakumar L, Senthikumar M, Banik A, Annapuma K (2017) Long-term aromatic rice cultivation effect on frequency and 16 diversity of diazotrophs in its rhizosphere. Ecol Eng 101:227–236

Kushwaha P, Kashyap PL, Kuppusamy P, Srivastava AK, Tiwari RK (2019) Functional characterization of endophytic bacilli from pearl millet (*Pennisetum glaucum*) and their possible role in multiple stress tolerance. Plant Biosyst. https://doi.org/10.1080/11263504.2019.1651773

Lata RK, Chowdhury S, Gond SK, White JF Jr (2018) Induction of abiotic stress tolerance in plants by endophytic microbes. Lett Appl Microbiol 66:268–276. https://doi.org/10.1111/lam.12855

Lata RK, Divjot K, Nath YA (2019) Endophytic microbiomes: biodiversity, ecological significance and biotechnological applications. Res J Biotechnol 14:142–162

Lesueur D, Deaker R, Herrmann L, Bräu L, Jansa J (2016) The production and potential of biofertilizers to improve crop yields. In: Arora NK, Menhaz S, Balestrini R (eds) Bioformulations for sustainable agriculture. Springer, New Delhi, pp 71–92

Li Y, Liu X, Hao T, Chen S (2017) Colonization and Maize growth promotion induced by phosphate solubilizing bacterial isolates. Int J Mol Sci 18:1253

Liaqat F, Eltem R (2016) Identification and characterization of endophytic bacteria isolated from in vitro cultures of peach and pea rootstocks. 3 Biotech 6:2–9

Liu H, Carvalhais LC, Crawford M, Singh E, Dennis PG, Pieterse CMJ, Schenk PM (2017) Inner plant values: diversity, colonization and benefits from endophytic bacteria. Front Microbiol 8:2552. https://doi.org/10.3389/fmicb.2017.02552

Loaces I, Ferrando L, Scavino AF (2011) Dynamics, diversity and function of endophytic siderophore-producing bacteria in rice. Microb Ecol 61:606–618

Maheshwari DK (2018) Endophytes: biology and biotechnology. Springer International Publishing, Cham

Maheshwari R, Bhutani N, Bhardwaj A, Suneja P (2019a) Functional diversity of cultivable endophytes from *Cicer arietinum* and *Pisum sativum*: bioprospecting their plant growth potential. Biocatal Agric Biotechnol 20:101229. https://doi.org/10.1016/j.bcab.2019.101229

Maheshwari R, Bhutani N, Suneja P (2019b) Screening and characterization of siderophore producing endophytic bacteria from *Cicer arietinum* and *Pisum sativum* plants. J Appl Biol Biotechnol 7:7–14. https://doi.org/10.7324/JABB.2019.70502

Manzoor M, Abbasi MK, Sultan T (2017) Isolation of phosphate solubilizing bacteria from maize rhizosphere and their potential for rock phosphate solubilization-mineralization and plant growth promotion. Geomicrobiol J 34:81–95. https://doi.org/10.1080/01490451.2016.1146373

Marcos FCC, Io´rio RPF, Silveira APDD, Ribeiro RV, Machado EC, Lagoˆa AMA (2016) Endophytic bacteria affect sugarcane physiology without changing plant growth. Bragantia 75:1–9

Matos ADM, Gomez ICP, Nietsche S, Xavier AA, Gomes WS, Dos Santos N, Jose A, Pereira MCT (2017) Phosphate solubilization by endophytic bacteria isolated from banana trees. An Acad Bras Ciênc 89:2945–2954

Meena VS, Maurya BR, Verma JP, Aeron A, Kim K, Bajpai V (2015) Potassium solubilizing rhizobacteria (KSR): isolation, identification, and K-release dynamics from waste mica. Ecol Eng 81:340–347

Meena VS, Maurya BR, Verma JP, Verma RS (eds) (2016) Potassium solubilizing microorganisms for sustainable agriculture. Springer, India

Meena SV, Maurya BR, Meena SK, Mishra PK, Bisht JK, Pattanayak A (2018) Potassium solubilization: strategies to mitigate potassium deficiency in agricultural soils. Glob J Biol Agricluture Health Sci 7:1–3

Mehta P, Walia A, Shirkot CK (2015) Functional diversity of phosphate solubilizing plant growth promoting rhizobacteria isolated from apple trees in the Trans Himalayan region of Himachal Pradesh, India. Biol Agric Hortic 31:265–288. https://doi.org/10.1080/01448765.2015.1014420

Mia MAB, Shamsuddin ZH (2010) Nitrogen fixation and transportation by rhizobacteria: a scenario of rice and banana. Int J Bot 6:235–242

Mishra DJ, Mishra UK, Shahi SK (2013) Role of bio-fertilizer inorganic agriculture: a review. Res J Recent Sci 2:39–41

Mitter B, Petric A, Shin MW, Ghain PSG, Hauberg-Lotte L, Reinhold-Hurek B, Nowak J, Sessitsch A (2013) Comparative genome analysis of *Burkholderia phytofirmans* PsJN reveals a wide spectrum of endophytic lifestyles based on interaction strategies with host plants. Front Plant Sci 4:120

Mohammadi K, Sohrabi Y (2012) Bacterial biofertilizers for sustainable crop production: a review. ARPN J Agric Biol Sci 7:307–316

Monteiro RA, Balsanelli E, Wassem R, Marin AM, Brussamarello-Santos LCC, Schmidt MA, Tadra-Sfeir MZ, Pankievicz VCS, Cruz LM, Chubatsu LS, Pedrosa FO, Souza EM (2012) *Herbaspirillum*-plant interactions: microscopical, histological and molecular aspects. Plant Soil 356:175–196

Mus F, Crook MB, Garcia K, Costas AG, Geddes BA, Kouri ED, Paramasivan P, Ryu H, Oldroyd GED, Poole PS, Udvardi MK, Voigt TA, Ane JM, Peters JW (2016) Symbiotic nitrogen fixation and the challenges to its extension to nonlegumes. Appl Environ Microbiol 82:3698–3710. https://doi.org/10.1128/aem.01055-16

Muthukumarasamy R, Clenwerck I, Revathi G, Vadivelu M, Janssens D, Hoste B, Park KD, Son CY, Sa T (2005) Natural association of *Gluconacetobacter diazotrophicus* and diazotrophic *Acetobacter peroxydans* with wetland rice. Syst Appl Microbiol 28:277–286

Mwajita MR, Murage H, Tani A, Kahangi EM (2013) Evaluation of rhizosphere, rhizoplane and phyllosphere bacteria and fungi isolated from rice in Kenya for plant growth promoters. SpringerPlus 2:606

Natheer SE, Muthukkaruppan S (2012) Assessing the in vitro zinc solubilization potential and improving sugarcane growth by inoculating *Gluconacetobacter diazotrophicus*. Ann Microbiol 62:435–441

Nawaz F, Khan N, Shah JA, Khan A, Liaqat A, Ullah S (2017) Yield and yield components of chickpea as affected by various levels of FYM and rhizobium inoculation. Pure Appl Biol 6:346–351. https://doi.org/10.19045/bspab.2017.60033

Ngamau C, Matiru V, Tani A, Muthuri C (2014) Potential use of endophytic bacteria as biofertilizer for sustainable banana (*Musa spp.*) production. Afr J Hortic Sci 8:1–11

Ohyama T, Momose A, Ohtake N, Sueyoshi K, Sato T, Nakanishi Y, Asis CA, Ruamsungsri S, Ando S (2014) Nitrogen fixation in sugarcane. Adv Biol Ecol Nitrogen Fix 3:49–70

Olanrewaju OS, Glick BR, Babalola OO (2017) Mechanisms of action of plant growth promoting bacteria. World J Microbiol Biotechnol 33:197

Olivares J, Bedmar EJ, Sanjuan J (2013) Biological nitrogen fixation in the context of global change. Mol Plant Microbe Interact 26:486–494

Oteino N, Lally RD, Kiwanuka S, Lloyd A, Ryan D, Germaine KJ, Dowling DN (2015) Plant growth promotion induced by phosphate solubilizing endophytic Pseudomonas isolates. Front Microbiol 6:745

Ouattara K, Coulibaly K, Konate I, Kebe BI, Tidou AS, Filali-Maltouf A (2019) Selection of Cocoa tree (*Theobroma cacao* Linn) endophytic bacteria solubilizing tri-calcium phosphate, isolated from seedlings grown on soils of six producing regions of Côte d'Ivoire. Biomed Life Sci 9:842–852

Ouma SO, Magiri EN, Maritu VN, Mugweru J, Ngamau C (2014) Evaluation of nitrogen fixation ability of endophytic bacteria in Kenyan bananas (Musa Spp.) using biochemical and molecular techniques. Int J Sci Technoledge 2:156–163

Pandey PK, Singh S, Singh MC, Singh AK, Yadav SK, Pandey AK, Heisnam P (2018) Diversity, ecology, and conservation of fungal and bacterial endophytes. In: Sharma S, Varma A (eds) Microbial resource conservation. Springer, Cham, pp 393–430

Patel A, Vyas RV, Mankad M, Subbash N (2017a) Isolation and biochemical characterization of rhizobia from rice rhizosphere and their effect on rice growth promotion. Int J Pure Appl Biosci 5:441–451

Patel DH, Naik JH, Amaresan N (2017b) Synergistic effect of root-associated bacteria on plant growth and certain physiological parameters of banana plant (*Musa acuminate*). Arch Agron Soil Sci 64:1021–1031. https://doi.org/10.1080/03650340.2017.1410703

Perez-Rosales E, Alcaraz-Melendez L, Puente ME, Vázquez-Juárez R, Quiroz-Guzmán E, Zenteno-Savín T, Morales-Bojórquez E (2017) Isolation and characterization of endophytic bacteria associated with roots of jojoba (*Simmondsia chinensis* [Link] Schneid). Curr Sci 112:396–401. https://doi.org/10.18520/cs/v112/i02/396-401

Pham VTK, Rediers H, Ghequire MGK, Nguyen HH, De Mot R, Vanderleyden J, Spaepen S (2017) The plant growth-promoting effect of the nitrogen-fixing endophyte *Pseudomonas stutzeri* A15. Arch Microbiol 199:513–517. https://doi.org/10.1007/s00203-016-1332-3

Phi QT, Yu MP, Keyung-Jo S, Choong-Min R, Seung-Hwan P, Jong-Guk K, Sa-Youl G (2010) Assessment of root-associated *Paenibacillus polymyxa* groups on growth promotion and induced systemic resistance in pepper. J Microb Biotechnol 20:1605–1613

Prakash J, Arora NK (2019) Phosphate-solubilizing *Bacillus* sp. enhances growth, phosphorus uptake and oil yield of *Mentha arvensis* L. 3 Biotech 9:126. https://doi.org/10.1007/s13205-019-1660-5

Proença DN, Schwab S, Baldani JI, Morais PV (2017) Diversity and function of endophytic microbial community of plants with economical potential. In: De Azevedo JL, Quecine MC (eds) Diversity and benefits of microorganisms from the tropics. Springer, Cham, pp 209–243

Quecine MC, Araujo WL, Rossetto PB, Ferreira A, Tsui S, Lacava PT, Mondin M, Azevedo JL, Pizzirani-Kleiner AA (2012) Sugarcane growth promotion by the endophytic bacterium *Pantoea agglomerans* 33.1. Appl Environ Microbiol 78:7511–7518. https://doi.org/10.1128/AEM.00836-12

Rafi MM, Krishnaveni MS, Charyulu PBBN (2019) Phosphate-solubilizing microorganisms and their emerging role in sustainable agriculture. In: Buddolla V (ed) Recent developments in applied microbiology and biochemistry. Academic Press, Dordrecht, pp 223–233

Rajkumar M, Ae N, Freitas H (2009) Endophytic bacteria and their potential to enhance heavy metal phytoextraction. Chemosphere 153e160

Rajkumar M, Ae N, Prasad MNV, Freitas H (2010) Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. Trends Biotechnol 28:142–149

Ramaswamy V, Boucher O, Haigh J, Hauglustaine D, Haywood J, Myhre G, Nakajina T, Solomon S (2001) Radiative forcing of climate change. Cambridge University Press, Cambridge, UK, pp 349–416

Ramesh A, Sharma SK, Sharma MP, Yadav N, Joshi OP (2014) Inoculation of zinc solubilizing *Bacillus aryabhattai* strains for improved growth, mobilization and biofortification of zinc in soybean and wheat cultivated in vertisols of central India. Appl Soil Ecol 73:87–96. https://doi.org/10.1016/j.apsoil.2013.08.009

Rfaki A, Nassiri L, Ibijbijen J (2015) Isolation and characterization of phosphate solubilizing bacteria from the rhizosphere of faba bean (*Vicia faba* L.) in Meknes region. Morocco Microbiol Res J Int 6:247–254. https://doi.org/10.9734/BMRJ/2015/14379

Ribeiro VP, Marriel IE, Sousa SM, Lana UGP, Mattos BB, Oliveira CA, Gomes EA (2018) Endophytic *Bacillus* strains enhance pearl millet growth and nutrient uptake under low-P. Braz J Microbiol 49:40–46. https://doi.org/10.1016/j.bjm.2018.06.005

Rosenblueth M, Martinez-Romero E (2006) Bacterial endophytes and their interactions with hosts. Mol Plant Microbe Interact 19:827–837

Ryan PR, Germaine KJ, Franks A, Ryan DJ, Dowling DN (2008) Bacterial endophytes: recent developments and applications. FEMS Microbiol Lett 278:1–9

Saha M, Sarkar S, Sarkar B, Sharma BK, Bhattacharjee S, Tribedi P (2016) Microbial siderophores and their potential applications: a review. Environ Sci Pollut Res 23:3984–3999

Sahu PK, Shivaprakash MK, Subbarayappa CT, Brahmaprakash GP (2018) Effect of bacterial Endophytes *Lysinibacillus* sp. on plant growth and fruit yield of tomato (*Solanum lycopersicum*). Int J Curr Microbiol Appl Sci 7:3399–3408

Saini R, Dudeja SS, Giri R, Kumar V (2015) Isolation, characterization, and evaluation of bacterial root and nodule endophytes from chickpea cultivated in Northern India. J Basic Microbiol 55:74–81

Sandhya V, Shrivastava M, Ali SZ, Prasad VSK (2017) Endophytes from maize with plant growth promotion and biocontrol activity under drought stress. Russ Agric Sci 43:22–34

Santoyo G, Moreno-Hagelsieb G, Orozco-Mosqueda MC, Glick BR (2016) Plant growth-promoting bacterial endophytes. Microbiol Res 183:92–99. https://doi.org/10.1016/j.micres.2015.11.008

Saravanan VS, Madhaiyan M, Thangaraju M (2007) Solubilization of zinc compounds by the diazotrophic, plant growth promoting bacterium *Gluconacetobacter diazotrophicus*. Chemosphere 66:1794–1798. https://doi.org/10.1016/j.chemosphere.2006.07.067

Senthilkumar M, Anandham R, Madhaiyan M, Venkateswaran V, Sa T (2011) Endophytic bacteria: perspectives and applications in agricultural crop production. In: Maheshwari DK (ed) Bacteria in agribiology: crop ecosystems. Springer, Berlin, Heidelberg, pp 61–96

Sessitsch A, Hardoim PR, Döring J, Weilhater A, Krause A, Woyke T, Mitter B, Hauberg-Lotte L, Friedrich F, Rahalkar M, Sarkar A, Bodrossy L, Van Overbeek LS, Brar D, Van Elsas JD, Reinhold-Hurek B (2012) Functional characteristics of an endophyte community colonizing rice roots as revealed by metagenomic analysis. Mol Plant Microbe Interact 25:28–36

Sev TM, Khai AA, Aung A, Yu SS (2016) Evaluation of endophytic bacteria from some rice varieties for plant growth promoting activities. J Sci Innov Res 5:144–148

Shabanamol S, Divya K, George TK, Rishad KS, Sreekumar TS, Jisha MS (2018) Characterization and in planta nitrogen fixation of plant growth promoting endophytic diazotrophic *Lysinibacillus sphaericus* isolated from rice (*Oryza sativa*). Physiol Mol Plant Pathol 102:46–54. https://doi.org/10.1016/j.pmpp.2017.11.003

Shaikh S, Saraf M (2017) Zinc biofortification: strategy to conquer zinc malnutrition through zinc solubilizing PGPR's. Biomed J Sci Tech Res 1:224–226. https://doi.org/10.26717/BJSTR.2017.01.000158

Shakeela S, Padder SA, Bhat ZA (2017) Isolation of phosphate solubilising rhizobacteria and endorhizobacteria from medicinal plant *Picrorhiza kurroa* and their optimization for tricalcium phosphate solubilization. The Pharma Inn 6:160–170

Sharifi P, Paymozd M (2016) Effect of zinc, iron and manganese on yield and yield components of green beans. Curr Opin Agric 5:15–18

Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA (2013) Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus 2:587. https://doi.org/10.1186/2193-1801-2-587

Sharma P, Kumawat KC, Kaur N (2014) Assessment of zinc solubilization by endophytic bacteria in legume rhizospheres. Microbiology 4:439–441

Shi Y, Yang H, Zhang T, Sun J, Lou K (2014) Illumina-based analysis of endophytic bacterial diversity and space-time dynamics in sugar beet on the north slope of Tianshan mountain. Appl Microbiol Biotechnol 98:6375–6385

Shrivastava M, Srivastava PC, D'Souza SF (2018) Phosphate-solubilizing microbes: diversity and phosphates solubilization mechanism. In: Meena V (ed) Role of rhizospheric microbes in soil. Springer, Singapore, pp 137–165

Silva JM, Santos TMC, Albuquerque LS, Montaldo YC, Oliveira JUL, Silva SGM, Nascimento MS, Teixeiria RRO (2015) Potential of endophytic bacteria (*Herbaspirillum* spp. and *Bacillus* spp.) to promote sugarcane growth. Aust J Crop Sci 9:754–760

Silveira APDD, Sala VMR, Cardoso BN, Labanca EG, Cipriano MAP (2016) Nitrogen metabolism and growth of wheat plant under diazotrophic endophytic bacteria inoculation. Appl Soil Ecol 107:313–319. https://doi.org/10.1016/j.apsoil.2016.07.005

Sindhu SS, Sharma R, Sindhu S, Phour M (2019) Plant nutrient management through inoculation of zinc-solubilizing bacteria for sustainable agriculture. In: Giri B, Prasad R, Wu QS, Varma A (eds) Biofertilizers for sustainable agriculture and environment. Springer, Cham, pp 173–201

Singh BK, Bardgett RD, Smith P, Reay DS (2010) Microorganisms and climate change: terrestrial feedback and mitigation options. Nat Rev Microbiol 8:779–790

Singh D, Geat N, Rajawat MVS, Prasanna R, Kar A, Singh AM, Saxena AK (2018) Prospecting endophytes from different Fe or Zn accumulating wheat genotypes for their influence as inoculants on plant growth, yield, and micronutrient content. Ann Microbiol 68:815–833. https://doi.org/10.1007/s13213-018-1388-1

Singh M, Singh D, Gupta AD, Pandey KD, Singh KP, Kumar A (2019) Plant growth promoting rhizobacteria. In: PGPR amelioration in sustainable agriculture. Elsevier, pp 41–66

Smith P, House JI, Bustamante M, Sobocká J, Harper R, Pan G, West PC, Clark JM, Adhya T, Rumpel C, Paustian K, Kuikman P, Cotrufo MF, Elliott JA, McDowell R, Griffiths RI, Asakawa S, Bondeau A, Jain AK, Meersmans J, Pugh TAM (2016) Global change pressures on soils from land use and management. Glob Change Biol 22:1008–1028. https://doi.org/10.1111/gcb.13068

Souza R, Ambrosini A, Passaglia LMP (2015) Plant growth-promoting bacteria as inoculants in agricultural soils. Genet Mol Biol 38:401–419

Sreejith S, Aswani R, Radhakrishnan EK (2019) Agriculturally important biosynthetic features of endophytic microorganisms. In: Verma S, White J Jr (eds) Seed endophytes. Springer, Cham, pp 423–447

Steffen W, Richardson K, Rockstrom J, Cornell SE, Fetzer I, Bennett EM (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:1259855. https://doi.org/10.1126/science.1259855

Suman A, Srivastava AK, Gaur A, Singh P, Singh J, Yadav RL (2008) Nitrogen use efficiency of sugarcane in relation to its BNF potential and population of endophytic diazotrophs at different N levels. Plant Growth Regul 54:1–11

Suman A, Yadav A, Verma P (2016) Endophytic microbes in crops: diversity and beneficial impact for sustainable agriculture. In: Singh DP, Singh H, Prabha R (eds) Microbial inoculants in sustainable agricultural productivity. Springer, New Delhi, pp 117–143

Szilagyi-Zecchin VJ, Ikeda AC, Hungria M, Adamoski D, Kava-Cordeiro VK, Glienke C, Galli-Terasawa LV (2014) Identification and characterization of endophytic bacteria from corn (*Zea mays* L.) roots with biotechnological potential in agriculture. AMB Express 4:1–9. https://doi.org/10.1186/s13568-014-0026-y

Taghavi S, van der Lelie D, Hoffman A, Zhang YB, Walla MD, Vangronsveld J, Newman L, Monchy S (2010) Genome sequence of the plant growth promoting endophytic bacterium *Enterobacter sp.* 638. PLOS Genet 6:e1000943

Taurian T, Anzuay MS, Luduena L, Angelini JG, Munoz V, Valetti L, Fabra A (2013) Effects of single and co-inoculation with native phosphate solubilising strain *Pantoea sp* J49 and the symbiotic nitrogen fixing bacterium Bradyrhizobium sp SEMIA 6144 on peanut (*Arachis hypogaea* L.) growth. Symbiosis 59:77–85

Tavallali V, Rahemi M, Eshghi S, Kholdebarin B, Ramezanian A (2010) Zinc alleviates salt stress and increases antioxidant enzyme activity in the leaves of pistachio (*Pistacia vera* L'.Badami') seedlings. Turk J Agric For 34:349–359

Thirumal G, Reddy RS, Triveni S, Nagaraju Y, Prasannakumar B (2017) Screening of native Rhizobia and *Pseudomonas* strains for plant growth promoting activities. Int J Curr Microbiol Appl Sci 6:616–625

Tkacz A, Cheema J, Chandra G, Grant A, Poole PS (2015) Stability and succession of the rhizosphere microbiota depends upon plant type and soil composition. Multidiscip J Microb Ecol 9:2349–2359. https://doi.org/10.1038/ismej.2015.41

Tsegaye Z, Assefa F, Beyene D (2017) Properties and application of plant growth promoting rhizobacteria. Int J Curr Trends Pharmacobiology Med Sci 2:30–43. https://doi.org/10.15413/ajmr.2017.0104

Turner TR, James EK, Poole PS (2013) The plant microbiome. Genome Biol 14:209. https://doi.org/10.1186/gb-2013-14-6-209

Upreti R, Thomas P (2015) Root-associated bacterial endophytes from Ralstonia solanacearum resistant and susceptible tomato cultivars and their pathogen antagonistic effects. Front Microbiol 6:1–12

Varma PK, Uppala S, Pavuluri K, Chandra KJ, Chapala MM, Kumar KVK (2017) Endophytes: role and functions in crop health. In: Singh D, Singh H, Prabha R (eds) Plant-microbe interactions in agro-ecological perspectives. Springer, Singapore, pp 291–310

Velázquez E, Silva LR, Ramírez-Bahena MH, Peix A (2016) Diversity of potassium-solubilizing microorganisms and their interactions with plants. In: Meena VS, Maurya BR, Verma JP, Meena RS (eds) Potassium solubilizing microorganisms for sustainable agriculture. Springer, India, pp 99–110

Vendan RT, Yu YJ, Lee SHH, Rhee YH (2010) Diversity of endophytic bacteria in ginseng and their potential for plant growth promotion. J Microbiol 48:559

Verma P, Yadav AN, Kazy SK, Saxena AK, Suman A (2013) Elucidating the diversity and plant growth promoting attributes of wheat (*Triticum aestivum*) associated acidotolerant bacteria from Southern hills zone of India. Natl J Life Sci 10:219–226

Verma P, Yadav AN, Khannam KS, Panjiar N, Kumar S, Saxena AK, Suman A (2015) Assessment of genetic diversity and plant growth promoting attributes of psychrotolerant bacteria allied with wheat (*Triticum aestivum*) from the Northern hills zone of India. Ann Microbiol. https://doi.org/10.1007/s13213-014-1027-4

Verma M, Mishra J, Arora NK (2019) Plant growth-promoting rhizobacteria: diversity and applications. In: Sobti R, Arora NK, Kothari R (eds) Environmental biotechnology: for sustainable future. Springer, Singapore, pp 129–173

Waghunde RR, Shelake RM, Shinde MS, Hayashi H (2017) Endophyte microbes: A weapon for plant health management. In: Microorganisms for Green Revolution. Singapore, pp 303–325

Walia A, Shirkot CK (2012) Screening of PGPR to promote early growth of tomato seedlings. Lap Lambert Academic Publishing, Deutschland

Walia A, Guleira S, Chauhan A, Mehta P (2017) Endophytic bacteria: role in phosphate solubilization. In: Maheshwari DK, Annapuma K (eds) Endophytes: crop productivity and protection. Springer, Cham, pp 61–93

Walitang D, Samaddar S, Choudhary A, Chatterjee C, Ahmed S, Sa T (2019) Diversity and plant growth promoting potential of bacterial endophytes in rice. In: Sayyed R, Reddy M, Antonius S (eds) Plant growth promoting rhizobacteria (PGPR): prospects for sustainable agriculture. Springer, Singapore, pp 3–17

Wani PA, Khan MS (2010) Bacillus species enhance growth parameters of chickpea (*Cicer arietinum* L.) in chromium stressed soils. Food Chem Toxicol 48:3262–3267

Wei CY, Lin L, Luo LJ, Xing YX, Hu CJ, Yang LT, Li YR, An Q (2014) Endophytic nitrogen-fixing *Klebsiella variicola* strain DX120E promotes sugarcane growth. Biol Fertil Soils 50:657–666

Yagedari M, Farahani GHN, Mosadeghzad Z (2012) Biofertilizers effects on quantitative and qualitative yield of Thyme (*Thymus vulgaris*). Afr J Agric Res 7:4716–4723

Yaish MW, Antony I, Glick BR (2015) Isolation and characterization of endophytic plant growth-promoting bacteria from date palm tree (*Phoenix dactylifera* L.) and their potential role in salinity tolerance. Antonie Van Leeuwenhoek 107:1519–1532. https://doi.org/10.1007/s10482-015-0445-z

Yasmin S, Zaka A, Imran A, Zahid MA, Yousaf S, Rasul G, Arif M, Mizra MS (2016) Plant growth promotion and suppression of bacterial leaf blight in rice by inoculated bacteria. PLoS ONE 11:e0160688

Youseif SH (2018) Genetic diversity of plant growth promoting rhizobacteria and their effects on the growth of maize plants under greenhouse conditions. Ann Agric Sci 63:25–35. https://doi.org/10.1016/j.aoas.2018.04.002

Zhang A, Zhao G, Gao T, Wang W, Li J, Zhang S, Zhu B (2013) Solubilization of insoluble potassium and phosphate by *Paenibacillus kribensis* CX-7: a soil microorganism with biological control potential. Afr J Microbiol Res 7:41–47