Chapter 11
Rhizobial Inoculants for Sustainable Agriculture: Prospects and Applications

Iqra Naseer, Maqshoof Ahmad, Sajid Mahmood Nadeem, Iqra Ahmad, Najm-ul-Seher, and Zahir Ahmad Zahir

Abstract Due to continuous growth of world population, there is dire need of serious efforts and innovative approaches to meet food demands through sustainable production practices, improvement in supply chain, and control of food wastage. All these efforts should ensure the access to nutritious food to all suffering from hunger and malnutrition. Due to intensive crop cultivation and use of synthetic fertilizers, soil health is seriously deteriorating. However, soil fertility can be improved by incorporating legumes in the cropping system and/or use of rhizobial inoculants, which not only increase nitrogen fixation but also improve soil fertility and crop production through several other attributes such as phosphate solubilization, siderophores production, phytohormones production, enzymes synthesis, and exopolysaccharides production. Moreover, these bacteria can be helpful for improvement in crop production on marginal lands due to their tolerance against various biotic and abiotic stresses. All these characteristics make rhizobia equally important for non-legumes as for legumes. The use of rhizobial inoculants can ensure improvement in crop productivity and environment sustainability by enhancing soil fertility and reduction in use of synthetic chemical fertilizers. Present review focuses on important plant growth-promoting mechanisms of rhizobia and the use of these rhizobia for sustainable crop production through improvement in crop nutrition, physiology, productivity, and stress tolerance of crop plants. The potential of the synergistic use of rhizobia with other soil microorganisms for sustainable agriculture has also been elucidated with examples, followed by their future prospects.

Keywords Rhizobium · Plant growth promotion · Sustainable agriculture · Soil health and fertility

---

I. Naseer · M. Ahmad · I. Ahmad · Najm-ul-Seher
Department of Soil Science, University College of Agriculture and Environmental Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

S. M. Nadeem
University of Agriculture Faisalabad, Sub-campus Burewala, Vehari, Pakistan

Z. A. Zahir (✉)
Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

B. Giri et al. (eds.), *Biofertilizers for Sustainable Agriculture and Environment*,
Soil Biology 55, https://doi.org/10.1007/978-3-030-18933-4_11

11.1 Introduction

Decline in soil fertility and organic matter contents is one of the major constraints of crop production in arid and semiarid regions that is attributed to low rainfall, high temperature, and increase in calcareousness of these soils. As the demand for increase in crop production is rising due to expansion of colonization on agricultural lands, farmers try to use more chemical fertilizer which deteriorates soil biology and environmental quality. The governments all over the globe are prioritizing the development of eco-friendly alternate strategies for crop production. Beneficial soil bacteria have significant impact on the growth and productivity of crop plants (Uren 2007). Among these, rhizobia are a group of bacteria which fix atmospheric nitrogen by developing symbiotic association with legumes (Wang et al. 2018). Rhizobia fix about 50% of the total annually fixed nitrogen in the world (Hatice et al. 2008). They develop special structures within the plant cells, called nodules (Beneduzi et al. 2013; Wang et al. 2018). Soil fertility can be improved by incorporating legumes in the cropping system and/or use of rhizobial inoculants which not only increase nitrogen fixation but also improve soil fertility and crop production through several other attributes (Zahir et al. 2018).

The incorporation of grain legumes in cropping system can also be helpful to improve the productivity of the following cereal crops. Moreover, the rhizobia in root nodules of these crops not only fix atmospheric nitrogen in the presence of legume host (Bhattacharyya and Jha 2012) but also help cereal crops through other growth-promoting characteristics such as phosphate solubilization (Khan et al. 2010), siderophores production (Chandra et al. 2007), phytohormones production (Chi et al. 2010), enzymes synthesis (Duan et al. 2009), and exopolysaccharides production (Monteiro et al. 2012). Rhizobia are ubiquitous microorganisms in soil; however, their diversity and population depend upon different factors including crop species, crop rotation, soil properties, agricultural practices, and the extent and distribution of wild species of leguminous plants (Sadowsky 2005; Roberts et al. 2017).

The efficiency of rhizobia varies greatly among different strains depending upon plant host variety, soil and environmental factors, and their interaction (Allito et al. 2014), so efficient host-cultivar-specific combination is recommended in diverse agro-ecological zones and soils with different fertility status. Although *Rhizobium* inoculation increases the nodulation, nitrogen uptake, physiology, shoot and root growth, and yield of legume crops (Sogut 2006; Ahmad et al. 2013a, b), the effectiveness of these inoculants for nodulation and nitrogen fixation is reduced in the presence of high dose of nitrogen-containing chemical fertilizers (Ogutcu et al. 2008). For example, nitrogen application rates greater than 40 kg N ha^{-1} decreased the nodulation and nitrogen fixation in field pea (Clayton et al. 2004), an initial dose of nitrogen is however, required for establishment of root system at early stages of crop growth (Simonsen et al. 2015). The organic amendments on the other hand increase the nodulation and yield of peanut (Agegnehu et al. 2015) and thus can be used in integration with rhizobial inoculants (Argaw and Mnalku 2017).

Rhizobial inoculants are cheaper than inorganic fertilizers, so less financial risks are present in using them as source to improve productivity of legume crops (Ronner et al. 2016). Rhizobial inoculation is considered to be effective for symbiotic nitrogen fixation (SNF) and is being advocated to be used in the absence of effective rhizobia for a specific crop, in low population of effective indigenous rhizobia that really slows down the nodulation process, and/or when more effective rhizobial inoculants are available for a specific crop variety to be grown than the indigenous rhizobial species (Giller 2001). The selection of native rhizobia is imperative for the development of effective and affordable rhizobial inoculants to improve productivity of agro-ecosystems (Koskey et al. 2017). Moreover, the compatibility of rhizobial strain and host plant species/variety must be taken into account along with plant growth-promoting characteristics. In the case of the combined use of rhizobia with other beneficial soil microbes, the compatibility of strains should be tested before their use as inoculants.

Under field conditions, the inoculated bacterial strains have survival disadvantage as compared to indigenous microbial populations. In addition to strong plant growth-promoting abilities, the bacterial strains in developed rhizobial inoculants should have the ability to effectively colonize plant roots and capability to compete for nutrients and space with indigenous microorganisms in the soil and rhizosphere (Stephens and Rask 2000). Genetic engineering and strain selection can be helpful in improving the survival competency of rhizobial inoculants (Geetha and Joshi 2013).

The application of rhizobial inoculants to improve crop productivity has potential for sustainability of agriculture systems. The integrated use of these rhizobial inoculants with other soil microbes can be more beneficial to improve plant growth (Figs. 11.1 and 11.2) and for sustainable crop production by meeting the climate

Fig. 11.1 Effect of *Rhizobium* and plant growth-promoting rhizobacteria on *Cicer arietinum* under wire house conditions in pot experiment

Fig. 11.2 Effect of *Rhizobium* and plant growth-promoting rhizobacteria on root growth of *Cicer arietinum* under wire house conditions in pot experiment

change challenges and nutrient depletions and biocontrol of plant pathogens. The combined use helps to increase the efficiency of rhizobial inoculants through synergistic effects and combination of various mechanisms of actions in legumes (Pierson and Weller 1994) and non-legumes.

11.2 Plant Growth-Promoting Mechanisms of Rhizobia

Rhizobia are a diverse group of bacteria which are ubiquitous in all types of soils in different agro-ecological zones. In addition to symbiotic nitrogen fixation in legumes, they can improve soil fertility and crop productivity through a number of growth-promoting characteristics. These characteristics have been summarized in Table 11.1. Moreover, these bacteria can help in improving crop productivity on marginal lands due to their tolerance against various biotic and abiotic stresses.

11.3 Nodulation and Symbiotic Nitrogen Fixation

Legumes are considered as important component of cropping systems for maintaining the soil fertility and productivity. These crops have the ability to fix atmospheric nitrogen by forming symbiotic associations with rhizobia present in root nodules. The symbiotic nitrogen fixation (SNF) accounts for major share of globally fixed nitrogen through all means that can meet about 50–60% of crop nitrogen requirements as reported in the case of soybean (Salvagiotti et al. 2008). The SNF in legumes is a complex process, mediated by chemical signals between legume host

Table 11.1 Plant growth-promoting characteristics of rhizobial strains

Bacterial species	Plant growth-promoting characteristics	References
Rhizobium sp.	IAA production, P solubilization, N fixation	Shengepallu et al. (2018)
Rhizobium sp.	Improved enzymatic activities, N fixation	Mouradi et al. (2018)
Rhizobium sp.	Antagonistic activity, P solubilization, IAA production, ammonia production, siderophores production, HCN production	Manasa et al. (2017)
Rhizobium hainanense	Nitrogen fixation, IAA production, exopolysaccharides production	Mujahidy et al. (2013)
Rhizobium sp.	IAA production, siderophores production, exopolysaccharides production, HCN production, ammonia production	Ahemad and Khan (2010)
Rhizobium sp.	P solubilization	Sridevi and Mallaiah (2009)
Rhizobium sp.	Exopolysaccharides production	Santaella et al. (2008)
Rhizobium leguminosarum	Exopolysaccharides production	Janczarek et al. (2015)
Rhizobium leguminosarum	P solubilization, IAA production, ACC deaminase activity, siderophores production	Prabha et al. (2013)
Rhizobium leguminosarum	Siderophores production, IAA production, P solubilization, N fixation	Flores-Felix et al. (2012)
Rhizobium sp.	Antimicrobial activity	Bhattacharya et al. (2013)
Rhizobium phaseoli	IAA production	Zahir et al. (2010)
Sinorhizobium sp.	Exopolysaccharides production	Castellane et al. (2015)
Sinorhizobium sp.	Chitinase activity, glucanase activity, IAA production, siderophores production, P solubilization	Kumar et al. (2010)
Sinorhizobium meliloti	IAA production, nitrogen fixation, P solubilization	Bianco and Defez (2010)
Mesorhizobium sp.	IAA production, siderophores production, benzoic acid production, exopolysaccharides production, HCN and ammonia production	Ahemad and Khan (2012)
Mesorhizobium sp.	Siderophores, IAA, ammonia, and HCN production, P solubilization, antifungal activity	Ahmad et al. (2008)
Mesorhizobium ciceri	Siderophores, HCN, and ammonia production	Wani et al. (2007b)
Mesorhizobium loti	Siderophores and IAA production, antagonistic activity, P solubilization	Maheshwari et al. (2007)
Bradyrhizobium sp.	P solubilization, IAA, siderophores, and HCN production	Badawi et al. (2011)
Rhizobium	P solubilization, K solubilization, IAA production	Patel et al. (2017)

(continued)

Table 11.1 (continued)

Bacterial species	Plant growth-promoting characteristics	References
Bradyrhizobium japonicum	ACC deaminase activity, IAA production	Shaharoona et al. (2006)
Azorhizobium sp.	ACC deaminase activity; IAA, ammonia, and siderophores production; P solubilization; Zn solubilization; S oxidation	Islam et al. (2009)
Rhizobium sp.	Exopolysaccharides production	Marczak et al. (2017)
Bradyrhizobium, Rhizobium	Nitrogen fixation, P solubilization, IAA and siderophores production, production of hydrolyzing enzymes (cellulase and pectinase)	Shamsuddin et al. (2014)
Rhizobium cellulosilyticum, Rhizobium radiobacter,	P solubilization, Zn solubilization, IAA production	Gontijo et al. (2018)
Rhizobium sp.	Production of IAA, GA, flavonoid, and siderophores, Zn and P solubilization	Routray and Khanna (2018)
Rhizobium nepotum *Rhizobium tibeticum*	P solubilization	Rfaki et al. (2015)
Rhizobium sp.	IAA production	Abrar (2017)
Rhizobium sp.	Nitrogen fixation	Malisorn and Prasarn (2014)
Rhizobium sp.	P solubilization	Karpagam and Nagalakshmi (2014)
Rhizobium leguminosarum, Bradyrhizobium japonicum, Mesorhizobium thiogangeticum	P solubilization, IAA production	Singha et al. (2016)

and rhizobia that facilitate nodulation and nitrogen fixation. Complex oxidation and reduction reactions occur during the process of nodulation which consume high amount of metabolic energy, thus reducing atmospheric dinitrogen to ammonia. During the nodulation process, the flavones are released by host plant in the rhizosphere where they trigger the *nod* (nodulation) genes in rhizobia (Subramanian et al. 2006). The activated *nod* genes mediate the production of *nod* (nodulation) factors by rhizobia (D'Haeze and Holsters 2002) which signal the host plant for curling and deformation of root hairs, thus trapping the rhizobia within these special structures (Gage 2004). Infection threads are developed in root hairs through which rhizobia enter in to the inner cortex of plant roots (Jones et al. 2007). Once bacteria enter into the cortical cells of nodule primordium (Mylona et al. 1995), they differentiate into nitrogen-fixing forms "the bacteroids." The bacteroids multiply in the root nodules and fix nitrogen. On nodule senescence, some of these bacteria may enter back into the soil (Denison and Kiers 2011). Bacteria live in the root nodules, supply fixed nitrogen to plant, and get carbon compounds from plant in return (Lodwig and Poole 2003; Andrews et al. 2009) which are being utilized by these rhizobia as carbon and energy source for respiration and nitrogen fixation, in the form of adenosine triphosphate (ATP) (Lodwig et al. 2003; Hungria and Kaschuk 2014). The SNF can contribute significantly to sustainable crop production.

Rhizobia are very specific to their host plants where they can form nodules and fix atmospheric nitrogen. For decades, scientists were of the opinion that each legume can make symbiotic association with only one rhizobial strain. For example, for decades *Bradyrhizobium japonicum* has been thought to be the only strain that can make symbiotic association with soybean (Rodriguez-Navarro et al. 2010). Later literature reports that there are a number of strains from different genera such as *Bradyrhizobium*, *Rhizobium*, *Sinorhizobium*, and *Mesorhizobium* which can also develop successful symbiosis with soybean, thus fixing atmospheric nitrogen in soybean crop (Biate et al. 2014). Beijerinck, a Dutch microbiologist and botanist, in 1901, reported the process of biological nitrogen fixation (BNF) for the first time (Wagner 2011). The SNF is the major process that contributes plant-available nitrogen; however, nitrogen-fixing efficiency of different crops varies with soil physicochemical conditions (Thies et al. 1992; Giller 2001), the mineral nitrogen status of soil (Thies et al. 1991), indigenous rhizobial population, soil organisms, and environmental factors (Al-Falih 2002; Liu et al. 2011).

11.4 Phosphate Solubilization

Phosphorus (P) is the second most limiting plant nutrient after nitrogen that has a major role in plant metabolic processes such as photosynthesis, respiration, energy transfer, transmission of phosphorus-associated heredity material, cell division and development, and synthesis of nucleic acid and phospholipids (Fernandez et al. 2007; Richardson and Simpson 2011). Farmers use synthetic chemical fertilizer for meeting the crop P requirements (Turan et al. 2006). Plants absorb P in the form of primary and secondary orthophosphates (Bhattacharyya and Jha 2012). When P fertilizer is applied in the soil, it becomes unavailable to plants due to complexation with calcium carbonate in alkaline calcareous soils under arid and semiarid climate (Leytem and Mikkelson 2005) and with sesquioxide in acidic soils (McLaughlin et al. 2011).

Soil microbes play an important role in the availability of phosphorus in soils (Sharma et al. 2013) which use different P-solubilizing mechanisms such as lowering of soil pH by production of low molecular weight organic acids, siderophores production, and release of hydroxyl ions (OH^-) and enzymes (Barroso et al. 2006; Rodriguez et al. 2006; Glick 2012). The microorganisms are also involved in the mineralization of phosphorus through decomposition of organic compounds, thus making P available to plants (Rodriguez et al. 2006) through the production of phosphatases (Aseri et al. 2009) and phytases (Maougal et al. 2014).

Rhizobia have the ability to make available the fixed inorganic P through solubilization and organic P through decomposition (Tao et al. 2008) by above-described mechanisms. A number of rhizobial strains have been documented which solubilize inorganic and mineralize organic P compounds in soil (Afzal and Bano 2008; Khan et al. 2010). Rhizobial species from the genera *Rhizobium* (Egamberdiyeva et al. 2004), *Bradyrhizobium* (Egamberdiyeva et al. 2004; Afzal and Bano 2008), *Sinorhizobium* (Bianco and Defez 2010), and *Mesorhizobium* (Rodrigues et al. 2006; Chandra et al. 2007) have been reported to solubilize P through production of low molecular weight organic acids.

11.5 Siderophores Production

Siderophores are low molecular weight organic compounds which have high affinity for Fe and other metals. These compounds are released by soil microbes especially bacteria in iron-deficient soils, make complexes with Fe, and make it available to plants (Raymond and Dertz 2004; Skaar 2010). Siderophores may chelate with ferric iron, making it available to crop plants and microorganisms (Ahmed and Holmstrom 2014); however, pathogenic fungi are unable to use chelated iron. Iron plays an important role in chlorophyll synthesis and respiration (Kobayashi and Nishizawa 2012). It is also essential for ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), metabolism of oxygen, transfer of electron, and catalysis/enzymatic processes in plants (Aguado-Santacruz et al. 2012). Iron is an important component of nitrogenase complex ferredoxin and leghemoglobin thus helps in nitrogen fixation (Raychaudhuri et al. 2005).

Iron converts into oxyhydroxides and hydroxides; the insoluble forms, under aerobic conditions, thus become unavailable to plants and microorganisms (Rajkumar et al. 2010). Soil pH also affects Fe availability to plants and microorganisms (Masalha et al. 2000). So, under such conditions, siderophores help the microorganisms and plants to meet their Fe needs. Siderophores also make complexes with other essential elements such as molybdenum, cobalt, nickel, and manganese, thus enhancing their availability to microorganisms and plants (Bellenger et al. 2008; Braud et al. 2009). Siderophores complex with heavy metals such as cadmium, copper, and aluminum and radioactive elements like neptunium and uranium (Neubauer et al. 2000) and thus alleviate the heavy metal stress.

It is a well-established fact that rhizobial strains from the genera *Azorhizobium* (Islam et al. 2009), *Rhizobium* (Carson et al. 2000; Arora et al. 2001; Mehboob et al. 2011; Prabha et al. 2013; Manasa et al. 2017; Routray and Khanna 2018), *Bradyrhizobium* (Badawi et al. 2011; Shamsuddin et al. 2014), *Mesorhizobium* (Chandra et al. 2007; Ahmad et al. 2008), and *Sinorhizobium* (Carson et al. 2000; Ahmad et al. 2008) can produce siderophores which chelate with ferric ion under iron-limiting soil conditions (Ahemad and Khan 2011a) and make it available to crop plants.

11.6 Phytohormones Production

Phytohormones are organic molecules, involved in important physiological processes of plants, and thus improve their growth and development. They are synthesized within the plant body at one point and transport to some other place for performing physiological functions (Saharan and Nehra 2011). Phytohormones when applied exogenously are termed as plant growth regulators, due to their involvement in plant growth regulation. They are classified in five major classes as cytokinins, gibberellins, auxins, abscisic acid, and ethylene (Khalid et al. 2006; Saharan and Nehra 2011).

Auxins are involved in root and shoot growth especially at seedling stage (Patten and Glick 1996). Indole-3-acetic acid (IAA), one of the important auxins, is involved in cell division, cell differentiation, gene regulation (Ryu and Patten 2008), apical dominance, cell enlargement, root development (Khan et al. 2014), and nodulation (Remans et al. 2007). It has been well documented that most of the rhizobial strains isolated from root nodules produce indole-3-acetic acid in the presence and absence of L-tryptophan, the immediate precursor of auxins (Ahmad 2011). A number of studies report the production of IAA by rhizobial strains from the genera *Azorhizobium* (Naidu et al. 2004), *Rhizobium* (Dazzo et al. 2005; Weyens et al. 2009; Abrar 2017; Shengepallu et al. 2018), *Mesorhizobium* (Ahemad and Khan 2012), *Bradyrhizobium* (Badawi et al. 2011), and *Sinorhizobium* (Bianco and Defez 2010). The auxins produced by bacteria are involved in production of more nodules and induce root morphogenesis (by improving its size, weight, number of branches, and the surface area of roots) and more adventitious roots (Dazzo and Yanni 2006; Solano et al. 2010).

Cytokinins are involved in plant cell division, development of roots, formation of root hairs, shoot and branching, chloroplast development, and leaf senescence. It also controls cell division in embryonic as well as mature plants (Srivastava 2002; Oldroyd 2007). Cytokinin is important for regulating the number of nodules in a symbiotic relationship between *Rhizobium* and legume crops. It is reported to play a critical role in the activation of nodule primordial, thus, a positive regulator of nodulation (Kisiala et al. 2013).

Cytokinins produced by bacteria stimulate shoot growth and reduce root/shoot ratio in drought-stressed plants (Arkhipova et al. 2007). Different rhizobial species such as *Rhizobium leguminosarum* (Zahir et al. 2010), *Sinorhizobium meliloti*, *Sinorhizobium fredii*, *Sinorhizobium medicae*, and *Mesorhizobium loti* (Kisiala et al. 2013) have the ability to produce cytokinins. Moreover, *Rhizobium* regulates the expression of signaling pathway and activates cortical cells to divide in plants and enhances the endogenous cytokinin production in plants (Oldroyd 2007).

Gibberellins (GA) play a role in leaf expansion and stem elongation of plants. Exogenous application of gibberellins helps to promote bolting of the plants and parthenocarpy in fruits, increases the number of buds and fruit size, and is involved in breaking of tuber dormancy. Soil microorganisms have been studied to produce gibberellins which help to improve plant growth. Bacterially produced gibberellins affect plant growth and nodulation positively as well as negatively. They induce nodule organogenesis however and inhibit the nodulation at infection stage (McAdam et al. 2018). A number of rhizobial strains from the genera *Rhizobium* (Bottini et al. 2004), *Bradyrhizobium* (Morrone et al. 2009; Afzal et al. 2010), and *Sinorhizobium* (Boiero et al. 2007) have been reported to produce the gibberellins (Mirza et al. 2007).

Abscisic acid (ABA) plays an important role in seed germination, leaf development, root growth, and stomatal closure (De Smet et al. 2006). Its production is mostly prominent in stress conditions like drought stress, where it is in guard cells and stimulates stomatal closure and prevents water loss through transpiration. Its role is also reported during salt stress, resistance against pathogen, and developmental processes, such as seed dormancy and germination (Goggin et al. 2009; Rodriguez-Gacio et al. 2009). The ABA also regulates nodulation in legumes (Suzuki et al. 2004). Rhizobial species from different genera including *Rhizobium* and *Bradyrhizobium* have been reported to produce abscisic acid (Dobbelaere et al. 2003; Boiero et al. 2007) and help in plant growth regulation.

11.7 Enzyme Synthesis

Enzyme production is an important attribute of soil bacteria including rhizobia. During recent years, a number of rhizobial strains have been reported to produce extracellular enzymes. Important rhizobial enzymes include chitinase, phosphatase, cellulase, catalase, and 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase (Prabha et al. 2013; Mouradi et al. 2018) which help plants to cope with biotic and abiotic stresses (Ahmad 2011). It has been well documented that ACC deaminase produced by bacteria in soil lowers the ethylene levels in plant body by cleaving the ACC, the immediate precursor of ethylene (Shaharoona et al. 2007). The lower concentration of ethylene is required for regulation of physiological processes in plants (Arshad and Frankenberger 2002; Owino et al. 2006); its higher concentration, however, under stress negatively affects plant growth (Zahir et al. 2008).

The bacterial ACC deaminase converts ACC into ammonia and α-ketobutyrate for use by bacteria as carbon and nitrogen source (Saleem et al. 2007; Singh et al. 2015). Inoculation of crop plants with bacteria containing ACC deaminase enzyme increases mineral uptake, nodulation, and seedling growth of plants (Ahmad et al. 2011, 2013b) leading to improved growth and productivity (Glick 2012; Ahmad et al. 2014). The ACC deaminase-containing bacteria help plants to cope with damaging effects of stresses such as salinity (Nadeem et al. 2007; Ahmad et al. 2011), heavy metals (Khan et al. 2013), flooding (Grichko and Glick 2001), drought (Zahir et al. 2008), and pathogenic stress (Wang et al. 2000).

A number of rhizobial strains having ACC deaminase activity from the genera *Azorhizobium* (Islam et al. 2009), *Rhizobium* (Mirza et al. 2007; Hafeez et al. 2008; Duan et al. 2009), *Bradyrhizobium* (Shaharoona et al. 2006), and *Sinorhizobium* (Ma et al. 2004) have been reported. Rhizobia also produce some other enzymes such as catalase (Bumunang and Babalola 2014), urease (Deshwal and Chaubey 2014; Nosheen and Bano 2014), and chitinase (Saha et al. 2012) and protect plants under stresses along with enhancing nutrient availability. Rhizobial strains also produce lipase, cellulase, protease, β-1,3-glucanase (Gopalakrishnan et al. 2014), and oxidase (Gauri et al. 2011). All these enzymes are important in nutrient availability and induction of tolerance against biotic and abiotic stresses.

11.8 Exopolysaccharides Production

Exopolysaccharides (EPSs) are complex polymers of high molecular weight which are released by soil microbes including rhizobia (Vijayabaskar et al. 2011; Rao et al. 2013). The bacterial EPSs include humic acids, nucleic acids, phospholipids, proteins, glycoproteins, and polysaccharides (Flemming et al. 2007). Exopolysaccharides are involved in biofilms formation (Sutherland 2001) and protect microorganisms against toxic effects of osmotic stress, desiccation (Sandhya et al. 2009), salinity (Ashraf et al. 2004; Qurashi and Sabri 2012), bacteriophage attacks, and poisonous compounds (Sutherland 2001). Exopolysaccharides improve root and shoot growth and increase fertilizer use efficiency through better water use (Alami et al. 2000).

Rhizobia have the ability to produce exopolysaccharides which help in biofilm formation. The EPSs-producing bacteria can better survive against environmental extremities and can efficiently utilize water and nutrients. Rhizobial exopolysaccharides increase soil aggregation, help plant roots to adhere with soil, and improve water holding capacity of soil and nutrient availability in the root zone (Donot et al. 2012; Hussain et al. 2014). The EPSs also help in the establishment of symbiotic association between plants and rhizobia (Skorupska et al. 2006). The EPS-producing species from different rhizobial genera including *Rhizobium* (Zafar-ul-Hye et al. 2013; Janczarek et al. 2015; Marczak et al. 2017), *Sinorhizobium* (Castellane et al. 2015), *Mesorhizobium* (Castellane et al. 2015), and *Bradyrhizobium* (Ahemad and Khan 2011b) have been reported.

11.9 Production of Other Compounds

Nitrogen is an essential element for plant and microbial growth that is involved in the synthesis of a number of compounds including nucleic acids, amino acids, and proteins. Certain rhizobial strains have the ability to produce ammonia and thus help plants in mineral nutrition (Goswami et al. 2014) and improve plant growth and biomass (Mia et al. 2005). The ammonia-producing bacteria also help in biological control of fungi (Al-Mughrabi 2010; Jha et al. 2012) and reduce the growth of competing microflora, thus increasing the growth of nitrifying bacteria in soil (Angus et al. 1999). Rhizobial species from the genera *Rhizobium* (Zafar-ul-Hye et al. 2013), *Bradyrhizobium* (Wani et al. 2007a, b; Ahemad and Khan 2011c), and *Mesorhizobium* (Ahmad et al. 2008; Ahemad and Khan 2012) have been reported as ammonia producers.

Lumichrome helps in plant growth (Zhang et al. 2002; Dakora 2003) by improving net carbon assimilation especially under water-stressed conditions (Matiru and Dakora 2005). Inoculation of plants with lumichrome-producing rhizobial strains induces water stress tolerance in plants through minimizing the stomatal conductance of water and transpiration losses in leaves (Mehboob et al. 2009). Riboflavin is a component of bacterial flavin coenzymes which are the typical cofactors of flavoproteins. These flavoproteins are important for various cellular processes, such as for energy production, DNA repairing, redox reactions, biosynthesis, and light emission (Burgess et al. 2009). Riboflavin also affects the rhizobial symbiotic relationship, rhizobial survival in the rhizosphere, and their ability to colonize plant roots (Victor et al. 2013).

Several strains of rhizobia including species from the genera *Rhizobium* and *Sinorhizobium* have been recognized as riboflavin producing which act as plant growth promoter (Yang et al. 2002). Riboflavin produced by bacteria can reduce Fe^{+3} into its more soluble Fe^{+2} forms where it acts as electron donor (Crossley et al. 2007). Rhizobia can also produce zeatin (Boiero et al. 2007), hydrogen cyanide, tensin, viscoinamide, pyrrolnitrin (Bhattacharyya and Jha 2012), and antibiotics (Chandra et al. 2007) such as phenazines (Krishnan et al. 2007) and thus help plants in biocontrol of pathogenic bacteria (Triplett et al. 1994). Rhizobia have the ability to produce bio-stimulatory agents which induce systemic resistance in the plant body (Yanni et al. 2001; Singh et al. 2006).

11.10 Rhizobial Inoculants for Sustainable Crop Production

Using rhizobial inoculants is an emerging technology not only for the improvement of leguminous crops but also for non-legumes due to their cost-effectiveness and environment-friendly nature. The specific group of rhizobia makes symbiotic relation with specific legume plant but may improve plant growth without making symbiotic association in non-legumes. Therefore, the inoculation with rhizobia improves plant growth and productivity in the most significant manner under both normal and stressed conditions as summarized in below sections and Table 11.2.

11.10.1 Crop Nutrition

Rhizobia have positive influence on soil nutrients and thus improve nutrient uptake (Allito et al. 2014) through phosphate solubilization (Khan et al. 2010), siderophores

Table 11.2 Effect of rhizobial inoculants on growth, nutrient uptake, and yield of different crops under in vitro, pot, and field conditions

Crop	Rhizobial strain	Growth conditions	Effects on plants	References
Soybean	*Bradyrhizobium* sp.	Field experiment	Increased N, P, and S contents and improved seed and straw yield	Raja and Takankhar (2018)
Soybean	*Bradyrhizobium* sp.	Field study	Increased number of pods, pods weight, and grain yield	Galindo et al. (2018)
Soybean	*Bradyrhizobium* sp.	Field experiment	Increased phosphorus use efficiency and plant N and P uptake	Fituma et al. (2018)
Soybean	*Bradyrhizobium japonicum*	Field experiment	Increased nodulation, dry matter production, and nitrogen uptake	Solomon et al. (2012)
Soybean	*Bradyrhizobium*	Field experiment	Increased nodulation, shoot nitrogen accumulation, and improved plant growth	Cerezini et al. (2016)
Peanut	*Bradyrhizobium* sp.	Field experiment	Increased plant N and P uptake and nodulation	Argaw (2018)
Peanut	*Rhizobium* sp.	Field conditions	Improved shoot growth and nodulation under saline conditions	Akhal et al. (2013)
Groundnut	*Rhizobium* sp.	Field study	Increased growth, oil contents, protein contents, and yield parameters	Mohammed and Sahid (2016)
Chickpea	*Rhizobium* sp.	Field study	Improved plant growth and yield	Laabas et al. (2017)
Wheat	*Rhizobium* sp.	Pot study	Improved shoot length, shoot and root dry weight	Kamran et al. (2017)
Maize	*Azospirillum brasilense Rhizobium tropici*	Greenhouse	Enhanced plant height, stem diameter, dry biomass of shoots and roots, and N accumulation in shoots	Picazevicz et al. (2017)
Legumes	*Rhizobium* sp.	In vitro	Improved plant growth, enhanced plant defense mechanisms, and resistance against herbivores	Thamer et al. (2011)
Chickpea	*Rhizobium* sp.	Field study	Increased growth and yield parameters and concentration of nitrogen and organic matter in soil	Zaman et al. (2011)
Common bean	*Rhizobium* sp.	Greenhouse Field study	Significant effect on chlorophyll contents, photosynthesis, intercellular CO_2 concentration, and the transpiration rate	Bambara and Ndakidemi (2009)
Pepper Tomato	*Rhizobium phaseoli*	In vitro Pot study	Promoted growth at different stages, increased yield and quality of seedlings and fruits	Garcia-Fraile et al. (2012)
Mung bean Mash bean	*Rhizobium japonicum*	Greenhouse Field study	Increased height, root and shoot growth, pod number, pod length, nodulation, and seed weight	Ravikumar (2012)

(continued)

Table 11.2 (continued)

Crop	Rhizobial strain	Growth conditions	Effects on plants	References
Carrot Lettuce	*Rhizobium leguminosarum*	In vitro Pot study	Promoted plant growth by increasing dry matter of shoots and roots and increased N, P, and Ca uptake	Flores-Felix et al. (2012)
Pea	*Rhizobium leguminosarum*	Pot study	Decreased disease severity, increased seed fresh and dry weights, and better seed filling in pods	Wienkoop et al. (2017)
Pea Lentil	*Rhizobium leguminosarum*	Field study	Increased seed yield and effective in disease control	Huang and Erickson (2007)
Kidney bean	*Rhizobium etli*	Pot study	More nodules with increased nitrogenase activity and higher biomass	Suarez et al. (2008)
Lettuce	*Bradyrhizobium japonicum*	Axenic conditions	Reduced heavy metal stress and increased shoot and root length	Seneviratne et al. (2016)
Cowpea	*Bradyrhizobium* sp.	Greenhouse	Increased biological nitrogen fixation, plant growth, and crop productivity	Rodrigues et al. (2015)
Cowpea	*Bradyrhizobium japonicum*	Field study	Increased plant height and chlorophyll contents	Nyoki and Ndakidemi (2014)
Peanut	*Bradyrhizobium* sp.	Axenic conditions	Improved plant growth, nodule number, and nitrogen contents	Castro et al. (2012)
Wheat	*Azorhizobium caulinodans*	Axenic conditions	Increased number and weight of leaves and roots	Liu et al. (2017)
Black medic	*Sinorhizobium meliloti*	Pot study	Increased biomass production under metal stress	Fan et al. (2011)
Chickpea	*Mesorhizobium* sp.	Field conditions	Improvement in symbiotic parameters leading to enhanced growth and yield	Kaur et al. (2015)
Chickpea	*Mesorhizobium mediterraneum*	Field study	Capable to nodulate in stress conditions and increased nodule number and grain yield	Romdhane et al. (2009)
Bean	*Rhizobium*	Field conditions	Increased growth and yield parameters and protein contents	Yadegari et al. (2010)
Bean	*Rhizobium* sp.	Hydroponic culture	Higher nodulation and increased phosphatase and phytase activity	Mandri et al. (2012)
Soybean	*Bradyrhizobium japonicum*	Field study Glasshouse experiment	Enhanced plant height, number of leaves, leaf chlorophyll content, stem girth, leaf area, and leaf area index	Tairo and Ndakidemi (2013)
Soybean	*Bradyrhizobium japonicum*		Increased N content of inoculated plants and increased root nodulation and yield	Dhami and Prasad (2009)
Kidney vetch	*Mesorhizobium metallidurans*	In vitro	Enhanced tolerance to high concentrations of heavy metals	Vidal et al. (2009)

production (Chandra et al. 2007), and phytohormones production (Chi et al. 2010), in addition to improvement in nitrogen uptake through SNF of atmospheric nitrogen. Rhizobial inoculation can minimize the dependence on chemical fertilizers as it enhances the nutrient uptake of crop plants. For example, Soumaya et al. (2016) conducted an experiment to study the effect of *Rhizobium* inoculation on mineral contents of sulla (*Hedysarum coronarium* L.) crop grown on calcareous soil and reported a significant increase in nutrients uptake leading to improved performance of crop in terms of growth and nodulation.

Rhizobium inoculation improves the nutrient (P, K, Ca, and Mg) uptake in different plant parts such as leaves, shoots, roots, and pods (Makoi et al. 2013), enhances the availability of macro- and micronutrients, and thus improves the nutritional quality of different plant components (Tairo and Ndakidemi 2014). Nyoki and Ndakidemi (2014) observed that inoculation of *Bradyrhizobium japonicum* in cowpea resulted in greater uptake of macronutrients such as N, P, K, Mg, Ca, and Na as compared to control. Similar results were obtained by Tairo and Ndakidemi (2014) where they reported that *B. japonicum* inoculation significantly enhanced the uptake of N, P, K, and Na within the roots, pods, shoots, and whole plant of cowpea (*Vigna unguiculata* (L.). In another study, rhizobial inoculation increased nitrogen fixation which resulted in increased root growth enabling it to acquire more nutrients (Rokhzadi and Toashih 2011; Das et al. 2012). It has been reported that *Mesorhizobium* inoculation not only improves growth and nutrient uptake, but it also positively affected the yield attributes, symbiotic relationship, and enhanced quality of chickpea grains (Singh and Singh 2018). The increased nitrogen content resulted in higher protein content which was also due to *Rhizobium* inoculation (Kumar et al. 2014). In another study, it was observed that *Mesorhizobium* sp. enhanced N and P uptake in both grain and shoot in chickpea as compared to uninoculated control (Sahai and Chandra 2011). Similarly, Chandra and Pareek (2015) reported 0.6%, 6.5%, and 4.3% increase in organic carbon, available N, and available P, in chickpea plant after *Rhizobium* inoculation. Further, Kaur et al. (2015) reported higher protein contents and increase in N and P contents after *Mesorhizobium* inoculation in chickpea. The application of *Rhizobium* improves the N and P content of soil which can be utilized by the next crop after harvesting of crop (Abdalla et al. 2013; Tagore et al. 2013). Studies revealed that *Mesorhizobium* inoculation increased the soil microbial biomass carbon (Bhattacharjya and Chandra 2013) that resulted in more crop biomass and subsequently higher return of organic matter into the soil, thus increasing microbial biomass and activities (Babu et al. 2015).

It has been well documented that rhizobial inoculation separately and in combination with other bacterial strains can improve the nodulation and nutrient uptake in crop plants (Ahmad et al. 2013a). For example, Elkoca et al. (2010) studied the effect of *Rhizobium leguminosarum* bv. *phaseoli* separately and in combination with *Bacillus subtilis* and *Bacillus megaterium* on nitrogen fixation and nutrient uptake of the common bean (*Phaseolus vulgaris* L. cv. “elkoca-05”) and reported that the triple inoculation of *Rhizobium leguminosarum*, *Bacillus subtilis*, and *Bacillus megaterium* increased the plant N (52.1%), K (25.6%), Mg (97.6%), and sulfur

(282.4%) as compared to uninoculated control. Similarly, it also improved the seed protein (30.1%), K (25.8%), Mg (95.5%), and S (282.8%) contents in seed of the common bean when compared with uninoculated control. The improvement in micronutrient contents (Zn and Cu in plant and seed) was also observed by inoculation with *Rhizobium leguminosarum* in combination with *Bacillus subtilis* and *Bacillus megaterium*.

11.10.2 Crop Physiology

Nitrogen is an essential nutrient that needs to be applied as a fertilizer for plant growth and development. Chlorophyll also contains nitrogen which is an integral component of photosynthesis. The biological nitrogen fixation (BNF) accounts for about 60% of the total fixed nitrogen (Bano and Iqbal 2016). In BNF, nodulating bacteria gain carbon and other energy resources from photosynthesis and in turn provide nitrogen. This mechanism depends on the activity of chloroplasts which is a structural component of photosynthesis (White et al. 2009). Besides nitrogen fixation, rhizobia that make symbiotic association with plants may also improve physiological status of plants by improving nutrient bioavailability and uptake (Afzal and Bano 2008), phytohormones production (Chandra et al. 2007), siderophores and osmolytes production (Grover et al. 2010; Saidi et al. 2013), and regulation of ACC deaminase (Duan et al. 2009). Rhizobial inoculation has the ability to improve chlorophyll contents of crop plants (Elkoca et al. 2010) and thus can improve the photosynthetic activity and productivity of crop plants. Hussain et al. (2018) found that *Rhizobium phaseoli*-RS-1 and *Mesorhizobium ciceri*-RS-8 improved the transpiration rate, photosynthetic rate, stomatal conductance of water, intrinsic water use efficiency, relative water contents, chlorophyll contents, and nutrients uptake of maize crop under normal and stressed conditions.

Rhizobium inoculation improves physiological characters of plants which direct toward maximum growth and yield. In a study rhizobium alone as well as in combination with *Pseudomonas* strains reduced the adverse effects of salinity by significantly improving the transpiration rate, photosynthetic rate, stomatal conductance of water, C assimilation rate, relative water contents, and chlorophyll contents in mung bean (Ahmad et al. 2013b). They improved the physiology, growth, and quality of plant by adapting several mechanisms mainly by lowering endogenous level of ethylene (Ahmad et al. 2011). The rhizobial inoculation enhanced leaf chlorophyll contents in both glasshouse and field conditions when compared with control treatment (Bambara and Ndakidemi 2009).

Literature reports the increased photosynthetic leaf area, chlorophyll content, and relative water contents due to inoculation of ACC deaminase- and IAA-producing or phosphate-solubilizing rhizobium strains (Saghafi et al. 2018). In another study, Jimenez-Gomez et al. (2018) observed that *Rhizobium laguerreae* possessing several plant growth-promoting abilities showed positive results for vegetative parameters of leafy vegetable which include leaf number, size and weight, as well as chlorophyll and nitrogen contents as compared to uninoculated control. *Rhizobium* inoculation in legumes enhances the leaf chlorophyll contents of crops (Tairo and Ndakidemi 2013). For example, in the case of soybean and cowpea, it was observed that *B. japonicum* inoculation and phosphorus supplementation significantly increased leaf chlorophyll contents both in field and glasshouse experiments (Makoi et al. 2013; Nyoki and Ndakidemi 2014). The increase in chlorophyll contents results in increased photosynthetic processes (Sylvie and Patrick 2009), and as a result plant produces more sugars for its growth and development.

11.10.3 Crop Productivity

Rhizobial inoculation has been well documented to improve productivity of legume crops under normal (Anjum 2011; Shurigin et al. 2015; Khaitov et al. 2016; Wolde-meskel et al. 2018) and stressed conditions (Aamir et al. 2013; Ahmad et al. 2014; Sistani et al. 2017). For example, it has been observed that rhizobial inoculation improved growth, yield, and nitrogen fixation in chickpea (Kyei-Boahen et al. 2002; Fatima et al. 2008), pea (Huang and Erickson 2007), and the common bean (Argaw 2016). Similarly, Sharma et al. (2011) observed significant improvement in nitrate reductase activity, number of effective nodules, and leghemoglobin contents in groundnut due to inoculation with *Rhizobium* strains. The improvement in plant height, straw yield, and grain yield was observed in lentil in response to rhizobial inoculation (Haque et al. 2014).

Indigenous population and cropping history affect the performance of crop-specific symbionts under field conditions. Higher population of indigenous rhizobia in soil where the same legume is being grown in previous years suppresses the influence of inoculated rhizobial strains, while, in the case of low indigenous population, rhizobial inoculants have the ability to improve production of legume crops. For example, about 57% higher seed yield of inoculated plots of soybean was observed by Martyniuk et al. (2018) when compared with uninoculated control. They studied the influence of rhizobial inoculation on productivity of soybean, pea, and yellow lupine in a soil with higher populations of indigenous pea and lupine symbionts and low population of soybean rhizobia. The improvement in grain yield of soybean might be due to higher nodulation in inoculated plots (169%) as compared to uninoculated plots. In the case of soil with relatively high populations of indigenous rhizobia of pea and yellow lupine, no response of inoculation was observed on yield or yield contributing parameters of these crops.

It has been observed that inoculation of *Bradyrhizobium japonicum* improved the root and shoot growth, grain yield and yield-related parameters, and grain nitrogen contents of mash bean (Hussain et al. 2011). Similarly, the inoculation with *Mesorhizobium* strains improved the grain yield in *Cicer arietinum* (Wolde-meskel et al. 2018). In another study, Bhatt and Chandra (2014) also observed that the inoculation with *Mesorhizobium* improved the straw yield, grain yield, nodulation, and phosphorus and nitrogen uptake in chickpea. Alam et al. (2015) found that in soybean plant, inoculation with *Rhizobium* sp. BARIRGm901 increased the nodule weight, nodule number, plant height, root biomass, shoot biomass, nitrogenase activity, nitrogen fixation and assimilation, strove yield, and seed yield as compared to uninoculated control. Argaw and Muleta (2017) reported that rhizobial inoculation improved the number of nodules, dry mass of nodules, and total biomass yield and grain yield of *Phaseolus vulgaris*.

The use of the most efficient rhizobial strain for specific host variety can maximize the profitability of inoculants, thus capitalizing the maximum productivity of crops (Allito et al. 2014). For example, Kulasooriya et al. (2017) conducted an experiment on *Trifolium repens* L. with the objective to develop cost-effective and eco-friendly technology for crops to minimize the use of nitrogenous fertilizers. They prepared inoculants by using efficient rhizobial strains. They observed significant improvement in biomass of inoculated *Trifolium* plants as compared to plants which were fertilized with urea, under field conditions. They attributed the increased biomass with significant increase in root nodulation of inoculated plants. In another study, Tena et al. (2016) studied the efficiency of different rhizobial strains on nodulation in lentil (*Lens culinaris* Medik.) under field conditions. They evaluated six rhizobial strains and reported a significant increase in nitrogen fixation and grain yield as compared to uninoculated control; however, these strains varied in their ability to improve grain yield of lentil under field conditions.

11.10.4 Stress Tolerance in Crop Plants

Heavy metals are among the main inorganic soil pollutants that are added from agrochemicals, industrial wastes, and mining (Marchiol et al. 2004). The persistence and non-degradable nature of heavy metals pose enormous harmful impacts on microorganisms (Broos et al. 2005; Krujatz et al. 2011), plants (Wani et al. 2008; Wani and Khan 2010), and ecosystem (Cheung and Gu 2007). For example, cadmium (Cd) negatively affects nitrogenase activity of rhizobia and photosynthesis activity of legume host, thus reducing nodulation efficiency (Ahmad et al. 2012). In another study, zinc toxicity adversely affected the symbiotic association between *Rhizobium leguminosarum* bv. *viciae* and pea by decreasing rhizobial population, thus reducing the nodulation and plant growth (Chaudri et al. 2000).

Using rhizobia under stress is not only beneficial for legume crops but can also improve growth of non-legumes (Fig. 11.3) and help in phytoremediation of contaminated soils. The use of rhizobia in combination with legumes is useful in phytoremediation and is recommended as eco-friendly, cost-effective, and easy-to-use approach under adverse soil conditions (Kang et al. 2018). They used *Sinorhizobium saheli* YH1 for reducing the uptake of metal by *Leucaena leucocephala* in mine tailings and metal-polluted soils. It was observed that *S. saheli* YH1 improved plant health of *L. leucocephala* by reduction in metal uptake by plants under heavy metal-polluted soils and recommended to use the approach for phytoremediation of Cd- or Mn-polluted soils.

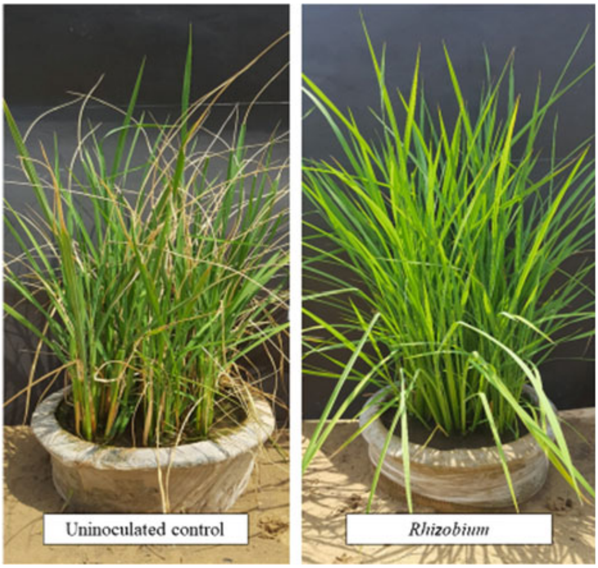

Fig. 11.3 Effect of *Rhizobium* inoculation on rice growth under water-stressed conditions

Rhizobial growth, survival, and distribution in soil are affected by environmental stresses including salinity (Tate 1995). Indigenous population can easily adapt to the local environmental conditions, so they are comparatively more efficient and competitive (Mrabet et al. 2005); however, inoculated rhizobial strains have been well documented to improve plant growth under normal as well as stressed conditions (Ahmad et al. 2014; Allito 2015; Khaitov et al. 2016). The strains vary in their growth under stressed environment with some strains showing more growth even at higher levels of stress that might be owing to stress tolerance ability of these rhizobial strains (Sgroy et al. 2009; Ahmad et al. 2011). Rhizobial strains use different mechanisms to deal with salinity stresses. Inoculation of crop plants with salt-tolerant rhizobia has the ability to improve crop productivity under salt stress (Ahmad et al. 2012, 2014).

Beneficial soil bacteria including several species of *Pseudomonas*, *Rhizobium*, and *Bacillus* have been reported to improve disease resistance in crop plants (Kang et al. 2006; El-Batanony et al. 2007; Samavat et al. 2011) through production of different antimicrobial compounds and hydrolytic enzymes and inducing plant defense mechanisms (Duan et al. 2009). For instance, El-Batanony et al. (2007) reported that *Rhizobium leguminosarum* in combination with AM fungi was effective in biocontrol of *Fusarium solani*, *F. oxysporum*, and *Rhizoctonia solani* in faba bean. In another study, Gao et al. (2012) reported that inoculation with AM fungi and rhizobia directly inhibited the growth and reproduction of pathogen and activated the overall defense system of plant by enhancing PR gene expressions and recommended it for controlling soybean red crown rot in acid soils.

11.11 Synergistic Effects of Rhizobial Inoculation with Other Soil Microbes and Organic Sources

Rhizobial strains can be used in combination with other soil microbes to develop inoculants having two or more strains: the co-inoculation or consortium inoculants. It has been observed that AM fungi in combination with *Rhizobium* improved the mineral nutrition of legume crops (Tavasolee et al. 2011). Similarly, Guo et al. (2010) conducted a study on udorthent to evaluate the efficacy of *Sinorhizobium meliloti* separately and in combination with arbuscular mycorrhiza and lime on growth, nodulation, and nutrient uptake of lucern. It was observed that integrated use was better in improving the nodulation and growth of lucern, as compared to alone application of rhizobial strain. The combined use also improved the nitrogen and phosphorus uptake in lucern crop as compared to uninoculated plants. In another study, the combined use of AMF fungi and *Rhizobium* enhanced productivity, nutrient use efficiency, and profitability of pea crop in addition to saving of about 25% N and P fertilizers in Himalayan acid Alfisol (Bai et al. 2016). The integrated use of *Rhizobium* and AM fungi can also be effective to enhance symbiotic nitrogen fixation under stressed conditions (Chalk et al. 2006). For instance, the integrated use of *Rhizobium* and AM fungi has been well documented to improve plant growth and control of pathogens under field conditions (Akhtar et al. 2011).

The use of *Rhizobium* in combination with plant growth-promoting bacteria can better improve the crop productivity under normal as well as marginal soil conditions. For example, use of consortium developed from *Rhizobium tropici* (CIAT 899), *Paenibacillus polymyxa* Loutit (L), and *P. polymyxa* (DSM 36) improved growth, phytohormone levels, nitrogen content, and nodulation in the common bean (*Phaseolus vulgaris* L.) under drought-stressed conditions, thus having the ability to induce drought stress tolerance in crop plants (Figueiredo et al. 2008).

Rhizobial inoculation in combination with other organisms has also been found beneficial for agriculture ecosystem. Co-inoculation of *Rhizobium* and *Pseudomonas fluorescens* in the common bean increased root and shoot growth, nitrogenase activity, nodulation, and chlorophyll contents in leaves. It also increased the nitrogen and phosphorus uptake by crop plants (Samavat et al. 2012). Similarly, the increase in plant growth and nodulation was observed due to the combined use of *Bradyrhizobium* and ACC deaminase-containing PGPR in mung bean (Shaharoona et al. 2006). The co-inoculation of *Cicer arietinum* with rhizobium and phosphate-solubilizing bacteria significantly improved the seed yield, strove yield, nodule number, and protein content in grain as well as in straw. This co-inoculation also improved the uptake of nitrogen and phosphorus in seed and straw (Singh et al. 2018). Similarly, *Rhizobium* in combination with phosphate-solubilizing bacterial inoculants increased the grain and straw yield, thousand-seed weight, pod number plant^{-1}, seed number pod^{-1}, nodule leghemoglobin content and its number, and fresh and dry biomass (Tagore et al. 2013).

The integrated use of rhizobial inoculants with organic sources can be helpful to increase the productivity of crop plants in soils with poor nutrient contents. The

Table 11.3 Synergistic effect of rhizobial inoculants with other soil microbes on growth, nutrient uptake, and yield of different crops

Crop	Rhizobial sp.	Synergizing organism	Effects on plant growth	References
Wheat	*Rhizobium* sp.	*Azospirillum* and *Pseudomonas*	Increased zinc contents in plant at different growth stages	Shah et al. (2016)
Wheat and soybean	*Bradyrhizobium*	*Azotobacter*	Increased nitrogen contents	Rawat et al. (2013)
Maize	*Rhizobium tropici*	*Azospirillum* sp.	Improved shoot dry weight, total N contents, and grain yield	Mark et al. (2015)
Rice	*Rhizobium* sp.	*Azospirillum brasilense*	Increased plant growth	Hahn et al. (2016)
Rice	*Bradyrhizobium*, *Rhizobium*	*Lysinibacillus*, *Alcaligenes*, and *Bacillus*	Early growth and vigor of rice	Shamsuddin et al. (2014)
Soybean	*Rhizobium japonicum*	*Azotobacter chroococcum* and *Azospirillum*	Improved membrane stability and chlorophyll contents	Zahedi et al. (2013)
Chickpea, pea, and lentil	*Rhizobium*	*Pseudomonas fluorescens*, *Anabaena laxa*	Enhances soil polysaccharide content and plant dry weight	Babu et al. (2015)
Black gram	*Rhizobium*	*Azotobacter* sp.	Increased shoot length, root length, fresh and dry biomass, number of leaves, root nodules per plant, chlorophyll contents, and reducing and non-reducing sugar contents	Gaur et al. (2017)
Chickpea	*Rhizobium* sp.	*Pseudomonas fluorescens*, *Azotobacter chroococcum*, and *Bacillus megaterium*	Significant increase in nodule number, dry weight of nodules, root and shoot growth, nitrogen and phosphorus contents, and grain and straw yield	Verma et al. (2010)
Chickpea	*Sinorhizobium ciceri*	*Pseudomonas* sp.	Increased nodulation and plant dry matter	Messele and Pant (2012)
Chickpea	*Mesorhizobium ciceri*	*Bacillus* sp.	Increased seed yield and grain protein contents	Wani et al. (2007b)
Chickpea	*Mesorhizobium* sp.	*Pseudomonas fluorescens*, *Azotobacter chroococcum*, and *Bacillus megaterium*	Increased root and shoot dry weight and nodulation	Werma et al. (2012)

(continued)

Table 11.3 (continued)

Crop	Rhizobial sp.	Synergizing organism	Effects on plant growth	References
Cowpea	*Bradyrhizobium* sp.	*Paenibacillus graminis*	Increased plant growth, enhanced efficiency of symbiotic association	Rodrigues et al. (2015)
Rajmash	*Rhizobium leguminosarum*	*Pseudomonas lurida*, *Pseudomonas putida*	Enhanced plant biomass and increased uptake of N, P, K, Zn, and Fe contents	Mishra et al. (2014)
Lentil	*Rhizobium* sp.	*Rhizobacteria*	Increased shoot length, root length and total biomass, and nodulation	Zafar-ul-Hye et al. (2013)
Lentil	*R. leguminosarum*	*Pseudomonas fluorescens*	Improved plant growth and nodulation	Khanna et al. (2011)
Pea	*Rhizobium leguminosarum*	Arbuscular mycorrhizal fungi	Increased plant biomass, photosynthetic rate, and N fixation activity	Geneva et al. (2006)
Common bean	*Rhizobium* sp.	*Paenibacillus polymyxa* and *Bacillus megaterium*	Enhanced shoot and nodule weight	Korir et al. (2017)
Common bean	*Rhizobium* sp.	*Paenibacillus polymyxa* and *Bacillus megaterium*	Increased plant growth and nodulation	Korir et al. (2017)
Pigeon pea	*Rhizobium* sp.	Arbuscular mycorrhizal fungi	Increased growth, nutrition, and chlorophyll contents	Havugimana et al. (2016)
Pigeon pea	*Sinorhizobium fredii*	*Pseudomonas fluorescens*	Enhanced growth and yield and potential biocontrol agent against *Fusarium* wilt	Kumar et al. (2010)
Soybean	*Bradyrhizobium* sp.	*Azospirillum* sp.	Increased grain yield and nodulation and enhanced nitrogen contents	Ferri et al. (2017)
Soybean	*Bradyrhizobium elkanii*	*Streptomyces griseoflavus*	Significantly increased plant growth, nodulation, N_2 fixation, N uptake, and yield	Htwe et al. (2018)
Soybean	*Bradyrhizobium* sp.	*Rhizobium*	Enhanced drought tolerance IAA production, EPS production, nodulation, and nodule N contents of plants	Uma et al. (2013)

(continued)

Table 11.3 (continued)

Crop	Rhizobial sp.	Synergizing organism	Effects on plant growth	References
Soybean	*Rhizobium* sp.	Arbuscular mycorrhizal fungi	Enhanced shoot dry weight and increased plant N and P contents	Wang et al. (2011)
Peanut	*Bradyrhizobium* sp.	Fungal endophyte, *Phomopsis liquidambar*	Increased nodule number, shoot nitrogen contents, and flavonoid synthesis	Zhang et al. (2016)
Peanut	*Bradyrhizobium* sp.	*Serratia marcescens* and *Trichoderma harzianum*	Increased number and mass of root nodules	Badawi et al. (2011)
Peanut	*Bradyrhizobium* sp.	*Ochrobactrum intermedium*	Promoted growth and tolerance against high temperature and salinity stress	Paulucci et al. (2015)
Corn and Soybean	*Bradyrhizobium japonicum*	*Azospirillum brasilense*	Promoted seed germination, nodule formation, and early seedling development	Cassan et al. (2009)
Soybean	*Bradyrhizobium japonicum*	*Bacillus amyloliquefaciens*	Better root colonization and increased number of nodules	Masciarelli et al. (2014)

effectiveness of the combined use of *Rhizobium* and different levels of vermicompost to improve the growth and productivity of faba bean was investigated by Argaw and Mnalku (2017) under field conditions. The integrated use of *Rhizobium* and vermicompost significantly improved all parameters of faba bean including number of nodules plant^{-1}, nodule dry weight plant^{-1}, and grain yield as compared to uninoculated control. They recommended using *Rhizobium* inoculant in combination with 8 tons ha^{-1} of vermicompost to boost the productivity of faba bean under field conditions in Haramaya, Ethiopia. More examples on the effectiveness of rhizobia in combination with other soil microbes for improving the productivity of different crops have been summarized in Table 11.3.

11.12 Conclusion and Future Prospects

It is evident from the above literature that rhizobia improve the productivity of cropping systems which not only increase nitrogen fixation but also improve soil fertility and crop production through several other attributes such as phosphate solubilization, siderophores production, phytohormones production, enzymes synthesis, and exopolysaccharides production. Moreover, these bacteria can be helpful for improvement in crop production on marginal lands due to their tolerance against various biotic and abiotic stresses. Their sole application and co-application with other plant growth-promoting rhizobacteria have the synergistic effects on crop plants both under normal and stressed environmental conditions.

Integrating legumes in the existing cropping systems and/or use of rhizobial inoculants can give better economic returns to farmers and contribute in maintaining soil fertility status for future use. Keeping in view the importance of rhizobia in sustainability of cropping systems, future research should focus on understanding the mechanisms involved in rhizobial-induced growth promotion. Strategies for improvement in plant-rhizobia interactions through molecular genetics, bioinformatics, and modeling tools should also be developed for sustainable crop production.

References

Aamir M, Aslam A, Khan MY, Jamshaid MU, Ahmad M, Asghar HN, Zahir ZA (2013) Co-inoculation with *Rhizobium* and plant growth promoting rhizobacteria (PGPR) for inducing salinity tolerance in mung bean under field condition of semi-arid climate. Asian J Agric Biol 1:17–22

Abdalla AS, Abdelgani ME, Osman AG (2013) Effects of biological and mineral fertilization on yield, chemical composition and physical characteristics of chickpea (*Cicer arietinum* L.) seeds. Pakistan J Nutrition 12:1–7

Abrar T (2017) Isolation and characterization of rhizobia from rhizosphere and root nodule of cowpea. IJNRIS 4:1–7

Afzal A, Bano A (2008) *Rhizobium* and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (*Triticum aestivum*). Inter J Agric Biol 10:85–88

Afzal A, Bano A, Fatima M (2010) Higher soybean yield by inoculation with N-fixing and P-solubilizing bacteria. Agron Sustain Dev 30:487–495

Agegnehu G, Bass AM, Nelson PN, Muirhead B, Wright G, Bird MI (2015) Biochar and biochar-compost as soil amendments: effects on peanut yield soil properties and greenhouse gas emissions in tropical North Queensland, Australia. Agric Ecosyst Environ 213:72–85

Aguado-Santacruz GAA, Moreno-Gomez BA, Jimenez-Francisco BB, Garcia-Moya EB, Preciado-Ortiz RE (2012) Impact of the microbial siderophores and phytosiderophores on the iron assimilation by plants: a synthesis. Rev Fitotec Mex 35:9–21

Ahemad M, Khan MS (2010) Growth promotion and protection of lentil (*Lens esculenta*) against herbicide stress by *Rhizobium* species. Ann Microbiol 60:735–745

Ahemad M, Khan MS (2011a) Ecotoxicological assessment of pesticides towards the plant growth promoting activities of Lentil (*Lens esculentus*) specific *Rhizobium* sp. strain MRL3. Ecotoxicology 20:661–669

Ahemad M, Khan MS (2011b) Effect of pesticides on plant growth promoting traits of green gram-symbiont, *Bradyrhizobium* sp. strain MRM6. Bull Environ Contam Toxicol 86:384–388

Ahemad M, Khan MS (2011c) Effect of tebuconazole-tolerant and plant growth promoting *Rhizobium* isolate MRP1 on pea-*Rhizobium* symbiosis. Sci Hort 129:266–272

Ahemad M, Khan MS (2012) Effects of pesticides on plant growth promoting traits of *Mesorhizobium* strain MRC4. J Saudi Soc Agric Sci 11:63–71

Ahmad M (2011) Microbial ACC-deaminase may improve the efficiency of *Rhizobium* inoculation in mung bean under salt affected conditions. PhD thesis, Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Ahmad F, Ahmad I, Khan MS (2008) Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol Res 163:173–181

Ahmad M, Zahir ZA, Asghar HN, Asghar M (2011) Inducing salt tolerance in mung bean through co-inoculation with *Rhizobium* and PGPR containing ACC-deaminase. Can J Microbiol 57:578–589

Ahmad E, Zaidi A, Khan MS, Oves M (2012) Heavy metal toxicity to symbiotic nitrogen-fixing microorganism and host legumes. In: Zaidi A (ed) Toxicity of heavy metals to legumes and bioremediation. Springer, Vienna, pp 29–44

Ahmad M, Zahir ZA, Nadeem SM, Nazli F, Jamil M, Khalid M (2013a) Field evaluation of *Rhizobium* and *Pseudomonas* strains to improve growth, nodulation and yield of mung bean under salt-affected conditions. Soil Environ 32:158–166

Ahmad M, Zahir ZA, Khalid M, Nazli F, Arshad M (2013b) Efficacy of *Rhizobium* and *Pseudomonas* strains to improve physiology, ionic balance and quality of mungbean under salt-affected conditions on farmer's fields. Plant Physiol Biochem 63:170–176

Ahmad M, Zahir ZA, Nadeem SM, Nazli F, Jamil M, Jamshaid MU (2014) Physiological response of mung bean to *Rhizobium* and *Pseudomonas* based biofertilizers under salinity stress. Pak J Agr Sci 51:557–564

Ahmed E, Holmstrom SJM (2014) Siderophores in environmental research: roles and applications. Microb Biotechnol 7:196–208

Akhal ELMR, Rincon A, Pena C, Lucas T, Mourabit MM, Barrijal S, Pueyo JJ (2013) Effects of salt stress and rhizobial inoculation on growth and nitrogen fixation of three peanut cultivars. Plant Biol 15:415–421

Akhtar MS, Siddiqui ZA, Wiemken A (2011) Arbuscular mycorrhizal fungi and rhizobium to control plant fungal diseases. In: Lichtfouse E (ed) Alternative farming systems, biotechnology, drought stress and ecological fertilization, vol 6. Sustainable agriculture reviews. Springer, Dordrecht, pp 263–292

Alam F, Bhuiyan MAH, Alam SS, Waghmode TR, Kim JP, Lee YB (2015) Effect of *Rhizobium* sp. BARIRGm901 inoculation on nodulation, nitrogen fixation and yield of soybean (*Glycine max*) genotype in gray terrace soil. Biosci Biotechnol Biochem 79:1660–1668

Alami Y, Achouak WA, Marol C, Heulin T (2000) Rhizosphere soil aggregation and plant growth promotion of sunflower by an exopolysaccharide producing *Rhizobium* sp. strain isolated from sunflower roots. Appl Environ Microbiol 66:3393–3398

Al-Falih AMK (2002) Factors affecting the efficiency of symbiotic nitrogen fixation by *Rhizobium*. Pak J Biol Sci 5:1277–1293

Allito BB (2015) Soil population and phenotypic characterization of soybean *(Glycin max)* and haricot bean *(Phaseolus vulgaris)* nodulating rhizobia at Hawassa and Ziway. Scholarly J Agric Sci 5:30–38

Allito BB, Ewusi-Mensah N, Alemneh AA (2014) Rhizobia strain and host-legume interaction effects on nitrogen fixation and yield of grain legume: a review. Mol Soil Biol 6:1–12

Al-Mughrabi KI (2010) Biological control of *fusarium* dry rot and other potato tuber diseases using *Pseudomonas fluorescens* and *Enterobacter cloacae*. Biol Control 53:280–284

Andrews M, Lea PJ, Raven JA, Azevedo RA (2009) Nitrogen use efficiency. 3. Nitrogen fixation: genes and costs. Ann Appl Biol 155:1–13

Angus JJ, Gupta VVSR, Good AJ, Pitson GD (1999) Wheat yield and protein response to anhydrous ammonia (Coldflo) and urea and their effects on soil. Final report on project CSP 169 for the grains research and development corporation. CSIRO, Canberra, p 17

Anjum MA (2011) Substrate dependent microbial biosynthesis of auxins and their effect on growth and yield of mung bean (*Vigna radiata* L.). PhD thesis, Institute of Soil and Environmental Sciences, University of Faisalabad, Faisalabad, Pakistan

Argaw A (2016) Effectiveness of *Rhizobium* inoculation on common bean productivity as determines by inherent soil fertility status. J Crop Sci Biotech 19:311–322

Argaw A (2018) Integrating inorganic NP application and *Bradyrhizobium* inoculation to minimize production cost of peanut (*Arachis hypogea* L.) in eastern Ethiopia. Agric & Food Secur 7:20

Argaw A, Mnalku A (2017) Vermicompost application as affected by *Rhizobium* inoculation on nodulation and yield of faba bean (*Vicia faba* L.). Ethiop J Agric Sci 27:17–29

Argaw A, Muleta D (2017) Effect of genotype-Rhizobium-environment interaction on nodulation and productivity of common bean (*Phaseolus vulgaris* L.) in eastern Ethiopia. Environ Syst Res 6:1–16

Arkhipova TN, Prinsen EA, Veselov SU, Martinenko EV, Melentiev LV, Kudoyarova GR (2007) Cytokinin producing bacteria enhance plant growth in drying soil. Plant Soil 292:305–315

Arora NK, Kang SC, Maheshwari DK (2001) Isolation of siderophores producing strains of *Rhizobium meliloti* and their biocontrol potential against *Macrophomina phaseolina* that causes charcoal rot of groundnut. Curr Sci 81:673–677

Arshad M, Frankenberger WT Jr (2002) Ethylene: agricultural sources and applications. Ann Bot 90(3):424

Aseri GK, Jain N, Tarafdar JC (2009) Hydrolysis of organic phosphate forms by phosphatases and phytase producing fungi of arid and semi-arid soils of India. JAES 5:564–570

Ashraf M, Berge SH, Mahmood OT (2004) Inoculating wheat seedling with exopolysaccharide-producing bacteria restricts sodium uptake and stimulates plant growth under salt stress. Biol Fert Soils 40:157–162

Babu S et al (2015) Synergistic action of PGP agents and *Rhizobium* spp. for improved plant growth, nutrient mobilization and yields in different leguminous crops. Biocatal Agric Biotechnol 4(4):456–464. https://doi.org/10.1016/j.bcab.2015.09.004i

Badawi FSF, Biomy AMM, Desoky AH (2011) Peanut plant growth and yield as influenced by co-inoculation with *Bradyrhizobium* and some rhizo-microorganisms under sandy loam soil conditions. AOAS 56(1):17–20

Bai B, Suri VK, Kumar A, Choudhary AK (2016) Influence of dual inoculation of AM fungi and *Rhizobium* on growth indices, production economics, and nutrient use efficiencies in garden pea (*Pisum sativum* L.). Commun Soil Sci Plant Anal 47:941–954

Bambara S, Ndakidemi PA (2009) Effects of *Rhizobium* inoculation, lime and molybdenum on photosynthesis and chlorophyll content of *Phaseolus vulgaris*. Afr J Microbiol Res 3 (11):791–798

Bano SA, Iqbal SM (2016) Biological nitrogen fixation to improve plant growth and productivity. IJAIR 4(4):15

Barroso CV, Pereira GT, Nahas E (2006) Solubilization of $CaHPO_4$ and $AlPO_4$ by *Aspergillus niger* in culture media with different carbon and nitrogen sources. Braz J Microbiol 37 (4):434–438

Bellenger JP, Wichard T, Kustka AB, Kraepiel AML (2008) Uptake of molybdenum and vanadium by a nitrogen-fixing soil bacterium using siderophores. Nat Geosci 1:243–246

Beneduzi A, Moreira F, Costa PB, Vargas LK, Lisboa BB, Favreto R, Baldani JI, Passaglia LMP (2013) Diversity and plant growth promoting evaluation abilities of bacteria isolated from sugarcane cultivated in the South of Brazil. Appl Soil Ecol 63:94–104

Bhatt P, Chandra R (2014) Inoculation effect of *Mesorhizobium ciceri* and rhizospheric bacteria on nodulation and productivity of chickpea (*Cicer arietinum* L.) and soil health. Indian J Plant Soil 1:5–10

Bhattacharjya S, Chandra R (2013) Effect of inoculation methods of *Mesorhizobium ciceri* and PGPR in chickpea (*Cicer arietinum* L.) on symbiotic traits, yield, nutrient uptake and soil properties. Legume Res 36:331–337

Bhattacharya C, Deshpande B, Pandey B (2013) Isolation and characterization of *Rhizobium* sp. form root of Legume plant (*Pisum sativum*) and its antibacterial activity against different bacterial strains. Int gric Food Sci 3(4):138–141

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Bianco C, Defez R (2010) Improvement of phosphate solubilization and *Medicago* plant yield by an indole-3-acetic acid-overproducing strain of *Sinorhizobium meliloti*. Appl Environ Microbiol 76:4626–4632

Biate DL, Kumar LV, Ramadoss D, Kumari A, Naik S, Reddy KK, Annapurna K (2014) Genetic diversity of soybean root nodulating bacteria. In: Maheshwari DK (ed) Bacterial diversity in sustainable agriculture. Springer, Heidelberg, pp 131–145

Boiero L, Perrig D, Masciarelli O, Penna C, Cassan F, Luna V (2007) Phytohormone production by three strains of *Bradyrhizobium japonicum* and possible physiological and technological implications. Appl Microbiol Biotechnol 74:874–880

Bottini R, Cassan F, Piccoli P (2004) Gibberellin production by bacteria and its involvement in plant growth promotion and yield increase. Appl Microbiol Biotechnol 65:497–503

Braud A, Hoegy F, Jezequel K, Lebeau T, Schalk IJ (2009) New insights into the metal specificity of the *Pseudomonas aeruginosa* pyoverdine–iron uptake pathway. Environ Microbiol 11:1079–1091

Broos K, Beyens H, Smolders E (2005) Survival of rhizobia in soil is sensitive to elevated zinc in the absence of the host plant. Soil Biol Biochem 37:573–579

Bumunang EW, Babalola OO (2014) Characterization of *Rhizobacteria* from field grown genetically modified (GM) and non-GM Maizes. Braz Arch Biol Technol 57:1–8

Burgess CM, Smid EJ, Sinderen D (2009) Bacterial vitamin B2, B11 and B12 overproduction: an overview. Int J Food Microbiol 133:1–7

Carson KC, Meyer JM, Dillworth MJ (2000) Hydroxamate siderophores of root nodule bacteria. Soil Biol Biochem 32:11–21

Cassan F, Perrig D, Sgroy V, Masciarelli O, Penna C, Luna C (2009) *Azospirillum brasilense* Az39 and *Bradyrhizobium japonicum* E109, inoculated singly or in combination, promote seed germination and early seedling growth in corn (*Zea mays* L.) and soybean (*Glycine max* L.). Eur J Soil Biol 45(1):28–35

Castellane TCL, Otoboni AMMB, Lemos EGM (2015) Characterization of exopolysaccharides produced by rhizobia species. R Bras Ci Solo 39:1566–1575

Castro S, Furlan A, Llanes AA, Luna V (2012) International scholarly research network. ISRN Agronomy. https://doi.org/10.5402/2012/318083

Cerezini P, Kuwanoa BH, Santosb MBD, Terassic F, Hungriad M (2016) Strategies to early nodulation in soybean under drought. Marco Antonio Nogueirad Field Crop Res 196:160–167

Chalk PM, Souza RDF, Urquiaga S, Alves BJR, Boddy RM (2006) The role of arbuscular mycorrhiza in legume symbiotic performance. Soil Biol Biochem 38:2944–2951

Chandra R, Pareek N (2015) Comparative performance of plant growth promoting rhizobacteria with rhizobia on symbiosis and yields in urdbean and chickpea. J Food Legumes 28:86–89

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 38:128–130

Chaudri AM, Allain CMG, Barbosa-Jefferson VL, Nicholson FA, Chambers BJ, McGrath SP (2000) A study of the impacts of Zn and Cu on two rhizobial species in soils of a long-term field experiment. Plant Soil 221:167–179

Cheung KH, Gu JD (2007) Mechanism of hexavalent chromium detoxification by microorganisms and bioremediation application potential: a review. Int Biodeterior Biodegradation 59:8–15

Chi F, Yang P, Han F, Jing Y, Shen S (2010) Proteomic analysis of rice seedlings infected by *Sinorhizobium meliloti* 1021. Proteomics 10:1861–1874

Clayton GW, Rice WA, Lupwayi NZ, Johnston AM, Lafond GP, Grant CA, Walley F (2004) Inoculant formulation and fertilizer nitrogen effects on field pea: nodulation, N fixation, and nitrogen partitioning. Can J Plant Sci 84:79–88

Crossley RA, Gaskin DGH, Holmes K, Mulholland F, Wells JM, Kelly DJ, van Vliet AHM, Walton NJ (2007) Riboflavin biosynthesis is associated with assimilatory ferric reduction and iron acquisition by Campylobacter jejuni. J Appl Environ Microbiol 73(24):7819–7825

D'Haeze W, Holsters M (2002) Nod factor structures, responses, and perception during initiation of nodule development. Glycobiology 12:79R–105R

Dakora FD (2003) Defining new roles for plant and rhizobial molecules in sole and mixed plant cultures involving symbiotic legumes. New Phytol 58:39–49

Das S, Pareek N, Raverkar KP, Chandra R, Kaustav A (2012) Effectiveness of micronutrient application and *Rhizobium* inoculation on growth and yield of chickpea. Int J Agric Environ Biotech 5:445–452

Dazzo FB, Yanni YG (2006) The natural rhizobium-cereal crop association as an example of plant-bacterial interaction. In: Uphoff N, Ball AS, Fernandes E, Herren H, Husson O, Laing M, Palm C, Pretty J, Sanchez P, Sanginga N, Thies J (eds) Biological approaches to sustainable soil systems. CRC, Boca Raton, FL, pp 109–127

Dazzo FB, Yanni YG, Rizk R, Zidan M, Gomaa M, Abu-Baker, Squartini A, Jing Y, Chi F, Shen SH (2005) Recent studies on the Rhizobium cereal association. In: Wang YP, Lin M, Tian ZX, Elmericj C, Newton WE (eds) Biological nitrogen fixation: sustainable agriculture and the environment. Proceedings of the 14th international nitrogen fixation congress. Springer, Dordrecht, pp 379–380

De Smet I, Zhang H, Inze D, Beeckman T (2006) A novel role for abscisic acid emerges from underground. Trends Plant Sci 11:434–439

Denison RF, Kiers ET (2011) Life histories of symbiotic rhizobia and mycorrhizal fungi. Curr Biol 21:R775–R785

Deshwal VK, Chaubey A (2014) Isolation and characterization of *Rhizobium leguminosarum* from root nodule of *Pisum sativum* L. J Academia Industrial Res 2:464–467

Dhami N, Prasad B (2009) Increase in root nodulation and crop yield of soybean by native *Bradyrhizobium japonicum* strains. J Plant Sci 6:1–3

Dobbelaere S, Vanderleyden J, Okon Y (2003) Plant growth promoting effects of diazotrophs in the rhizosphere. Crit Rev Plant Sci 22:107–149

Donot F, Fontana A, Baccou JC, Schorr-Galindo S (2012) Microbial exopolysaccharides: main examples of synthesis, excretion, genetics and extraction. Carbohydr Polym 87:951–962

Duan J, Muller KM, Charles TC, Vesely S, Glick BR (2009) 1-Aminocyclopropane-1carboxylate (ACC) deaminase gene in *Rhizobium* from Southern Saskatchewan. Microbial Ecol 57:423–436

Egamberdiyeva D, Juraeva D, Poberejskaya S, Myachina O, Teryuhova P, Seydalieva L, Aliev A (2004) Improvement of wheat and cotton growth and nutrient uptake by phosphate solubilizing bacteria. In: The "26th Southern Conservation Tillage Conference for Sustainable Agriculture". J.S. Mckimmon Centre, North Carolina State University, Raleigh, North Carolina, 8–9 June 2004, pp 58–66

El-Batanony NH, Massoud ON, Mazen MM, Abd El-Monium MM (2007) The inhibitory effects of cultural filtrates of some wild rhizobium spp. on some faba bean root rot pathogens and their antimicrobial synergetic effect when combined with Arbuscular Mycorrhiza (AM). World J Agric Sci W J Agric 3:721–730

Elkoca E, Turan M, Donmez MF (2010) Effects of single, dual and triple inoculations with *Bacillus subtilis*, *Bacillus megaterium* and *Rhizobium leguminosarum* bv. *phaseoli* on nodulation, nutrient uptake, yield and yield parameters of common bean (*Phaseolus vulgaris* L. cv. 'elkoca-05'). J Plant Nutr 33:2104–2119

Fan LM, Maa ZQ, Liang JQ, Li HF, Wangc ET, Wei GH (2011) Characterization of a copper-resistant symbiotic bacterium isolated from *Medicago lupulina* growing in mine tailings. Bioresour Technol 102:703–709

Fatima Z, Bano A, Sial R, Aslam M (2008) Response of chickpea to plant growth regulators on nitrogen fixation and yield. Pak J Bot 40:2005–2013

Fernandez LA, Zalpa P, Gomez MA, Sagardoy MA (2007) Phosphate solubilization activity of bacterial strains in soil and their effect on soybean growth under greenhouse conditions. Biol Fert Soils 43:805–809

Ferri GC, Braccini AL, Anghinoni FBG, Pereira LC (2017) Effects of associated co-inoculation of *Bradyrhizobium japonicum* with *Azospirillum brasilense* on soybean yield and growth. AJAR 12(1):6–11

Figueiredo MVB, Burity HA, Martınez CR, Chanway CP (2008) Alleviation of drought stress in the common bean (*Phaseolus vulgaris* L.) by co-inoculation with *Paenibacillus polymyxa* and *Rhizobium tropici*. Appl Soil Ecol 40:182–188

Fituma T, Tamado T, Anteneh A (2018) Effect of inoculating *Bradyrhizobium* on phosphorus use efficiency and nutrient uptake of soybean intercropped with sugarcane in calcareous soil of metehara, central rift valley, Ethiopia. Adv Crop Sci Tech 28(1):17–32

Flemming HC, Neu TR, Wozniak DJ (2007) The EPS matrix: the house of biofilm cells. J Bacteriol 189:7945–7947

Flores-Felix JD, Menendez E, Rivera LP (2012) Use of *Rhizobium leguminosarum* as a potential biofertilizer for *Lactuca sativa* and *Daucus carota* crops. J Plant Nutr Soil Sci 176:876–882

Gage DJ (2004) Infection and invasion of roots by symbiotic, nitrogen-fixing rhizobia during nodulation of temperate legumes. Microbiol Mol Biol Rev 68:280–300

Galindo FS, Filho TMC, Salatier B, Ludkiewicz MGZ, Rosa PAL, Tritapepe CA (2018) Technical and economic viability of co-inoculation with *Azospirillum brasilense* in soybean cultivars in the Cerrado. Rev Bras Eng Agríc Ambient 22(1):51–56

Gao X, Lu X, Wu M, Zhang H, Pan R, Tian J, Li S, Liao H (2012) Co-inoculation with rhizobia and AMF inhibited soybean red crown rot: from field study to plant defense-related gene expression analysis. PLoS One 7(3):e33977

Garcia-Fraile P, Carro L, Robledo M (2012) *Rhizobium* promotes non-legumes growth and quality in several production steps: towards a biofertilization of edible raw vegetables healthy for humans. PLoS One 7(5):e38122. https://doi.org/10.1371/journal.pone.0038122

Gaur R, Tiwari S, Chauhan RK, Singh R, Shukla R (2017) Integrated effect of *Rhizobium* and *Azotobacter* cultures on the leguminous crop black gram (*Vigna mungo*). Adv Crop Sci Tech doi 5(3):289. https://doi.org/10.4172/2329-8863

Gauri SAK, Bhatt RB, Pant S, Bedi MK, Naglot A (2011) Characterization of *Rhizobium* isolated from root nodules of *Trifolium alexandrinum*. J Agric Technol 7:1705–1723

Geetha SJ, Joshi SJ (2013) Engineering Rhizobial bioinoculants: a strategy to improve iron nutrition. Sci World J 2013:1–15

Geneva M, Zehirov G, Djonova E, Kaloyanova N, Georgiev G, Stancheva I (2006) The effect of inoculation of pea plants with Mycorrhizal fungi and *Rhizobium* on nitrogen and phosphorus assimilation. Plant Soil Environ 52(10):435–440

Giller KE (2001) Nitrogen fixation in tropical cropping systems. CAB International, Wallingford

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:15. https://doi.org/10.6064/2012/963401

Goggin DE, Steadman KJ, Emery RJN, Farrow SC, Benech-Arnold RL, Powles SB (2009) ABA inhibits germination but not dormancy release in mature imbibed seeds of *Lolium rigidum* gaud. J Exp Bot 60:3387–3396. https://doi.org/10.1093/jxb/erp175

Gontijo JB, Andrade GVS, Baldotto MA, Baldotto LEB (2018) Bioprospecting and selection of growth-promoting bacteria for *Cymbidium* sp. Orchids Sci Agric 75(5):368–374

Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Gowda CCL, Krishnamurthy L (2014) Plant growth promoting rhizobia: challenges and opportunities. Biotechnology 3:1–23

Goswami D, Pithwa S, Dhandhukia P, Thakker JN (2014) Delineating Kocuria turfanensis 2M4 as a credible PGPR: a novel IAA-producing bacteria isolated from saline desert. J Plant Interact 9:566–576

Grichko VP, Glick BR (2001) Amelioration of flooding stress by ACC deaminase containing plant growth promoting bacteria. Plant Physiol Biochem 39:11–17

Grover M, Ali SZ, Sandhya V, Rasul A, Venkateswarlu B (2010) Role of microorganisms in adaptation of agriculture crops to abiotic stresses. World J Microbiol Biotechnol 27:1231–1240

Guo Y, Ni Y, Huang J (2010) Effects of rhizobium, arbuscular mycorrhiza and lime on nodulation, growth and nutrient uptake of lucerne in acid purplish soil in China. Trop Grasslands 44:109–114

Hafeez FY, Hassan Z, Naeem F, Basher A, Kiran A, Khan SA, Malik KA (2008) *Rhizobium leguminosarum* bv. *viciae* strain LC–31: analysis of novel bacteriocin and ACC-deaminase gene (s). In: Dakora FD, Chimphango SBM, Valentine AJ, Elmerich C, Newton WE (eds) Biological nitrogen fixation: towards poverty alleviation through sustainable agriculture. Springer, Dordrecht, pp 247–248

Hahn L, Sa ELS, Filho BDO, Machado RG, Damasceno RG, Giongo A (2016) Rhizobial inoculation, alone or coinoculated with *Azospirillum brasilense*, promotes growth of wetland rice. Rev Bras Cienc Solo 40:e0160006

Haque MA, Bala P, Azad AK (2014) Performance of lentil varieties as influenced by different *Rhizobium* inoculations. Bangladesh Agron J 17:41–46

Hatice O, Omer F, Erdal E, Faik K (2008) The determination of symbiotic effectiveness of *Rhizobium* strains isolated from wild chickpeas collected from high altitudes in Erzurum. Turk J Agric For 32:241–248

Havugimana E, Bhople BS, Byiringiro E, Mugabo BP (2016) Role of dual inoculation of *Rhizobium* and Arbuscular Mycorrhizal (AM) fungi on pulse crops production. J Sci Tech 13(1):1–7

Htwe ZA, Seinn MM, Moe M, Yamakawa K (2018) Effects of co-inoculation of *Bradyrhizobium elkanii* BLY3-8 and *Streptomyces griseoflavus* P4 on Rj 4 soybean varieties. Soil Sci Plant Nutr 64(4):449–454. https://doi.org/10.1080/00380768.2018.1452574

Huang HC, Erickson RS (2007) Effect of seed treatment with *Rhizobium leguminosarum* on *pythium* damping-off, seedling height, root nodulation, root biomass, shoot biomass, and seed yield of pea and lentil. J Phytopathol 155:31–37

Hungria M, Kaschuk G (2014) Regulation of N_2 fixation and NO_3-/NH_4^+ assimilation in nodulated and N-fertilized *Phaseolus vulgaris* L. exposed to high temperature stress. Environ Exp Bot 98:32–39

Hussain MI, Akhtar MJ, Asghar HN, Ahmad M (2011) Growth, nodulation and yield of mash bean (*Vigna mungo* L.) as affected by *Rhizobium* inoculation and soil applied L-tryptophan. Soil Environ 30:13–17

Hussain MB, Zahir ZA, Asghar HN, Asghar M (2014) Can catalase and exopolysaccharides producing rhizobia ameliorate drought stress in wheat? Int J Agric Biol 16:3–13

Hussain MB, Mahmood S, Ahmed N, Nawaz H (2018) Rhizobial inoculation for improving growth physiology, nutrition and yield of maize under drought stress conditions. Pak J Bot 50 (5):1681–1689

Islam MR, Madhaiyan M, Deka HPB, Yim W, Lee G, Saravanan VS, Fu Q, Hu H, Sa T (2009) Characterization of plant growth-promoting traits of free-living diazotrophic bacteria and their inoculation effects on growth and nitrogen uptake of crop plants. J Microbiol Biotechnol 19 (10):1213–1222

Janczarek M, Rachwał K, Cieśla J, Ginalska G, Bieganowski A (2015) Production of exopolysaccharide by *Rhizobium leguminosarum* bv. *trifolii* and its role in bacterial attachment and surface properties. Plant Soil 388:211–227

Jha CK, Patel B, Sarf M (2012) Stimulation of the growth of *Jatropha curcas* by the plant growth bacterium *Enterobacter cancerogenus* MSA2. World J Microbiol Biotechnol 28:891–899

Jimenez-Gomez A, Flores-Felix JD, Garcia-Fraile P, Mateos PF, Menendez E, Velazquez E, Rivas R (2018) Probiotic activities of *Rhizobium laguerreae* on growth and quality of spinach. Sci Rep 8(1):295. https://doi.org/10.1038/s41598-017-18632-z

Jones KM, Kobayashi H, Davies BW, Taga ME, Walker GC (2007) How rhizobial symbionts invade plants: the *Sinorhizobium-Medicago* model. Nat Rev Microbiol 5:619–633

Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA, Mehnaz S (2017) Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. Front Microbiol 8:2593. https://doi.org/10.3389/fmicb02593

Kang BR, Yang KY, Cho BH, Han TH, Kim IS, Lee MC, Anderson AJ, Kim YC (2006) Production of indole-3-acetic acid in the plant-beneficial strain *Pseudomonas chlororaphis* O6 is negatively regulated by the global sensor kinase GacS. J Current Microbiol 52:473–476

Kang X, Yu X, Zhang Y, Cui Y, Tu W, Wang Q, Li Y, Hu L, Gu Y, Zhao K, Xiang Q, Chen Q, Ma M, Zou L, Zhang X, Kang J (2018) Inoculation of *Sinorhizobium saheli* YH1 heads to reduced metal uptake for *Leucaena leucocephala* grown in mine tailings and metal-polluted soils. Front Microbiol 9:1–13

Karpagam T, Nagalakshmi PK (2014) Isolation and characterization of phosphate solubilizing microbes from agricultural soil. J Curr Microbiol App Sci 3(3):601–614

Kaur N, Sharma P, Sharma S (2015) Co-inoculation of *Mesorhizobium* sp. and plant growth promoting rhizobacteria *Pseudomonas* sp. as bio-enhancer and bio-fertilizer in chickpea (*Cicer arietinum* L.). ARCC Res 38:367–374

Khaitov B, Kurbonov A, Abdiev A, Adilov M (2016) Effect of chickpea in association with *Rhizobium* to crop productivity and soil fertility. Eurasian J Soil Sci 5:105–112

Khalid M, Arshad M, Zahir ZA (2006) Phytohormones: microbial production and application. In: Uphoff N, Ball AS, Palm C, Fernandes E, Pretty J, Herren H, Sanchez P, Husson O, Sanginga N, Laing M, Thies J (eds) Biological approaches to sustainable soil systems. Taylor & Francis, Boca Raton, pp 207–220

Khan MS, Zaidi A, Ahemad M, Oves M, Wani PA (2010) Plant growth promotion by phosphate solubilizing fungi—current perspective. Arch Agron Soil Sci 56:73–98

Khan MY, Asghar HN, Jamshaid MU, Akhtar MJ, Zahir ZA (2013) Effect of microbial inoculation on wheat growth and phyto-stabilization of chromium contaminated soil. Pak J Bot 45:27–34

Khan MS, Zaidi A, Ahmad E (2014) Mechanism of phosphate solubilization and physiological functions of phosphate-solubilizing microorganisms. In: Khan M, Zaidi A, Musarrat J (eds) Phosphate solubilizing microorganisms. Springer Cham, pp 31-62

Khanna V, Sharma P, Sharma S (2011) Studies on synergism between *Rhizobium* and plant growth promoting rhizobacteria in lentil (*Lens culinaris* Medikus). J Food Legume 24(2):158–159

Kisiala A, Laffont C, Emery RJN, Frugier F (2013) Bioactive cytokinins are selectively secreted by *Sinorhizobium meliloti* nodulating and nonnodulating strains. Mol Plant-Microbe Interact 26:1225–1231

Kobayashi T, Nishizawa NK (2012) Iron uptake, translocation, and regulation in higher plants. Annu Rev Plant Biol 63:131–152

Korir H, Mungai NW, Thuita M, Hamba Y, Masso Y (2017) Co-inoculation effect of rhizobia and plant growth promoting rhizobacteria on common bean growth in a low phosphorus soil front. Plant Sci 8:141. https://doi.org/10.3389/fpls.2017.00141

Koskey G, Mburu SW, Njeru EM, Kimiti JM, Ombori O, Maingi JM (2017) Potential of native rhizobia in enhancing nitrogen fixation and yields of climbing beans (*Phaseolus vulgaris* L.) in contrasting environments of Eastern Kenya. Front Plant Sci 8:1–12

Krishnan HB, Kang BR, Krishnan AH, Kil Kim KY, Kim YC (2007) *Rhizobium etli* USDA9032 engineered to produce a phenazine antibiotic inhibits the growth of fungal pathogens but is impaired in symbiotic performance. Appl Environ Microbiol 73:327–330

Krujatz F, Haarstrick A, Neortemann B, Greis T (2011) Assessing the toxic effects of nickel, cadmium and EDTA on growth of the plant growth-promoting rhizobacterium *Pseudomonas brassicacearum*. Water Air Soil Pollut 223(3):1281–1293. https://doi.org/10.1007/s11270-011-0944-0

Kulasooriya SA, Ekanayake EMHGS, Kumara RKGK, Bandar AMS (2017) Rhizobial inoculation of *Trifolium repens* L. in Sri Lanka. J Natn Sci Foundation Sri Lanka 45:361–366

Kumar H, Bajpai VK, Dubey RC (2010) Wilt disease management and enhancement of growth and yield of *Cajanus cajan* (L) var. Manak by bacterial combinations amended with chemical fertilizer. Crop Protect 29:591–598

Kumar D, Arvadiya LK, Kumawat AK, Desai KL, Patel TU (2014) Yield, protein content, nutrient content and uptake of chickpea (*Cicer arietinum* L.) as influenced by graded levels of fertilizers and bio-fertilizers. Res J Chem Environ Sci 2:60–64

Kyei-Boahen S, Slinkard AE, Walley FL (2002) Evaluation of Rhizobial inoculation methods for chickpea. J Agron 94:851–859

Laabas S, Boukhatem ZS, Bouchiba Z, Benkritly S, Abed NE, Yahiaoui H, Bekki A, Tsaki H (2017) Impact of single and co-inoculations with Rhizobial and PGPR isolates on chickpea (*Cicer arietinum*) in cereal-growing zone soil. J Plant Nutr 40(11):1616–1626

Leytem AB, Mikkelson RL (2005) The nature of phosphorus in calcareous soils. Better Crops 89:11–13

Liu Y, Wu L, Baddeley JA, Watson CA (2011) Models of biological nitrogen fixation of legumes. A review. Agron Sustain Dev 31:155–172

Liu H, Wang X, Qi H, Wang Q, Chen Y, Li Q (2017) The infection and impact of *Azorhizobium caulinodans* ORS571 on wheat (*Triticum aestivum* L.). PLoS One 12(11):e0187947

Lodwig EM, Poole PS (2003) Metabolism of *Rhizobium* bacteroids. Crit Rev Plant Sci 22:37–38

Lodwig EM, Hosie AHF, Bourdes A, Findlay K, Allaway D, Karunakaran R, Downie JA, Poole PS (2003) Amino-acid cycling drives nitrogen fixation in the legume- *Rhizobium* symbiosis. Nature 422:722–726

Ma W, Carles TC, Glick BR (2004) Expression of an exogenous 1-aminocyclopropane carboxylate deaminase gene in *Sinorhizobium meliloti* increases its ability to nodulate alfalfa. Appl Environ Microbiol 70(10):5891–5897

Maheshwari DK, Chandra S, Choure K, Dubey RC (2007) Rhizosphere competent *Mesorhizobium loti* mp6 induces root hair curling, inhibits *Sclerotinia sclerotiorum* and enhances growth of Indian mustard (*Brassica campestris*). BJM 38:124–130

Makoi JH, Bambara S, Ndakidemi PA (2013) *Rhizobium* inoculation and the supply of molybdenum and lime affect the uptake of macroelements in common bean (*P. vulgaris* L.) plants. Aust J Crop Sci 7:784–793

Malisorn K, Prasarn C (2014) Isolation and characterization of *Rhizobium spp.* from root of legume plants species. Agron J 4:157–160

Manasa K, Reddy SR, Triveni S (2017) Characterization of potential PGPR and antagonistic activities of *Rhizobium* isolates from different rhizosphere soils. J Pharmacogn Phytochem 6 (3):51–54

Mandri B, Drevon J, Bargaz A, Oufdou K, Faghire M, Plassard C, Payer H, Goulam C (2012) Interactions between common bean genotypes and rhizobia strains isolated from Moroccan soils for growth, phosphatase and phytase activities under phosphorus deficiency conditions. J Plant Nutr 35:1477–1490

Maougal RT, Brauman A, Plassard C, Abadie J, Djekoun J, Drevon JJ (2014) Bacterial capacities to mineralize phytate increase in the rhizosphere of nodulated common bean (*Phaseolus vulgaris*) under P deficiency. Eur J Soil Biol 62:8–14

Marchiol L, Assolari S, Sacco P, Zerbi G (2004) Phytoextraction of heavy metals by canola (*Brassica napus*) and radish (*Raphanus sativus*) grown on multi contaminated soil. Environ Pollut 132:21–27

Marczak M, Mazur A, Koper P, Żebracki K, Genes AS (2017) Synthesis of rhizobial exopolysaccharides and their importance for symbiosis with legume plants. Genes 8(12):360. https://doi.org/10.3390/genes8120360

Mark BB, Megias M, Ollero FJ, Araujo RS (2015) Maize growth promotion by inoculation with *Azospirillum brasilense* and metabolites of *Rhizobium tropici* enriched on lipo-chitooligosaccharides (LCOs). AMB Express 5:71

Martyniuk S, Kozieł M, Gałązk A (2018) Response of pulses to seed or soil application of rhizobial inoculants. Ecol Chem Eng S 25:323–329

Masalha J, Kosegarten H, Elmaci O, Mengel K (2000) The central role of microbial activity for iron acquisition in maize and sunflower. Biol Fertil Soils 30:433–439

Masciarelli O, Llanes A, Luna V (2014) A new PGPR co-inoculated with *Bradyrhizobium japonicum* enhances soybean nodulation. Microbiol Res 169(7–8):609–661

Matiru VN, Dakora FD (2005) The rhizosphere signal molecule lumichrome alters seedling development in both legumes and cereals. New Phytol 166:439–444

McAdam EL, Reid JB, Foo E (2018) Gibberellins promote nodule organogenesis but inhibit the infection stages of nodulation. J Exp Bot 69:2117–2130

McLaughlin MJ, McBeath TM, Smernik R, Stacey SP, Ajiboye B, Guppy C (2011) The chemical nature of P accumulation in agricultural soils-implications for fertilizer management and design: an Australian perspective. Plant Soil 349:69–87

Mehboob I, Naveed M, Zahir ZA (2009) Rhizobial association with non-legumes: mechanisms and applications. Crit Rev Plant Sci 28:432–456

Mehboob I, Zahir ZA, Arshad M, Tanveer A, Farroq-E-Azam (2011) Growth promoting activities of different *Rhizobium* sp. in wheat. Pak J Bot 43:1643–1650

Messele B, Pant LM (2012) Effects of inoculation of *Sinorhizobium ciceri* and phosphate solubilizing bacteria on nodulation, yield and nitrogen and phosphorus uptake of chickpea (*Cicer arietinum* L.) in Shoa Robit area. J Biofert Biopest 3:5. https://doi.org/10.4172/2155-6202.1000012

Mia MD, Shamsuddin ZH, Wahab Z, Marziah M (2005) High yielding and quality banana production through plant growth promoting rhizobacterial (PGPR) inoculation. Fruits 60:179–185

Mirza BS, Mirza MS, Bano A, Malik KA (2007) Coinoculation of chickpea with *Rhizobium* isolates from roots and nodules and phytohormones-producing *Enterobacter* strains. Austr J Exp Agr 47:1008–1015

Mishra P, Bisht K, Jeevanandan K, Kumar S, Bisht JK, Bhatt JC (2014) Synergistic effect of inoculating plant growth-promoting *Pseudomonas* spp. and *Rhizobium leguminosarum*-FB1 on growth and nutrient uptake of raj mash (*Phaseolus vulgaris* L.). Arch Agron Soil Sci 60:799–815

Mohammed H, Sahid IB (2016) Evaluation of *Rhizobium* inoculation in combination with phosphorus and nitrogen fertilization on groundnut growth and yield. J Agron 15:142–146

Monteiro NK, Aranda-Selverio G, Exposti DTD, Silva MLC, Lemos EGM, Campanharo JC, Silveira JLM (2012) Caracterização química dos géis produzidos pelas bactérias diazotróficas *Rhizobium tropici* e *Mesorhizobium* sp. Química Nova 35(4):705–708

Morrone D, Chambers J, Lowry L, Kim G, Anterola A, Bender K, Peters RJ (2009) Gibberellin biosynthesis in bacteria: separate ent-copalyl diphosphate and entkaurene synthases in *Bradyrhizobium japonicum*. FEBS Lett 583:475–480

Mouradi M, Farissi M, Khadraji A, Makoudi B, Ghoulam C (2018) Biochemical and antioxidant proprieties associated with the adaptation of faba bean (*Vicia faba* L.) rhizobia symbiosis to phosphorus deficit. J Mater Environ Sci 9(5):1574–1581

Mrabet M, Mhamdi R, Tajini F, Tiwari R, Trabelsi M, Aouani ME (2005) Competitiveness and symbiotic effectiveness of a *R. gallicum* strain isolated from root nodules of *Phaseolus vulgaris*. Eur J Agron 22:209–216

Mujahidy SKMDJ, Hassan M, Rahman M, Rashid ANM (2013) Isolation and characterization of *Rhizobium* spp. and determination of their potency for growth factor production. IRJOB 4 (7):117–123

Mylona P, Pawlowski K, Bisseling T (1995) Symbiotic nitrogen fixation. Plant Cell 7:869–885

Nadeem SM, Zahir ZA, Naveed M, Arshad M (2007) Preliminary investigations on inducing salt tolerance in maize through inoculation with rhizobacteria containing ACC deaminase activity. Can J Microbiol 53:1141–1149

Naidu VSGR, Panwar JDS, Annapurna K (2004) Effect of synthetic auxins and Azorhizobium caulinodans on growth and yield of rice. Indian J Microbiol 44:211–213

Neubauer U, Furrer G, Kayser A, Schulin R (2000) Siderophores, NTA, and citrate: potential soil amendments to enhance heavy metal mobility in phytoremediation. Int J Phytoremed 2:353–368

Nosheen A, Bano A (2014) Potential of plant growth promoting rhizobacteria and chemical fertilizers on soil enzymes and plant growth. Pak J Bot 46:1521–1530

Nyoki D, Ndakidemi PA (2014) Effects of phosphorus and *Bradyrhizobium japonicum* on growth and chlorophyll content of cowpea. Am J Exp Agric 4:1120–1136

Ogutcu H, Algur OF, Elkoca E, Kantar F (2008) The determination of symbiotic effectiveness of *Rhizobium* strains isolated from wild chickpea collected from high altitudes in Erzurum. Turk J Agric For 32:241–248

Oldroyd GED (2007) Nodules and hormones. Science 315(5808):52–53

Owino WO, Manabe Y, Mathooko FM, Kubo Y, Inaba A (2006) Regulatory mechanisms of ethylene biosynthesis in response to various stimuli during maturation and ripening in fig fruit (*Ficus carica* L.). Plant Physiol Biochem 44:335–342

Patel A, Vyas RV, Mankad M, Subhash N (2017) Isolation and biochemical characterization of rhizobia from rice rhizosphere and their effect on rice growth promotion. Int J Pure App BioSci 5(4):441–451

Patten CL, Glick BR (1996) Bacterial biosynthesis of indole-3-acetic acid. Can J Microbiol 42:207–220

Paulucci NS, Gallarato LA, Reguera YB, Vicario JC (2015) *Arachis hypogaea* PGPR isolated from Argentine soil modifies its lipids components in response to temperature and salinity. Microbiol Res 173:1–9

Picazevicz AAC, Kusdra JF, Moreno ADL (2017) Maize growth in response to *Azospirillum brasilense*, *Rhizobium tropici*, molybdenum and nitrogen. Rev Bras Eng Agric Ambient 21 (9):623–627

Pierson EA, Weller DM (1994) Use of mixtures of fluorescent pseudomonads to suppress take-all and improve the growth of wheat. J Phytopathol 84:940–947

Prabha C, Maheshwari DK, Bajpai VK (2013) Diverse role of fast growing rhizobia in growth promotion and enhancement of psoralen content in *Psoralea corylifolia*. Phcog Mag 9:57–65

Qurashi AW, Sabri AN (2012) Bacterial exopolysaccharides and biofilm formation stimulate chickpea growth and soil aggregation under salt stress. Braz J Microbiol 43:1183–1191

Raja D, Takankhar VJ (2018) Response of liquid biofertilizers (*Bradyrhizobium* and PSB) on nutrient content in soybean. IJCMAS 7(5):3701–3706

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

Rao BP, Sudharsan K, Reshma CH, Sekaran G, Mandal AB (2013) Characterization of exopolysaccharide from *Bacillus amyloliquefaciens* BPRGS for its Bioflocculant activity. Int J Sci Eng Res 4(10):1696–1704

Ravikumar R (2012) Growth effects of *Rhizobium* inoculation in some Legume plants. Int J Curr Sci 1:1–6

Rawat AK, Rao DLN, Sahu RK (2013) Effect of soybean inoculation with *Bradyrhizobium* and wheat inoculation with *Azotobacter* on their productivity and N turnover in a Vertisol. Arch Agron Soil Sci 59:1559–1571

Raychaudhuri N, Das SK, Chakraborty PK (2005) Symbiotic effectiveness if siderophore overproducing mutant of *Mesorhizobium ciceri*. Pol J Microbiol 54:37–41

Raymond K, Dertz EM (2004) Biochemical and physical properties of siderophores. In: Crosa JM, Mey AM, Pyne SM (eds) Iron transport in Bacteria. ASM, Washington, DC, pp 1–16

Remans R, Beebe S, Blair M, Manrique G, Tovar E, Rao I, Croonenborghs A, Torres-Gutierrez R, El-Howeity M, Michiels J, Vanderleyden J (2007) Physiological and genetic analysis of root responsiveness to auxin-producing plant growth-promoting bacteria in common bean (*Phaseolus vulgaris* L.). Plant Soil 302:149–161

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. BMRJ 6(5):247–254

Richardson AE, Simpson RJ (2011) Soil microorganisms mediating phosphorus availability. Plant Physiol 156:989–996

Roberts R, Jackson RW, Mauchline TH, Hirsh PR, Shaw LJ, Doring TF et al (2017) Is there sufficient *Ensifer* and *Rhizobium* species diversity in UK farmland soils to support red clover (*Trifolium pretense*), white clover (*T. repens*), lucerne (*Medicago sativa*) and black medic (*M. lupulina*)? Appl Soil Ecol 120:35–43

Rodrigues C, Laranjo M, Oliveira S (2006) Effect of heat and pH stress in the growth of chickpea mesorhizobia. Curr Microbiol 53:1–7

Rodrigues AC, Vendruscolo CT, Moreira ADS (2015) *Rhizobium tropici* exopolysaccharides as carriers improve the symbiosis of cowpea-*Bradyrhizobium Paenibacillus*. Afr J Microbiol Res 9 (37):2037–2050

Rodriguez H, Fraga R, Gonzalez T, Bashan Y (2006) Genetics of phosphate solubilization and its potential applications for improving plant growth-promoting bacteria. Plant Soil 287:15–21

Rodriguez-Gacio MC, Matilla-Vázquez MA, Matilla AJ (2009) Seed dormancy and ABA signaling: the breakthrough goes on. Plant Signal Behav 4:1035–1048

Rodriguez-Navarro DN, Oliver IM, Contreras MA, Ruiz-Sainz JE (2010) Soybean interactions with soil microbes, agronomical and molecular aspects. Agron Sustain Dev 31:173–190

Rokhzadi A, Toashih V (2011) Nutrient uptake and yield of chickpea (*Cicer arietinum* L.) inoculated with plant growth promoting rhizobacteria. Aust J Crop Sci 1:44–48

Romdhane SB, Trabelsi M, Aouani ME, Lajudie P, Mhamdi R (2009) The diversity of rhizobia nodulating chickpea (*Cicer arietinum*) under water deficiency as a source of more efficient inoculants. Soil Biol Biochem 41:2568–2572

Ronner E, Franke AC, Vanlauwe B, Dianda M, Edeh E, Ukem B, Bala A, van Heerwaarden J, Giller KE (2016) Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. Field Crops Res 186:133–145

Routray S, Khanna V (2018) Characterization of rhizobacteria for multiple plant growth promoting traits from mung bean rhizosphere. Int J Curr Microbiol App Sci 7(1):2264–2269

Ryu RJ, Patten CL (2008) Aromatic amino acid-dependent expression of indole-3 pyruvate decarboxylase is regulated by TyrR in *Enterobacter cloacae* UW5. J Bacteriol 190:7200–7208

Sadowsky MJ (2005) Soil stress factors influencing symbiotic nitrogen fixation. In: Werner D, Newton WE (eds) Nitrogen fixation in agriculture, forestry and the environment. Springer, Dordrecht, pp 89–112

Saghafi D, Ghorbanpour M, Lajayer BA (2018) Efficiency of *Rhizobium* strains as plant growth promoting rhizobacteria on morpho-physiological properties of *Brassica napus* L. under salinity stress. J Soil Sci Plant Nutr 18(1):253–268

Saha D, Purkayastha GD, Ghosh A, Isha M, Saha A (2012) Isolation and characterization of two new *Bacillus subtilis* strains from the rhizosphere of eggplant as potential biocontrol agents. J Plant Pathol 94:109–118

Sahai P, Chandra R (2011) Co-inoculation effect of liquid and carrier inoculants of *Mesorhizobium ciceri* and PGPR on nodulation, nutrient uptake and yield of chickpea. J Food Legumes 23:159–161

Saharan BS, Nehra V (2011) Plant growth promoting rhizobacteria: a critical review. Life Sci Med Res 21:1–30

Saidi S, Chebil S, Gtari M, Mhamdi R (2013) Characterization of root-nodule bacteria isolated from *Vicia faba* and selection of plant growth promoting isolates. World J Microbiol Biotechnol 29:1099–1106

Saleem M, Arshad M, Hussain S, Bhatti AS (2007) Perspective of plant growth promoting rhizobacteria (PGPR) containing ACC deaminase in stress agriculture. J Ind Microbiol Biotechnol 34:635–648

Salvagiotti F, Cassman KG, Specht JE, Walters DT, Weiss A, Dobermann A (2008) Nitrogen uptake, fixation and response to fertilizer N in soybeans: a review. Field Crops Res 108:1–13

Samavat S, Besharati H, Behboudi K (2011) Interactions of rhizobia cultural filtrates with *Pseudomonas fluorescens* on bean damping-off control. J Agri Sci Tech 13:965–976

Samavat S, Samavat S, Mafakheri S, Shakouri MJ (2012) Promoting common bean growth and nitrogen fixation by the co-inoculation of *Rhizobium* and *Pseudomonas fluorescens* isolates. Bulg J Agric Sci 18:387–395

Sandhya V, Ali SKZ, Grover M, Reddy G, Venkateswarlu B (2009) Alleviation of drought stress effects in sunflower seedlings by the exopolysaccharides producing *Pseudomonas putida* strain GAP-P45. Biol Fertil Soils 46:17–26

Santaella C, Schue M, Berge O, Heulin T, Achouak W (2008) The exopolysaccharide of *Rhizobium* sp. YAS34 is not necessary for biofilm formation on *Arabidopsis Thaliana* and *Brassica napus* roots but contributes to root colonization. Environ Microbiol 10:2150–2163

Seneviratne I, Gunaratne S, Bandara T, Weerasundara L, Rajakaruna N, Seneviratne G, Vithanage M (2016) Plant growth promotion by *Bradyrhizobium japonicum* under heavy metal stress. S Afr J Bot 105:19–24

Sgroy V, Cassan F, Masciarelli O, Del Papa MF, Lagares A, Luna V (2009) Isolation and characterization of endophytic plant growth-promoting (PGPB) or stress homeostasis-regulating

(PSHB) bacteria associated to the halophyte *Prosopis strombulifera*. Appl Microbiol Biotechnol 85:371–381

Shah AH, Naz I, Ahmad H, Khokhar SN, Khan K (2016) Impact of zinc solubilizing bacteria on zinc contents of wheat. American Eurasian J Agric Environ Sci 16(3):449–454

Shaharoona B, Arshad M, Zahir ZA (2006) Effect of plant growth promoting rhizobacteria containing ACC-deaminase on maize (*Zea mays* L.) growth under axenic conditions and on nodulation in mung bean (*Vigna radiata* L.). Appl Microbiol 42:155–159

Shaharoona B, Jamro GM, Zahir ZA, Arshad M, Memon KS (2007) Effectiveness of various *Pseudomonas* sp., and *Burkholderia caryophylli* containing ACC-deaminase for improving growth and yield (*Triticum aestivum* L.). J Microbiol Biotechnol 17(8):1300–1307

Shamsuddin H, Tan Z, Zuan K, Radziah O, Khairuddin AR, Habib SH, Halimi MS (2014) Isolation and characterization of rhizobia and plant growth-promoting rhizobacteria and their effects on growth of rice seedlings. AJABS 9(3):342–360

Sharma P, Sardana V, Kandola SS (2011) Response of groundnut (*Arachis hypogaea* L.) to *Rhizobium* inoculation. Libyan Agric Res Cen J Intl 2:101–104

Sharma P, Padh H, Shrivastava N (2013) Hairy root cultures: a suitable biological system for studying secondary metabolic pathways in plants. Eng Life Sci 13:62–75

Shengepallu MD, Gaikwad RT, Chavan VA, Anand YR (2018) Isolation and characterization of nitrogen fixing bacteria from babchi (*Psoralea corylifolia* L.) and testing them for plant growth promotion traits *in vitro*. Int J Curr Microbiol App Sci 7:441–447

Shurigin V, Davranov K, Abdiev A (2015) Screening of salt tolerant rhizobia for improving growth and nodulation of chickpea (*Cicer arietinum*) under arid soil conditions of Uzbekistan. J Biol Chem Res 32(2):534–540

Simonsen AK, Han S, Rekret P, Rentschler CS, Heath KD, Stinchcombe JR (2015) Short-term fertilizer application alters phenotypic traits of symbiotic nitrogen fixing bacteria. PeerJ 3:e1291. https://doi.org/10.7717/peerj.1291

Singh Z, Singh G (2018) Role of *Rhizobium* in chickpea (*Cicer arietinum*) production – a review. Agric Rev 39(1):31–39

Singh RK, Mishra RPN, Jaiswal HK, Kumar V, Pandev SP, Rao SB, Annapurna K (2006) Isolation and identification of natural endophytic rhizobia from rice (*Oryza sativa* L.) through rDNA PCR-RFLP and sequence analysis. Curr Microbiol 52:345–349

Singh RP, Shelke GM, Kumar A, Jha PN (2015) Biochemistry and genetics of ACC deaminase: a weapon to stress ethylene produced in plants. Front Microbiol 6:1–14

Singh A, Sachan AK, Pathak RK, Srivastava S (2018) Study on the effects of PSB and *Rhizobium* with their combinations on nutrients concentration and uptake of chickpea (*Cicer arietinum* L.). J Pharmacogn Phytochem 7(1):1591–1593

Singha B, Mazumder PB, Pandey P (2016) Characterization of plant growth promoting rhizobia from root nodule of *Crotalaria pallida* grown in Assam. IJBT 15:210–216

Sistani NR, Kaul H, Desalegn G, Wienkoop S (2017) *Rhizobium* impacts on seed productivity quality and protection of *Pisum sativum* upon disease stress caused by *Didymella pinodes*: phenotypic, proteomic and metabolomics traits. Front Plant Sci 8:1–15

Skaar EP (2010) The battle for iron between bacterial pathogens and their vertebrate hosts. PLoS Pathog 6:1–4

Skorupska A, Janczarek M, Marczak M, Mazur A, Krol J (2006) Rhizobial exopolysaccharides: genetic control and symbiotic functions. Microbiol Cell Fact 5:1–19

Sogut T (2006) *Rhizobium* inoculation improves yield and nitrogen accumulation in soybean (*Glycine max*) cultivars better than fertilizer. New Zeal J Crop Hort 34:115–120

Solano RB, Garcıa JAL, Garcia-Villaraco A, Algar E, Garcia-Cristobal J, Manero FJG (2010) Siderophore and chitinase producing isolates from the rhizosphere of *Nicotiana glauca* Graham enhance growth and induce systemic resistance in *Solanum ycopersicum* L. Plant Soil 334:189–197

Solomon T, Lalit MP, Tsige A (2012) Effects of inoculation by *Bradyrhizobium japonicum* strains on nodulation nitrogen fixation and yield of soybean (*Glycine max* L) varieties on nitisols of bako, western Ethiopia. ISRN 2012:8. https://doi.org/10.5402/2012/261475

Soumaya T, Sana DF, Faysal BJ, Imran H (2016) Effect of *Rhizobium* inoculation on growth and nutrient uptake of sulla (*Hedysarum coronarium* L.) grown in calcareous soil of northern Tunisia. Romanian Biotechnol Lett 21:11632–11639

Sridevi M, Mallaiah KV (2009) Phosphate solubilization by *Rhizobium* strains. Indian J Microbiol 49(1):98–102

Srivastava LM (2002) Plant growth and development: hormones and environment. Academic, San Diego

Stephens JHG, Rask HM (2000) Inoculant production and formulation. Field Crops Res 65:249–258

Suarez R, Wong A, Ramirez M, Barraza A, Orozco MC, Cevallos MA, Lara M, Hernandez G, Iturriaga G (2008) Improvement of drought tolerance and grain yield in common bean by overexpressing trehalose-6-phosphate synthase in rhizobia. Mol Plant-Microbe Interact 21:958–966

Subramanian S, Stacey G, Yu O (2006) Endogenous isoflavones are essential for the establishment of symbiosis between soybean and *Bradyrhizobium japonicum*. Plant J 48:261–273

Sutherland IW (2001) Biofilm exopolysaccharides: a strong and sticky framework. Microbiology 147:3–9

Suzuki A, Akune M, Kogiso M, Imagama Y, Osuki K, Uchiumi T, Higashi S, Han SY, Yoshida S, Asami TM, Abe M (2004) Control of nodule number by the phytohormone abscisic acid in the roots of two leguminous species. Plant Cell Physiol 45:914–922

Sylvie B, Patrick AN (2009) Effects of *Rhizobium* inoculation, lime and molybdenum on photosynthesis and chlorophyll content of *Phaseolus vulgaris* L. Afr J Microbiol Res 3:791–798

Tagore GS, Namdeo SL, Sharma SK, Kumar N (2013) Effect of *Rhizobium* and phosphate solubilizing bacterial inoculants on symbiotic traits, nodule leghemoglobin, and yield of chickpea genotypes. Int J Agron 2013:1–8

Tairo EV, Ndakidemi PA (2013) *Bradyrhizobium japonicum* inoculation and phosphorus supplementation on growth and chlorophyll accumulation in soybean (*Glycine max* L.). AJPS 4:2281–2289

Tairo EV, Ndakidemi PA (2014) Macronutrients uptake in soybean as affected by *bradyrhizobium japonicum* inoculation and phosphorus (p) supplements. AJPS 5:488–496

Tao G, Tian S, Cai M, Xie G (2008) Phosphate solubilizing and mineralizing abilities of bacteria isolated from soils. Pedosphere 18:515–523

Tate RL (1995) Soil microbiology (symbiotic nitrogen fixation). Wiley, New York, pp 307–333

Tavasolee A, Aliasgharzad N, SalehiJouzani G, Mardi M, Asgharzadeh A (2011) Interactive effects of Arbuscular mycorrhizal fungi and rhizobial strains on chickpea growth and nutrient content in plant. Afr J Biotechnol 10:7585–7591

Tena W, Wolde-Meskel E, Walley F (2016) Symbiotic efficiency of native and exotic rhizobium strains nodulating lentil (*Lens culinaris* Medik.) in soils of Southern Ethiopia. Agronomy 6:1–11

Thamer S, Schadler M, Bonte D (2011) Dual benefit from a belowground symbiosis: nitrogen fixing rhizobia promote growth and defense against a specialist herbivore in a cyanogenic plant. Plant Soil 341:209–219

Thies JE, Singleton PW, Bohlool BB (1991) Modeling symbiotic performance of introduced rhizobia in the field by use of indices of indigenous population size and nitrogen status of the soil. Appl Environ Microbiol 57:29–37

Thies JE, Bohlool BB, Singleton PW (1992) Environmental effects on competition for nodule occupancy between introduced and indigenous rhizobia and among introduced strains. Can J Microbiol 38:493–500

Triplett EW, Breil BT, Splitter GA (1994) Expression of tfx and sensitivity to the rhizobial antipeptide trifolitoxin in a taxonomically distinct group of α-proteobacteria including the animal pathogen *Brucella abortus*. Appl Environ Microbiol 60:4163–4166

Turan M, Ataoglu N, Sahin F (2006) Evaluation of the capacity of phosphate solubilizing bacteria and fungi on different forms of phosphorus in liquid culture. J Sustain Agr 28:99–108

Uma C, Sivagurunathan P, Sangeetha D (2013) Performance of *Bradyrhizobial* isolates under drought conditions. Int J Curr Microbiol App Sci 2:228–232

Uren NC (2007) Types, amounts, and possible functions of compounds released into the rhizosphere by soil-grown plants. In: Pinton R, Varanini Z, Nannipieri P (eds) The Rhizosphere: biochemistry and organic substances at the soil–plant interface. CRC, Boca Raton, Florida, pp 1–22

Verma JP, Yadav J, Tiwari KN (2010) Application of *Rhizobium* sp. BHURC01and plant growth promoting rhizobacteria on nodulation, plant biomass and yield of chickpea (*Cicer arietinum L.*). Int J Agric Res 5:148–156

Victor A, Angulo G, Bonomi HR, Posadas DM, Serer MI, Torres AG, Zorreguiet A, Goldbauma FA (2013) Identification and characterization of RibN, a novel family of riboflavin transporters from *Rhizobium leguminosarum* and other Proteobacteria. J Bacteriol 195(20):4611–4619

Vidal C, Chantreuil C, Berge O, Maure L, Escarree J, Bena G, Brunel B, Marel JC (2009) *Mesorhizobium metallidurans* sp. nov., a metal-resistant symbiont of *Anthyllis vulneraria* growing on metallicolous soil in Languedoc France. Int J Syst Evol Microbiol 59:850–855

Vijayabaskar P, Babinastarlin S, Shankar T, Sivakumar T, Anandapandian KTK (2011) Quantification and characterization of exopolysaccharides from *Bacillus subtilis* (MTCC 121). Adv Biol Res 5:71–76

Wagner SC (2011) Biological nitrogen fixation. Nat Edu Knowl 2:14

Wang C, Knill E, Glick BR, Defago G (2000) Effect of transferring 1-aminocyclopropane 1-carboxylic acid (ACC) deaminase genes into *Pseudomonas fluorescens* strain CHA0 and its gacA derivative CHA96 on their growth promoting and disease suppressive capacities. Can J Microbiol 46:898–907

Wang X, Pan Q, Chen F, Yan X, Liao H (2011) Effects of co-inoculation with Arbuscular mycorrhizal fungi and Rhizobia on soybean growth as related to root architecture and availability of N and P. Mycorrhiza 21(3):173–181

Wang Q, Liu J, Zhu H (2018) Genetic and molecular mechanisms underlying symbiotic specificity in legume-rhizobium interactions. Front Plant Sci 9:1–8

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

Wani PA, Khan MS, Zaidi A (2007a) Effect of metal tolerant plant growth promoting *Bradyrhizobium* sp. (vigna) on growth, symbiosis, seed yield and metal uptake by green gram plants. Chemosphere 70:36–45

Wani PA, Khan MS, Zaidi A (2007b) Synergistic effects of the inoculation with nitrogen fixing and phosphate solubilizing rhizobacteria on the performance of field grown chickpea. J Plant Nutr Soil Sci 170:283–287

Wani PA, Khan MS, Zaidi A (2008) Effect of metal-tolerant plant growth promoting *Rhizobium* on the performance of pea grown in metal-amended soil. Arch Environ Contam Toxicol 55:33–42

Werma JP, Yadav J, Tiwari KN (2012) Enhancement of nodulation and yield of chickpea by co-inoculation of indigenous *Mesorhizobium spp.* and plant growth promoting rhizobacteria in eastern Uttar Pradesh. Commun Soil Sci Plant Anal 43:605–621

Weyens N, van der Lelie D, Taghavi S, Vangronsveld J (2009) Phytoremediation: plant-endophyte partnerships take the challenge. Curr Opin Biotechnol 20:248–254

White JP, Prell J, Ramachandran VK, Poole PS (2009) Characterization of a γ-aminobutyric acid transport system of *Rhizobium leguminosarum* bv. viciae 3841. J Bacteriol 191(5):1547–1555

Wienkoop S, Sistani NR, Kaul HP, Desalegn G (2017) *Rhizobium* impacts on seed productivity, quality, and protection of *Pisum sativum* upon disease stress caused by *Didymella pinodes*:

phenotypic, proteomic, and metabolomic traits. Front Plant Sci 8:1961. https://doi.org/10.3389/fpls.2017.01961

Wolde-meskel E, van Heerwaaarden J, Abdulkadir B, Kassa S, Aliyi I, Degefu T, Wakweya K, Kanampiu F, Ciller KC (2018) Additive yield response of chickpea (*Cicer arietinum* L.) to rhizobium inoculation and phosphorus fertilizer across smallholder farms in Ethiopia. Agric Ecosyst Environ 261:144–152

Yadegari M, Mehrab M, Rahmani H, Noormohammadi G, Ayneband A (2010) Evaluation of bean (*Phaseolus vulgaris*) seeds inoculation with *Rhizobium phaseoli* and plant growth promoting rhizobacteria on yield and yield components. PJBS 11:1935–1939

Yang G, Bhuvaneswari TV, Joseph CM, King MD, Phillips DA (2002) Roles for riboflavin in the *Sinorhizobium*-alfalfa association. Mol Plant-Microbe Interact 5:456–462

Yanni YG, Rizk RY, Abd El-Fattah FK, Squartini A, Corich V, Giacomini A, De Bruijn F, Rademaker J, Maya-Flores J, Ostrom P, Vega-Hernandez M, Hollingsworth RI, Martinez-Molina E, Mateos P, Velazquez E, Wopereis J, Triplett E, Umali-Gracia M, Anarna JA, Rolfe BG, Ladha JK, Hill J, Mujoo R, Ng PK, Dazzo FB (2001) The beneficial plant growth promoting association of *Rhizobium leguminosarum* bv. *trifolii* with rice roots. Aust J Plant Physiol 28:845–870

Zafar-ul-Hye M, Ahmad M, Shahzad SM (2013) Synergistic effect of rhizobia and plant growth promoting rhizobacteria on the growth and nodulation of lentil seedlings under axenic conditions. Soil Environ 32:79–86

Zahedi H, Abbasi S, Sadeghipour O, Akbari R (2013) Effect of plant growth promoting rhizobacteria (PGPR) on physiological parameters and nitrogen content of soybean grown under different irrigation regimes. Res Crops 14(3):798–803

Zahir ZA, Munir A, Asghar HN, Shaharoona B, Arshad M (2008) Effectiveness of rhizobacteria containing ACC deaminase for growth promotion of peas (*Pisum sativum*) under drought conditions. J Microbiol Biotechnol 18(5):958–963

Zahir ZA, Shah MK, Naveed M, Akhter MJ (2010) Substrate dependent auxin production by Rhizobium phaseoli improves the growth and yield of *Vigna radiata* L. under salt stress conditions. J Microbiol Biotechnol 20:1288–1294

Zahir ZA, Ahmad M, Hilger TH, Dar A, Malik SR, Abbas G, Rasche F (2018) Field evaluation of multistrain biofertilizer for improving the productivity of different mungbean genotypes. Soil Environ 37(1):45–52

Zaman S, Mazid MA, Kabir G (2011) Effect of *Rhizobium* inoculant on nodulation, yield and yield traits of chickpea (*Cicer arietinum* l.) in four different soils of greater Rajshahi. J Life Earth Sci 6:45–50

Zhang S, Reddy MS, Kloepper JW (2002) Development of assays for assessing induced systemic resistance by plant growth-promoting rhizobacteria against blue mold of tobacco. Biol Control 23:79–86

Zhang W, Wang HW, Wan XX, Xie XG, Siddikee A, Xu RS, Da CC (2016) Enhanced nodulation of peanut when co-inoculated with fungal endophyte *Phomopsis liquidambari* and *bradyrhizobium*. Plant Physiol Biochem 98:1–11