https://doi.org/10.17221/130/2020-PPS

The multifaceted plant-beneficial rhizobacteria toward agricultural sustainability

*Oluwaseun Adeyinka Fasusi, Olubukola Oluranti Babalola**

Food Security and Safety Niche, Faculty of Natural and Agricultural Science, North-West University, Mmabatho, South Africa

**Corresponding author: olubukola.babalola@nwu.ac.za*

Citation: Fasusi O.A., Babalola O.O. (2021): The multifaceted plant-beneficial rhizobacteria toward agricultural sustainability. Plant Protect. Sci., 57: 95–111.

Abstract: Agricultural practices depend mainly on the use of chemical fertilisers, pesticides, and herbicides which have caused serious health hazards and have also contributed to the pollution of the environment at large. The application of plant-beneficial rhizobacteria in agrarian practices has become paramount in increasing soil fertility, promoting plant growth, ensuring food safety, and increasing crop production to ensure sustainable agriculture. Beneficial rhizobacteria are soil microorganisms that are eco-friendly and serve as a modern method of improving the plant yield, protecting the plant and soil fertility that pose no harm to humans and the environment. This eco-friendly approach requires the application of beneficial rhizobacteria with plant growth-promoting traits that can improve the nutrient uptake, enhance the resistance of plants to abiotic and biotic stress, protect plants against pathogenic microorganisms and promote plant growth and yield. This review article has highlighted the multitasking roles that beneficial rhizobacteria employ in promoting plant growth, food production, bioremediation, providing defence to plants, and maintaining soil fertility. The knowledge acquired from this review will help in understanding the bases and importance of plant-beneficial rhizobacteria in ensuring agricultural sustainability and as an alternative to the use of agrochemicals.

Keywords: biofertiliser; biocontrol; crop yield; bioremediation; food security

Agriculture greatly contributes to the national income and earnings in developing countries, in a quest to ensure food security and employment. The act of practicing sustainable agriculture is crucial in the world today because it meets the need for more food production in the agricultural sector. The traditional method of practicing agriculture that involves the use of agrochemicals that are harmful to human health and the ecological system will not be able to meet the agricultural demand, because its harmful effects will keep increasing as the human population increases (Enagbonma & Babalola 2019b). The rhizosphere is a region of the soil where microbiological activity takes place as a result of the release of different kinds of plant metabolites called root exudates. These root exudates are made up of various vitamins, proteins, sugars, and amino acids that are important to microorganisms that dwell in the rhizosphere. Various types of plant-beneficial microorganisms live in the soil and interact with plants and other types of microorganisms (Igiehon & Babalola 2018). Large numbers of rhizobacteria with plant growth-promoting traits and other beneficial microorganisms' growth are supported in the rhizosphere (Bhattacharyya & Jha 2012, Shoaib et al. 2016).

The major problems that have caused a reduction in the crop yields worldwide among farmers are soil infertility, heavy metal contamination, and the infestation of plants by pathogenic microorganisms (Gouda et al. 2018). This challenge could be tackled by improving the quality of the soil through a reduction in land degradation and encouraging the application

Supported by the The National Research Foundation, South Africa, Grant No. UID123634 OOB.

https://doi.org/10.17221/130/2020-PPS

of plant-beneficial rhizobacteria as bioinoculants which require knowledge of good agricultural practices. It was reported by Mfilinge et al. (2014) that the major challenge facing the farming system is a reduction in the crop productivity. These low yields in most cereal and leguminous crops can be associated with a reduction in the soil fertility as well as attacks by pathogenic microorganisms. The microorganisms that live in the root region of a plant serve a beneficial purpose to theplant by improving its development and protection (Barea 2015). Rhizobacteria are among these beneficial organisms that can fix atmospheric nitrogen and phosphate solubilisers which are beneficial to plants (Bharti & Barnawal 2019). The application of agrochemicals has contributed to increasing the food production, but it has resulted in the pollution of water bodies, the air and has a deleterious effect on human health (Alori et al. 2017b; Ojuederie et al. 2019). Similarly, the application of agrochemicals has also increased the soil acidification (Gupta et al. 2015). The soil properties, soil fertility, structure, water holding capacity and diversity of the beneficial soil microorganisms have also been affected as a result of the prolonged use of agrochemicals (Enagbonma & Babalola 2019a). Considering the deleterious effect of agrochemicals on humans, plant health and the environment, which will keep increasing with an increase in the human population, there is a need for alternative methods of increasing the soil fertility, preventing pathogen attacks, and also improving food production, which should be inexpensive and should constitute no harm to humans, or the abiotic and biotic components (Igiehon & Babalola 2017; Pathak et al. 2018). The parameters used to access a plant's health the function and structure of the microorganisms that live within the soil (Zhu et al. 2017). The potential role that beneficial rhizobacteria can play is the transformation of carbon-based organic materials that enhance plant health and promote sustainable agriculture (Olanrewaju et al. 2017).

Therefore, there is a need for the biological means of promoting plant growth and controlling attacks by pathogenic microorganisms which constitute one of the potential solutions and also play a crucial function in improving the crop yield and meeting the challenges caused by the application of agrochemicals.

Plant-beneficial rhizobacteria inoculants are preparations containing cells of efficient rhizobacteria strains that can be applied to the soil or plants to increase the metabolic processes in the plants by providing the plants with the nutrients that will enhance their growth and also serve as a defence for the plants against microbial pathogens and pests. This review summarises the beneficial role played by beneficial rhizobacteria as environmentally friendly and inexpensive microbial inoculants in improving plant growth, reducing heavy metal contamination, and controlling phytopathogens to ensure sustainable agriculture.

Agrochemical impact on the environment and human health

A large number of people are engaged in farming using agrochemicals to increase food production, which results in the consumption of contaminated farm products by the final consumer, which could constitute a health hazard and a reduction in the diversity of soil microorganisms that are beneficial to promote plant health and development (Alori et al. 2017a). The runoff of these agrochemicals also contributes to surface water and groundwater contamination (Burant et al. 2018). The major ways through in which these agrochemicals that are applied to plants find their way into the human body and constitute health problems are through inhalation, penetration through the skin, and through the consumption of food products (Roychowdhury et al. 2014). Several health hazards that affect farmers and consumers of farm products have been recorded as a result of the use of agrochemicals. These include respiratory disorders, skeletal problems, and diseases that are related to the skin (Singh et al. 2018). The major contributing factor why the negative effects of using agrochemicals are more pronounced is inadequate knowledge of the precautions to be taken during application of the agrochemicals, especially those that are hazardous, and their effect in limiting the potential of the beneficial soil microbiota because only a few of these farmers have been trained on the harm attached to the application of agrochemicals and the preventive measures to take during application (Magauzi et al. 2011; Bhandari 2014). A report by the United States Environmental Protection Agency in 2016 has shown that, in some developing countries where the use of agrochemicals is high, there are health problem issues in the population. The major factors that cause the increase in health hazards due to the use of pesticides are the application of the cheapest, but the toxic type of agrochemicals and the presence, in residues, of agrochemicals on the consumable products (Dhananjayan et al. 2020).

https://doi.org/10.17221/130/2020-PPS

The novelty in the application of plant-beneficial rhizobacteria for agricultural sustainability

Rhizobacteria are microorganisms that are found in the rhizosphere of plants, those that form a beneficial association with the plant root are called plant growth-promoting rhizobacteria (Hashem et al. 2019a). These groups of bacteria form an interaction with the plant to promote their growth and development (Lobo et al. 2019). Bacteria are among the biotic components of the ecological system and their presence in the rhizosphere serves a beneficial purpose in promoting plants using a scale sequential bioreactor during the plant's growth (Alka et al. 2020).

More importantly, the plant root can stimulate the colonisation of beneficial rhizobacteria in the rhizosphere by releasing ions, enzymes, and some primary and secondary metabolites that are beneficial and can be absorbed by the bacteria (Olanrewaju et al. 2017). Additionally, through the beneficial association of the rhizobacteria with the plant root, their population becomes higher in the plant root region over the bulk soil and serves a beneficial purpose in plant growth promotion and protection (Pathan et al. 2020). The classification of beneficial rhizobacteria can be made into two categories which includes extracellular rhizobacteria that are found in the rhizosphere or the rhizoplane and intracellular rhizobacteria which are found inside the plant root (Gouda et al. 2018).

Beneficial rhizobacteria employ different mechanisms to ensure the nutrient availability and uptake by the plants to promote their growth, (Khan & Bano 2016), which act as biological control agents in protecting plants against pathogenic attacks (Jha & Saraf 2015), preventing plants from experiencing biotic and abiotic stress (Tiwari et al. 2017; Enebe & Babalola 2018) and helping in the bioremediation of heavy metal soil contamination which is beneficial to improve a plant's health (Vishan et al. 2019).

Furthermore, beneficial-plant rhizobacteria are considered crucial in ensuring sustainable agricultural practices with a greater worldwide demand and their eco-friendly approach when compared to the use of agrochemicals because of their beneficial interaction with the plant and other soil microorganisms. In developing countries, changes in the climatic conditions, an increase in the human population, and industrialisation have contributed to a negative impact on food security and the plants' accessibility to nutrient requirements for their growth (Myers et al. 2017). The application of rhizosphere engineering using beneficial rhizobacteria is an ecological-friendly technique to meet the global demand for food and ensuring agricultural sustainability (Ahmadi et al. 2017). Recently, in increasing the interaction of rhizobacteria with plants, the application of a metaorganism approach is now being employed which involves bringing together different strains of microorganisms, conducting molecular investigations of the rhizobacteria strains, selecting specific host plants and investigating their sole and microbial consortium in situ (Thijs et al. 2016).

Additionally, the application of plant growth-promoting rhizobacteria is receiving more awareness because they are environmentally friendly, easy to handle, and cost-effective (Guo et al. 2020). The bigger delivery strength of applying plant growth-promoting rhizobacteria is their biological control activity against plant pathogens, their bioremediation ability in reducing heavy metal contaminated soil, promoting plant growth, and improving food safety and quality (Vejan et al. 2016).

Underlying plant-beneficial rhizobacteria mechanisms of action

Beneficial rhizobacteria promote plant growth through different mechanisms which include phosphate solubilisation, nitrogen fixation, the production of siderophore, the production of phytohormones, the production of 1-aminocyclopropane-1-carboxylate deaminase (ACC), the induction of systemic resistance and could also act as biological control agents (Figure 1).

Phosphate solubilisation

Phosphorus can be regarded as a nutrient that is important to plants because it helps to improve their growth. Phosphate solubilising bacteria are beneficial rhizobacteria that solubilise phosphorus into a form that can be useful to plants and could equally enhance their growth (Alori et al. 2017b). The absence of phosphorus in the soil limits plant growth. The amount of phosphorus in the soil depends largely on the soil properties, such as the pH and type of soil. Organic phosphorus accounts for 29–65% of the total soil phosphorous content, but it contributes up to 90% of the total soil phosphorus in some soil types (Ghorbani-Nasrabadi et al. 2012). Usually, the phosphorus content in the soil must be present in large amounts for plant use. Nevertheless, a very little fraction of this huge amount is readily made available to the plants because phosphorus is highly reactive,

https://doi.org/10.17221/130/2020-PPS

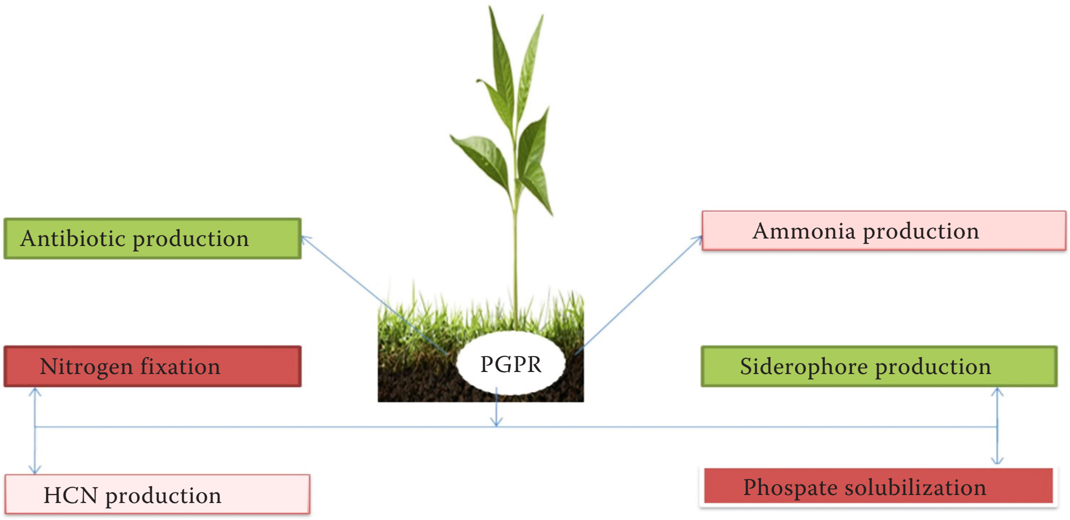

Figure 1. Mechanisms of beneficial rhizobacteria on plant

PGPR – plant growth-promoting rhizobacteria

which makes complexes with other elements that are not taken up by the plants. Plants can only uptake monobasic and dibasic forms of phosphorus. To fulfil the requirements of phosphorus, traditional agricultural practices make use of rock phosphate fertilisers, which result in the depletion of phosphate reservoirs. Several bacterial genera such as *Bacillus, Rhizobium*, *Pseudomonas*, *Azotobacter,* and *Azospirillum* species can be classified among phosphate solubilising rhizobacteria (Shah et al. 2018). Likewise, actinomycetes like *Streptomyces alboniger, S. venezuelae, S. aureofaciens,* and *S. lienomycini,* have been demonstrated to produce extracellular phytate-degrading enzymes, i.e., phytases which correspond to a group of phosphomonoesterases that initiate the stepwise breakdown of phytate (Barman et al. 2019). These phytases have been recorded as acid and alkaline phytases. The production of acidic compounds by soil microbial flora could also be a process by which phosphate can be solubilised, and it depends on the metabolic pathways to utilise different carbon sources. However, the mechanism of acidification in phosphate solubilisation by *Actinobacteria* has rarely been reported (Jog et al. 2014). Therefore, enzymatic degradation of phosphate complexes plays a crucial role in making the phosphorus and essential compounds available that are needed for plant growth.

Production of phytohormones

Plant growth is controlled by phytohormones like auxin and ethylene, which have a positive effect on plants. Phytohormones are messengers which are chemicals that play an important function in improving the plant development, seed germination, and flowering time in plants (Jiang et al. 2017). More so, root exudates secreted by plants in the rhizosphere help to modulate the microflora around plant roots and construct a potential environment for the synthesis of indole-3-acetic acid (IAA) by the beneficial microorganisms in the rhizosphere. One of the major direct mechanisms of beneficial rhizobacteria is the production of phytohormones like gibberellic acid and IAA (García-Fraile et al. 2015). Interestingly, the biological synthesis of phytohormones by beneficial rhizobacteria can be associated with nutrient availability and the promotion of growth in plants (Stamenković et al. 2018). The major auxin that is found in the plant is called IAA. The roles performed by IAA in plants are cell division, root elongation, and cell differentiation. *Actinobacteria* have been studied to produce phytohormone belonging to a class of auxins, i.e., IAA which is a common hormone produced by plants (Ranveer et al. 2014). Likewise, ethylene, another important phytohormone, regulates plant growth by promoting root growth, flowers and fruits, as well as interacts with the microorganisms that are present in the plant root (Dubois et al. 2018). Besides plants, some beneficial bacteria genera produce IAA, such as *Streptomyces* (Vurukonda et al. 2018), *Rhizobium* (Tan et al. 2015), *Pantoea,* and *Agrobacterium* (Paiter et al. 2019). However, Mishra et al. (2020) reported the production of IAA in *Pseudomonas* and *Ochrobactrum* species. Similarly, the production of cytokinins was reported

https://doi.org/10.17221/130/2020-PPS

in *Bacillus megaterium*, *Bacillus subtilis*, *Bacillus cereus,* and *Pseudomonas fluorescens* G20 (Hashem et al. 2019b). The production of IAA is an indication of the part of the communication between the plants and the beneficial bacteria that reside in the rhizosphere (Hassan et al. 2019). Their IAA producing trait makes them a potential candidate in agricultural practices as natural fertilisers in maintaining agricultural sustainability.

Utilisation of 1-aminocyclopropane-1-carboxylate (ACC)

Some rhizobacteria genera like *Actinobacteria* have the potential to utilise ACC that acts as a molecule for the biological synthesis of ethylene (Nascimento et al. 2018). However, ethylene performs a lot of biological activities in plants which helps in regulating the process of ripening fruits and in seed germination. Ethylene is often called the "ageing hormone" because of its role in enhancing plant developmental processes which include ripening, senescence, and abscission (Schaller 2012). An enzyme known as ACC-deaminase catalyses the hydrolysis of ACC into NH_3 and alpha-ketobutyrate. Some bacteria genera were reported to produce ACC-deaminase, this includes *Streptomyce*s, *Pseudomonas*, *Bacillus*, *Azotobacter,* and they are considered as beneficial rhizobacterial strains in improving plant health (Glick 2014). A recent research study has revealed an increase in tomato growth (*Lycopersicum esculentum*) inoculated with *Streptomyces filipinensis* and *S. atrovirens* due to the production of aminocyclopropane-1-carboxylate-deaminase (Buzón-Durán et al. 2020).

Production of siderophore

Siderophore can be referred to as a compound that is produced by some groups of microorganisms in the condition where the availability of iron is limited (Mhlongo et al. 2018). They are small peptide molecules that consist of side chains and a functional group where ferric iron can be attached (Goswami et al. 2016). Iron is an essential element in living things because it is responsible for the catalysis of numerous enzymatic reactions where it acts as a co-factor. Furthermore, microorganisms that produce siderophore reduce the amount of iron that is available to plant pathogens which could eventually reduce the percentage of pathogen proliferation by plants and promote plant growth (Etesami & Maheshwari 2018). Earlier, iron was usually present in the ferrous form (Fe^{2+}) in soils when the atmosphere was oxygen-deficient and it was easily utilised by the microorganisms. However, with time, as the oxygen-deficiency in the atmosphere has been replaced by an oxygen-rich environment, iron gets oxidised into a ferric form (Fe^{3+}) which is not readily utilised by microorganisms. The competition for iron acquisition occurs between plants and phytopathogens as microbial siderophores have a higher affinity towards iron chelation making the iron unavailable to plants. High levels of siderophore production have been reported in *Bacillus* that were isolated from the maize rhizosphere (Bjelić et al. 2018).

More importantly, plant growth-promoting rhizobacteria that produce siderophores are becoming more relevant because they improve the iron nutrition in plants that are grown in iron-deficient soils (Figueiredo et al. 2016). Siderophores also help in alleviating heavy metal stress in a plant grown in a heavy metal polluted soil, which can be detrimental to plant health (Ahemad & Kibret 2014; Asad et al. 2019). Several bacteria genera have been reported to produce siderophores, this includes *Streptomyces* (Goudjal et al. 2016), *Azospirillum* (Banik et al. 2016), *Paenibacillus* (Liu et al. 2017), *Pseudomonas* (Deori et al. 2018), *Azotobacter* (Romero-Perdomo et al. 2017).

Production of hydrogen cyanide (HCN)

An important feature of some beneficial rhizobacteria is the production of HCN. The action mechanism of HCN is considered to inhibit the terminal cytochrome c oxidase in the respiratory chain as it binds to metalloenzymes which confers it as a property suppressing phytopathogens (Rosier et al. 2018). The *Rhizobium, Pseudomonas, Alcaligenes, Bacillus, Aeromonas,* and *Streptomyces* species are hydrogen cyanide producers. Hydrogen cyanide has also been reported to contribute to the mineral mobilisation and phosphate release which results in an indirect increase in the nutrient availability to both *Actinobacteria* and their host plants (Rijavec & Lapanje 2016). Based on the ability of HCN to prevent plant pathogens and to enhance nutrient availability, HCN producing rhizobacteria can be used as a biocontrol agent and biofertiliser for plant growth promotion and protection.

Nitrogen fixation

Approximately 80% of the nitrogen in the atmosphere cannot be made available to plants because it occurs as an inert gas (Patel & Minocheherhomji 2018). Besides, nitrogen is an important nutrient

Plant Protection Science, 57, 2021 (2): 95–111

https://doi.org/10.17221/130/2020-PPS

that is responsible for plant growth. However, for atmospheric nitrogen to be used directly by plants, it must be converted to ammonia and this process is called nitrogen fixation (Byrne et al. 2019). The process of conversion of atmospheric nitrogen to ammonia is performed by beneficial microorganisms that can fix nitrogen and the action is aided by an enzyme called nitrogenase (Kumar et al. 2019).

The association built by nitrogen-fixing microorganisms with the host plant could be symbiotic or non-symbiotic. In a soil that is nitrogen deficient, a large amount of nitrogenous based fertiliser needs to be applied to the soil so that the amount of nitrogen required by plants to improve their growth is available to the plant. Some rhizobacterial species that have the ability to fix nitrogen are *Azospirillum*, *Acinetobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Pseudomonas*, *Rhizobium, Bradyrhizobium, Azorhizobium* and *Serratia*. They colonise plant roots and fix the atmospheric nitrogen which improves the plant growth (Babalola 2010).

Production of lytic enzymes

The cell wall of microorganisms is responsible for maintaining the integrity of cells under all kinds of environments, i.e., isotonic, hypotonic, and hypertonic. The cell wall of different organisms is composed of various kinds of complex polymeric substances. For instance, the composition of the fungal cell wall is made up from chitin, while the bacterial cell wall is made up from peptidoglycan, i.e., a polysaccharide chain cross-linked with unusual peptides (Arroyo et al. 2016; Walter & Mayer 2019). The cell wall of pathogenic bacteria, fungi, and protozoa are hydrolysed by lytic enzymes, such as protease, acylases, and lactonases that are produced by beneficial rhizobacteria, thereby preventing pathogenic microorganisms from causing diseases in plants (Felestrino et al. 2018). Recently, *Streptomyces* spp. has been reported to produce chitinases, *Streptomyces* RC1071 isolated from cerrado soils was tested against a phytopathogenic fungus and was reported to have an antifungal activity (Shafi & Khattab 2020). Similarly, *Actinomycetes* have also been reported to produce proteases, lipases, chitinases, and cellulases (El-Sherbiny et al. 2017). The production of lytic enzymes by *Actinobacteria* grants them a biocontrol potential and helps improve plant growth characteristics (Wani & Gopalakrishnan 2019).

Several genera of bacteria have proved their importance as antagonistic agents against plant pathogens, these include *Bacillus*, *Azospirillum*, *Serratia, Pseudomonas*, *Pythium,* and *Coniothyrium* (Heidarzadeh & Baghaee-Ravari 2015). The application of these microorganisms over time has proved successful in colonising the plant rhizosphere and in promoting their growth (Becker et al. 2018).

Production of antibiotics

The production of secondary metabolites has been studied in beneficial rhizobacteria, i.e., by-products of metabolism that are not generally essential for their growth. These metabolites are known as antibiotics (Gislason et al. 2020). Antibiotic production by beneficial soil bacteria exhibits antitumor, antifungal, immunosuppressive, insecticidal, herbicidal and many clinically commercially important activities. Among the bacteria, *Streptomyces* spp. has been reported to produce a wide variety of antibiotics belonging to class β-lactam (Ogawara 2016). However, antibiotic production by beneficial soil bacteria differs in their chemical structure and effects on the different plant pathogens. In the rhizosphere, antibiotics produced by soil-dwelling bacteria inhibit plant pathogens fungistatics by targeting either the essential molecules or biosynthetic pathways and its production depends upon several factors like: the temperature, aeration, and presence of competing microorganisms (Shaikh & Sayyed 2015; Omran & Kadhem 2016). *Bacillus subtilis* has been reported to produce antibiotics known as zwittermicin and mycosubtilin that are effective against some fungal pathogens (Saraf et al. 2014). Recently, the deteriorative effect of *Rhizoctonia solani* on plants has been inhibited by pyrrolnitrin antibiotics produced by *P. fluorescens* BL915 (Tariq et al. 2017). Additionally, *Pseudomonas chlororaphis* that synthesised phenazine with an antagonistic activity have been reported by Chen et al. (2015) to inhibit the growth of pathogenic fungi *Fusarium oxysporum*, *Rhizoctonia solani,* and *Pythium ultimum*. Therefore, beneficial bacteria that live in the soil produce different types of antibiotics depending upon the environmental conditions to protect the plant against pathogen attacks which could be detrimental to the plant growth and productivity.

Multitasking role of beneficial rhizobacteria in agriculture

The role of rhizobacteria as biofertilisers in crop production. Microorganisms that are living in the soil are crucial because they decompose organic matter

https://doi.org/10.17221/130/2020-PPS

and also ensure that the nutrients needed for plant development are made available to the plants (Bahadur et al. 2016). The presence of beneficial bacterial in the soil certainly increases the nutrients that are present in the soil and improves the plant growth and yield which results in sustainable agriculture. A biofertiliser serves as an inexpensive source of nutrients to the plant so that the quality of the crop yield can be improved (Shabbir et al. 2019). Soil microorganisms help in the fixation of nitrogen to the plants by converting atmospheric nitrogen to a form that is assimilated by the plants and will result in improving their growth. *Rhizobium, Bradyrhizobium,* and *Azorhizobium* fix nitrogen to the legume through a symbiotic association which results in the formation of nodules in the plants (Igiehon & Babalola 2018). *Rhizobium* inoculation helps to enhance the root nodulation, improve the plant growth, and produce an increase in grain yield under cultivated conditions when compared to an uninoculated plant. The microorganisms used in the production of biofertilisers increase the plant yield through the fixation of atmospheric nitrogen, phosphate solubilisation, and phosphate mobilisation. The application of beneficial rhizobacteria fertilisers by farmers is increasing because they improve the soil quality, are cost-effective and pose no harm to humans and the environment, and result in limiting the application of chemical fertilisers (Singh et al. 2019).

More so, a lot of success has been recorded in the application of beneficial rhizobacteria as biofertilisers in promoting plant growth (Table 1). Recently, the research conducted by Bharti and Barnawal (2019) on the inoculation of wheat plants with *Dietzia natronolimnaea* was reported to increase the plant biomass and enhance its tolerance to salinity. In addition to this, Kuan et al. (2016) were able to screen some selected beneficial rhizobacteria like *Klebsiella pneumoniae*, *Bacillus pumilus* and the *Acinetobacter* species in improving maize

Table 1. Summary of the beneficial rhizobacteria strains used as a biofertiliser with their effect on the crop enhancement

Plant growth-promoting rhizobacteria strain	Plants	Effect on crops enhancement	References
Pseudomonas granadensis T6	rice (*Oryza sativa*)	plant growth promotion	(Shen et al. 2019)
Rhizobium leguminosarum sv *viciae* NGB-FR 126	faba beans (*Vicia faba*)	enhances the root length, weight and promote growth by 81%	(Youseif et al. 2017)
Alcaligenes faecalis	okra (*Abelmoschus esculentus*)	responsible for the production of IAA in okra (*Abelmoschus esculentus*)	(Perez-Harguindeguy et al. 2016)
Azospirillum brasilense	Wheat (*Triticum aestivum*)	responsible for an increase in height.	(Karimi et al. 2018b)
Bradyrhizobium yuanmingenes VIBA-2	cowpea (*Vigna unguiculata*)	promote growth by 38% when compared with uninoculated plant	(Gómez Padilla et al. 2016)
Rhizobium leguminosarum sv phaseoli HB-429	common beans (*Phaseolus vulgaris*)	plant growth promotion	(Samago et al. 2018)
Pseudomonas aeruginosa	broad beans (*Vicia faba*)	promote the remediation ability of plant	(Babalola 2010)
Rhizobium spp.	mung beans (*Vigna mungo*)	promote the growth and improve weight in *Vigna mungo*	(Ravikumar 2012)
Azospirillum brasilense Ab-V5 and Ab-V6	maize (*Zea mays*)	plant growth promotion	(Galindo et al. 2019)
Bradyrhizobium spp.	soybeans (*Glycine max*)	enhance nodulation in leguminous crop as their plant part grows	(Igiehon et al. 2019)
Bacillus tequilensis PBE1	tomato (*Solanum lycopersicum*)	plant growth promotion	(Bhattacharya et al. 2019)
Pseudomonas, Bacillus	turmeric	plant growth promotion	(Kumar et al. 2015)

IAA – indole-3- acetic acid

https://doi.org/10.17221/130/2020-PPS

growth. In the research, it was reported that the plant growth-promoting rhizobacteria improved the maize ear yield when compared with the uninoculated plants. The positive effect of beneficial rhizobacteria *Pseudomonas* and *Agrobacterium* isolated from the root of *Arthrocnemum indicum* possessed plant growth-promoting activity which includes phosphate solubilisation, the production of indole-3-acetic acid, the ability to reduce acetylene and showed a positive reaction to ACC deaminase activity was recorded when the peanut plant was inoculated. They colonised the peanut roots and were capable of increasing the peanut growth over the uninoculated plants (Sharma et al. 2016). Similarly, Panwar et al. (2016) have also evaluated the effect of *Pantoea* and *Enterococcus* with plant growth-promoting traits on mung beans, the two rhizobacteria showed a better performance in increasing the plant growth over uninoculated mung bean plants under a salt stress condition. Likewise, the inoculation of the plant growth-promoting strain of *Bacillus* sp RZ2MS9 and *Burkholderia ambifaria* RZ2MS16 was reported by Batista et al. (2018) in promoting corn and soybean growth under greenhouse conditions when compared with an uninoculated control for both strains and crops. Chukwuneme et al. (2020) reported the plant growth-promoting potential of *Arthrobacter arilaitensis* and *Streptomyces pseudovanezuelae* in promoting maize growth under water-stressed conditions. In the research, the maize plants were protected against the deleterious effect of drought and a significant increase in the physiological parameters was recorded over the control plant.

Role of plant beneficial rhizobacteria as biological control agents against phytopathogens. The application of beneficial rhizobacteria as bioinoculants in controlling pests and pathogenic microorganisms that affect plants has been confirmed to be the best alternative to the use of agrochemicals because it is cheap, environmentally friendly and acts as a sustainable agricultural management approach in protecting plants. This makes plant growth-promoting rhizobacteria an acceptable biological tool for controlling plant diseases and ensuring good agricultural practices (Farha et al. 2018). There are a lot of biocontrol agents that are present in the market, but it is crucial to understand their interaction with plants, pathogens, and the environment before their use because the purpose of the application may not be achieved if the plant is already under attack from diseases (Liang et al. 2015). A biocontrol can be defined as an interrelationship that occurs in plants through the action of some beneficial microorganisms, aimed at reducing the negative effects of pathogenic microorganisms that harm the plants, thereby enhancing the plant growth (Farha et al. 2018).

Some plant growth-promoting rhizobacteria have been reported for their potential to reduce diseases caused by pathogenic fungi and bacteria in plants which makes them the best option to be used as biocontrol agents (Table 2) (Rani et al. 2018). Adopting the use of beneficial rhizobacteria as a biocontrol agent in suppressing diseases in plants is also a low cost and safe method of crop management. Considering the toxicological aspect of chemical pesticides, it can be confirmed that most biopesticides are less toxic and more environmentally friendly than chemical pesticides. More importantly, the need to use beneficial rhizobacteria as an alternative that have not been chemically synthesised, especially biopesticides, are increasing globally because they pose no harm to the ecological system (Gross et al. 2014; Czaja et al. 2015). The action mechanisms that allow beneficial rhizobacteria to be used as biocontrol agents are the production of lytic enzymes, the competition for nutrient availability and the production of secondary metabolites/antibiotics that suppress the proliferation of plant pathogens (Alori & Babalola 2018). The application of beneficial rhizobacteria as biocontrol agents modulate hormones, like ethylene and auxin, in plants and reduce the rate of damage to the plants by pathogenic microorganisms.

Interestingly, the control of fungal infections and herbicidal activities is part of the important role played by plant growth-promoting rhizobacteria bioinoculants on plants, for example, *Aspergillus flavus*, in stored and field products, was reported to be controlled by *Bacillus subtilis*. *Rhizobium* had also served as a biocontrol agent against *Pythium* diseases (Alori & Babalola 2018). *Pseudomonas* was also used as a biocontrol agent for Fusarium wilt (Cepeda 2012). The biocontrol ability of plant growth-promoting rhizobacteria was conducted by Kumar et al. (2016), the report from the findings revealed that the inoculation of *Paenibacillus lentimorbus* with *Nicotiana tabacum* improved the plant growth and acted as a biocontrol agent against the mosaic virus in cucumbers. Beneficial rhizobacteria are seen as an alternative to the use of agrochemicals in suppressing soil-borne pathogens and are responsible for the mobilisation of nutrients in the soil (Meena et al. 2017).

https://doi.org/10.17221/130/2020-PPS

Table 2. Some beneficial rhizobacteria that have been tested as microbial inoculants in controlling plant diseases

Microbial isolates	Host plant	Diseases causative agent	Diseases	Mechanisms involved	Effect on plants	References
Pseudomonas fluorescens	olive trees (*Olea europaea*)	*Verticillium dahlia*	Verticillium wilt	improve plant growth and induce systemic resistance	reduce the severity of the disease caused by the pathogen	(Gómez-Lama Cabanás et al. 2014)
Serratia plymuthica	oilseed rape (*Verticillium longisporum*)	*Verticillium dahlia*	Verticillium wilt	interference of signal (Quorum sensing)	reduce the severity of the disease caused by pathogens	(Kaouthar et al. 2016)
Bacillus subtilis S499	tomato (*Solanum lycopersicum*)	*Fusarium* spp.		induction of systemic resistance	suppress the effect of pathogen attack on plant	(Tabassum et al. 2017)
Pseudomonas fluorescens	sugar cane (*Saccharum officinarum*)	*Colletotrichum falcatum*	red rot	activation of induced systemic resistance	production of defensive enzymes for treatment of the plant tissue	(Farha et al. 2018)
Pseudomonas denitrificans, *Pseudomonas putida*	oaks (*Quercus* spp)	*Ceratocystis fagacearum*	oak wilt	induced systemic resistance defence	reduce crown loss	(Zheng et al. 2012)
Pseudomonas fluorescens PNA1	chickpea (*Cicer arietinum*)	*Fusarium* spp.	*Fusarium* wilt	induced systemic resistance defence	limit severity of diseases by causative organisms	(Babalola & Glick 2012)

The application of *Bacillus cereus* TSH77 that are known to contain fengycin and surfactin through investigation of an acid cell-free culture filtrate has been reported by Chauhan et al. (2016) to suppress the proliferation of the *Fusarium solani* plant pathogen that caused rot disease in potatoes. Likewise, *Bacillus methylotrophicus* was reported for its antifungal activity against *Fusarium oxysporum* and *Rhizoctonia solani* (Devi et al. 2018). In the quest for more food production globally, the research conducted by Fu et al. (2017) revealed that the inoculation of a newly established banana plantation with *Bacillus amyloliquefaciens* NJN-6 suppressed Fusarium wilt. Likewise, the biocontrol activity of *Rhizobium* isolated from the rhizosphere of different plants was reported to suppress the growth of the plant pathogens *Rhizoctonia solani* and *Sclerotium rolfsii* under *in vitro* condition (Manasa et al. 2017). Similarly, the application of *Bacillus subtilis* and *Bacillus amyloliquefaciens* in suppressing the pathogenic effect of *Phytophthora sojae* was reported by Liu et al. (2019) to inhibit the *Phytophthora sojae* hyphae growth that causes soybean blight. The plant growth-promoting trait and biocontrol potential of the beneficial rhizobacteria strain *Acinetobacter* spp. PKA and *Ochrobactrum intermedium* TRD14 was conducted in a greenhouse against a root rot pathogen in the sugarcane *Colletotrichum falcatum*. The bacteria were reported to suppress pathogen growth and promote the plant growth parameters in the sugarcane (Patel et al. 2019). *Streptomyces cochorusii* have been reported by Yang et al. (2017) to be effective against *Rhizoctonia solani* that causes sheath blight diseases in rice. Rice sheath blight is among the worst rice diseases globally because it causes yield losses in rice of more than 50% approximately (Yang et al. 2017).

Significance of plant-beneficial rhizobacteria on heavy metal bioremediation

Bioremediation is a process that involves the use of beneficial rhizobacteria as inoculants to resolve the negative effects of industrialisation on the environment and plant health as a result of metal spillage (Ojuederie & Babalola 2017). Notably, agricultural practices are negatively affected by the presence of heavy metals because it results in soil contamination which makes it unfit for agricultural purposes and could be harmful for the plant development (Ayangbenro & Babalola 2017). Though metals are important to plants, their presence in excess

https://doi.org/10.17221/130/2020-PPS

amounts becomes hazardous to the plant's health (Asati et al. 2016). Therefore, there is a need for metals to remain in a stable state for them to be useful to plants, but if they are available in an unstable state, they become detrimental to plant health by disrupting the biological processes that occur in the plant (Masood & Bano 2016). More so, metals can attach to some enzymes or molecules which cause stress to the plant and they can also attack protein formation, thereby becoming toxic to plants (Wang et al. 2016). The application of microorganisms like plant beneficial rhizobacteria in bioremediating metal polluted environments is an approach that is non-hazardous to the ecological system when compared with agrochemicals that pose harm to the biotic and abiotic components (Dixit et al. 2015). Similarly, rhizobacteria with a plant growth-promoting ability through the production of siderophores has helped in plant development by removing heavy metals from the polluted soil and providing the nutrients needed for plant survival in a soil polluted by heavy metals (Kumar et al. 2020). The application of plant growth-promoting rhizobacteria in the bioremediation of a soil polluted by heavy metals is attached to features such as the ubiquity, size, and ability to grow in both controlled and stressed conditions (Srivastava 2015). Several genera of plant growth-promoting rhizobacteria have been reported in the bioremediation of heavy metals such as the *Bacillus*, *Pseudomonas,* and *Micrococcus* species (Table 3). Some of the processes through which the microorganisms remediate their environment are rhizofiltration, biosorption, bioaccumulation, and biomineralisation (Wang et al. 2016).

The bioremediation ability of *Bacillus cereus* to remove mercury from a synthetic effluent was conducted in a laboratory experiment designed by Sinha et al. (2012) using a scale sequential bioreactor. In the research, it was reported that *Bacillus cereus* was able to remove approximately 104 mg/g of mercury on the third day. The report of *Micrococcus luteus* in removing a large amount of lead from a synthetic medium with the removal capacity of 1964 mg/g was reported by Puyen et al. (2012). Similarly, the application of *Desulfovibrio desulfuricans* in the removal of nickel, copper, and chromium from contaminated

Table 3. Summary of potential plant growth-promoting rhizobacteria strains employed in heavy metal bioremediation

Plant growth-promoting bacteria strains	Tested plants	Plant growth-promoting trait	Heavy metal	References
Rhizobium leguminosarum pr1	*Vicia faba*	IAA	Pb, Cd, Cu	(Saadani et al. 2016)
Pseudomonas aeruginosa CPSB1	*Triticum aestivum*	production of siderophore, HCN phosphate solubilization	Cr, Cu, Mn	(Hassan et al. 2017)
Bacillus licheniformis, Micrococcus luteus	*Vitis vinifera*	siderophore production, nitrogen fixation, phosphate solubilization	As	(Pinter et al. 2017)
Pseudomonas spp.	*Centaurea cyanus*	production of ACC deaminase siderophore	Pb	(Karimi et al. 2018a)
Bacillus megaterium H3	*Bactris campestris*	production of siderophore and IAA	Cd, Pb	(Wang et al. 2018)
Enterobacter spp. HU38	*Leptochloa fusca*	production of IAA and siderophore	Cr	(Ashraf et al. 2018)
Acinetobacter iwoffii RJB-2	*Vigna radiata*	production of siderophore phosphate solubilization and IAA	As	(Das and Sarkar 2018)
Pseudomonas agglomeran RSO6	*Spartina densiflora*	phosphate solubilization and nitrogen fixation	Zn, As, Pb	(Paredes-Páliz et al. 2018)
Variovorax paradoxus 5C-2	*Pisum sativum*	production of ACC deaminase	Cd	(Kumar et al. 2020)
Pseudomonas spp. A3R3	*Ricinus communis*	production of siderophore	Zn	(Ma et al. 2015)

IAA – indole-3- acetic acid; ACC – aminocyclopropane-1-carboxylate; HCN – hydrogen cyanide

https://doi.org/10.17221/130/2020-PPS

seawater have been reported by Kim et al. (2015) with the capacity of removal ranging from 90–100 mg/g after seven days of the application.

Application of plant-beneficial rhizobacteria as biostimulant for plants

Biostimulants are materials of biological origin that contain microorganisms that can enhance the natural soil and, when applied in a small quantity, they promote plant growth (Yakhin et al. 2017). *Azospirillum,* which is the most popular genus of rhizobacteria, has been known to improve plant development in the plant's roots, where it can obtain a large carbon source and exudates that could serve as a nutrient for the beneficial rhizobacteria that live around the root region (Ramos et al. 2011). With this association of beneficial microbes with the plant root, the microorganisms will be able to produce some enzymes and plant hormones that will serve as protection for the plant against plant pathogens (Lawal and Babalola 2014). In the plant's roots and in the soil, millions of plant beneficial rhizobacteria are found that live symbiotically with them. Different strains of *Azospirillum* like *A. brasilense* and *A. lipoferum* have been used as a biostimulant in crops to improve their yield (Fei et al. 2019).

The benefits obtained by plants through the use of *Azospirillum* as a biostimulant are the nitrogen fixation and the production of indole-3-acetic acid, which enhances the root hair growth in the plants for the proper uptake of minerals (Lawal & Babalola 2014). Similarly, the stimulatory activity of plant growth-promoting rhizobacteria in promoting the plant have been reported in *Bacillus subtilis* KB105, *Peanibacillus graminis* FL400, *Bacillus amiloliquefaciens* SQR9 and *Bacillus pumilus* OS15, which makes the bacteria strains a good source of microbial inoculants in ensuring sustainable agriculture (Rouphael & Colla 2020).

CONCLUSION

The rate at which we use agrochemical products that caused ecological imbalance has encouraged industries responsible for the production. Therefore, there is a need to look for an alternative means of increasing food production, enhancing the plant health, reducing pathogen infections, and increasing the soil fertility, which will pose no harm to humans and the environment. The knowledge of the multifaceted role of plant-beneficial rhizobacteria as bioinoculants can fill the gap in the food production, bioremediation, and pathogen control to meet the food demand by the increased global population. Also, it is important to appreciate the usefulness of beneficial rhizobacteria with their plant-growth-promoting and biocontrol potential as a modern way of improving crop productivity, food quality, and ensuring sustainable agriculture.

Conclusively, there is a need for more research to unveil the potential beneficial rhizobacteria as bioinoculants in increasing the plant development, plant defence and productivity toward ensuring sustainable agriculture.

Acknowledgement: OAF appreciates the National Research Foundation, South Africa, The World Academy of Science (NRF-TWAS) for PhD stipend.

REFERENCES

Ahemad M., Kibret M. (2014): Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. Journal of King Saud University, 26: 1–20.

Ahmadi K., Zarebanadkouki M., Ahmed M.A., Ferrarini A., Kuzyakov Y., Kostka S.J., Carminati A. (2017): Rhizosphere engineering: Innovative improvement of root environment. Rhizosphere, 3: 176–184.

Alka S., Shahir S., Ibrahim N., Chai T.T., Bahari Z.M., Manan F.A. (2020): The role of plant growth promoting bacteria on arsenic removal: A review of existing perspectives. Environmental Technology and Innovation, 17: 100602. doi: 10.1016/j.eti.2020.100602

Alori E.T., Babalola O.O. (2018): Microbial inoculants for improving crop quality and human health in Africa. Frontiers in Microbiology, 9: 2213. doi: 10.3389/fmicb.2018.02213

Alori E.T., Dare M.O., Babalola O.O. (2017a): Microbial inoculants for soil quality and plant health. In: Sustainable Agriculture Reviews. Cham, Springer: 281–307.

Alori E.T., Glick B.R., Babalola O.O. (2017b): Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in Microbiology, 8: 971. doi: 10.3389/fmicb.2017.00971

Arroyo J., Farkaš V., Sanz A.B., Cabib E. (2016): Strengthening the fungal cell wall through chitin–glucan cross-links: Effects on morphogenesis and cell integrity. Cellular Microbiology, 18: 1239–1250.

Asad S.A., Farooq M., Afzal A., West H. (2019): Integrated phytobial heavy metal remediation strategies for a sustainable clean environment – A review. Chemosphere, 217: 925–941.

Asati A., Pichhode M., Nikhil K. (2016): Effect of heavy metals on plants: An overview international. Journal of

Application or Innovation in Engineering & Management, 5: 2319–4847.

Ashraf S., Afzal M., Naveed M., Shahid M., Ahmad Zahir Z. (2018): Endophytic bacteria enhance remediation of tannery effluent in constructed wetlands vegetated with *Leptochloa fusca*. International Journal of Phytoremediation, 20: 121–128.

Ayangbenro A.S., Babalola O.O. (2017): A new strategy for heavy metal polluted environments: A review of microbial biosorbents. International Journal of Environmental Research and Public health, 14: 94. doi: 10.3390/ijerph14010094

Babalola O.O. (2010): Beneficial bacteria of agricultural importance. Biotechnology Letter, 32: 1559–1570.

Babalola O.O., Glick B.R. (2012): The use of microbial inoculants in African agriculture: Current practice and future prospects. Journal of Food Agriculture and Environment, 10: 540–549.

Bahadur I., Maurya B.R., Kumar A., Meena V.S., Raghuwanshi R. (2016): Towards the soil sustainability and potassium-solubilizing microorganisms. In: Potassium Solubilizing Microorganisms for Sustainable Agriculture. Springer: 255–266.

Banik A., Mukhopadhaya S.K., Dangar T.K. (2016): Characterization of N_2-fixing plant growth promoting endophytic and epiphytic bacterial community of Indian cultivated and wild rice (*Oryza* spp.) genotypes. Planta, 243: 799–812.

Barea J. (2015): Future challenges and perspectives for applying microbial biotechnology in sustainable agriculture based on a better understanding of plant-microbiome interactions. Journal of Soil Science and Plant Nutrition, 15: 261–282.

Barman S., Das S., Bhattacharya S.S. (2019): The prospects of bio-fertilizer technology for productive and sustainable agricultural growth. In: New and Future Developments in Microbial Biotechnology and Bioengineering. Chennai, Elsevier: 233–253.

Batista B.D (2018): Screening of tropically derived, multi-trait plant growth-promoting rhizobacteria and evaluation of corn and soybean colonization ability. Microbiological Research, 206: 33–42.

Becker M. (2018): Comparative genomics reveal a flagellar system, a type VI secretion system and plant growth-promoting gene clusters unique to the endophytic bacterium *Kosakonia radicincitans.* Frontiers in Microbiology, 9: 1997. doi: 10.3389/fmicb.2018.01997

Bhandari G (2014) An overview of agrochemicals and their effects on environment in Nepal. Journal of Applied Ecology and Environmental Science, 2: 66–73.

Bharti N., Barnawal D. (2019): Amelioration of salinity stress by PGPR: ACC deaminase and ROS scavenging enzymes activity. In: PGPR Ammelioration in Sustainable Agriculture. Cambridge, Elsevier: 85–106.

Bhattacharya A. (2019): Intervention of bio-protective endophyte *Bacillus tequilensis* enhance physiological strength of tomato during Fusarium wilt infection. Biological Control, 139: 104074. doi: 10.1016/j.biocontrol.2019.104074

Bhattacharyya P.N., Jha D.K. (2012): Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. World Journal of Microbiology and Biotechnology, 28: 1327–1350.

Bjelić D., Marinković J., Tintor B., Mrkovački N. (2018): Antifungal and plant growth promoting activities of indigenous rhizobacteria isolated from maize (*Zea mays* L.) rhizosphere Com. Soil Science and Plant Analysis, 49: 88–98.

Burant A., Selbig W., Furlong E.T., Higgins C.P. (2018): Trace organic contaminants in urban runoff: Associations with urban land-use. Environmental Pollution, 242: 2068–2077.

Buzón-Durán L., Pérez-Lebeña E., Martín-Gil J., Sánchez-Báscones M., Martín-Ramos P. (2020): Applications of *Streptomyces* spp. enhanced compost in sustainable agriculture. In: Biology of Composts. Cham, Springer: 257–291.

Byrne M.P., Tobin J.T., Forrestal P., Richards K., Danaher M., Cummins E., O'Callaghan T.F. (2019): The nitrogen cycle a mini review. Biosystems and Food Engineering Research Review. Dublin, University college Dublin.

Cepeda M.V. (2012): Effects of microbial inoculants on biocontrol and plant growth promotion. Columbus, The Ohio State University.

Chauhan A.K., Maheshwari D.K., Kim K., Bajpai V.K. (2016): Termitarium-inhabiting *Bacillus endophyticus* TSH42 and *Bacillus cereus* TSH77 colonizing *Curcuma long*a L.: Isolation, characterization, and evaluation of their biocontrol and plant-growth-promoting activities. Canadian Journal of Microbiology, 62: 880–892.

Chen Y., Shen X., Peng H., Hu H., Wang W., Zhang X. (2015) Comparative genomic analysis and phenazine production of *Pseudomonas chlororaphis*, a plant growth-promoting rhizobacterium. Genomics Data, 4: 33–42.

Chukwuneme C.F., Babalola O.O., Kutu F.R., Ojuederie O.B. (2020): Characterization of actinomycetes isolates for plant growth promoting traits and their effects on drought tolerance in maize. Journal of Plant Interactions, 15: 93–105.

Czaja K. (2015): Biopesticides –Towards increased consumer safety in the European Union. Journal of Pest Managment Science, 71: 3–6.

Das J., Sarkar P. (2018): Remediation of arsenic in mung bean (*Vigna radiata*) with growth enhancement by unique arsenic-resistant bacterium *Acinetobacter lwoffii*. Science of the Total Environment, 624: 1106–1118.

Deori M., Jayamohan N.S, Kumudini B.S. (2018): Production, characterization and iron binding affinity of hydroxamate siderophores from rhizosphere associated fluorescent *Pseudomonas.* Journal of Plant Protection Research, 58: 36–43.

Devi R., Thakur R., Gupta M. (2018): Isolation and molecular characterization of bacterial strains with antifungal activity from termite mound soil. International Journal of Current Microbiology and Applied Science, 7: 1–7.

Dhananjayan V., Jayakumar S., Ravichandran B. (2020): Conventional methods of pesticide application in agricultural field and fate of the pesticides in the environment and human health. In: Controlled Release of Pesticides for Sustainable Agriculture. Cham, Springer: 1–39.

Dixit R. (2015): Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes. Sustainability, 7: 2189–2212.

Dubois M., Van den Broeck L., Inzé D. (2018): The pivotal role of ethylene in plant growth. Trends in Plant Science, 23: 311–323.

El-Sherbiny G.M., Darwesh O.M., El-Hawary A.S. (2017): Taxonomic characterization of the chitinolytic actinomycete *Cellulomonas chitinilytica* strain HwAC11. International Journal of Advanced Research in Biological Sciences, 4: 292–299.

Enagbonma B.J., Babalola O.O. (2019a): Environmental sustainability: A review of termite mound soil material and its bacteria. Sustainability, 11: 3847. doi: 10.3390/su11143847

Enagbonma B.J., Babalola O.O. (2019b): Potentials of termite mound soil bacteria in ecosystem engineering for sustainable agriculture. Annals of Microbiology, 69: 211–219.

Enebe M.C., Babalola O.O. (2018): The influence of plant growth-promoting rhizobacteria in plant tolerance to abiotic stress: a survival strategy. Applied Microbiology and Biotechnology, 102:7821–7835.

Etesami H., Maheshwari D.K. (2018): Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: Action mechanisms and future prospects. Ecotoxicology and Environmental Safety, 156: 225–246.

Farha W., Abd El-Aty A.M., Rahman M.M., Jeong J.H., Shin H.-C., Wang J., Shin S.S., Shim J.H. (2018): Analytical approach, dissipation pattern and risk assessment of pesticide residue in green leafy vegetables: A comprehensive review. Biomedical Chromatomatography, 32:e4134. doi: 10.1002/bmc.4134

Fei H., Crouse M., Papdopoulos Y.A., Vessey J.K. (2019): Improving biomass yield of giant *Miscanthus* by application of beneficial soil microbes and a plant biostimulant. Canadian Journal of Plant Science, 100: 209–219.

Felestrino É.B. (2018): Biotechnological potential of plant growth-promoting bacteria from the roots and rhizospheres of endemic plants in ironstone vegetation in southeastern Brazil. World Journal of Microbiology and Biotechnology, 34: 156. doi: 10.1007/s11274-018-2538-0.

Figueiredo M.V.B., Bonifacio A., Rodrigues A.C., de Araujo F.F. (2016): Plant growth-promoting rhizobacteria: Key mechanisms of action. In: Microbial-mediated Induced Systemic Resistance in Plants. Singapore, Springer: 23–37.

Fu L., Penton C.R., Ruan Y., Shen Z., Xue C., Li R., Shen Q. (2017): Inducing the rhizosphere microbiome by biofertilizer application to suppress banana Fusarium wilt disease. Soil Biology and Biochemistry, 104: 39–48.

Galindo F.S. (2019): Maize yield response to nitrogen rates and sources associated with *Azospirillum brasilense*. Agronomy Journal, 111: 1985–1997.

García-Fraile P., Menéndez E., Rivas R. (2015:) Role of bacterial biofertilizers in agriculture and forestry. AIMS Bioengineering, 2: 183–205.

Ghorbani-Nasrabadi R., Greiner R., Alikhani H.A., Hamedi J. (2012): Identification and determination of extracellular phytate-degrading activity in *Actinomycetes.* World Journal of Microbiology and Biotechnology, 28: 2601–2608.

Gislason A.S., Fernando W.D., de Kievit T.R. (2020): Biosynthesized secondary metabolites for plant growth promotion. In: Bioeconomy for Sustainable Development. Singapore, Springer: 217–250.

Glick B. (2014): Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiological Research, 169: 30–39.

Gómez-Lama Cabanás C., Schilirò E., Valverde-Corredor A., Mercado-Blanco J. (2014): The biocontrol endophytic bacterium *Pseudomonas fluorescens* PICF7 induces systemic defense responses in aerial tissues upon colonization of olive roots. Frontiers in Microbiology, 5: 427. doi: 10.3389/fmicb.2014.00427

Gómez Padilla E., Ruiz-Díez B., Fernández-Pascual M., López Sánchez R., Bloem E., Eichler-Loebermann B. (2016): Inoculation with native bradyrhizobia strains improved growth of cowpea plants cultivated on a saline soil. Communications in Soil Science and Plant Analysis, 47: 2218–2224.

Goswami D., Thakker J.N., Dhandhukia P.C. (2016): Portraying mechanics of plant growth promoting rhizobacteria (PGPR): A review. Cognent Food & Agriculture, 2: 1127500. doi: 10.1080/23311932.2015.1127500

Gouda S., Kerry R.G., Das G., Paramithiotis S., Shin H.S., Patra J.K. (2018): Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiological Research, 206: 131–140.

Goudjal Y., Zamoum M., Sabaou N., Mathieu F., Zitouni A. (2016): Potential of endophytic *Streptomyces* spp. for biocontrol of Fusarium root rot disease and growth promotion of tomato seedlings. Biocontrol Science and Technology, 26: 1691–1705.

Gross A., Holdenrieder O., Pautasso M., Queloz V., Sieber T.N. (2014). *Hymenoscyphus pseudoalbidu*s, the causal agent of European ash dieback. Journal of Molecular Plant Pathology, 15: 5–21.

https://doi.org/10.17221/130/2020-PPS

Gupta G., Parihar S.S., Ahirwar N.K., Snehi S.K., Singh V. (2015): Plant growth promoting rhizobacteria (PGPR): current and future prospects for development of sustainable agriculture. Journal of Microbiology and Biochemical Techechnology, 7: 96–102.

Hashem A., Alqarawi A.A., Al-Hazzani A.A., Egamberdieva D., Tabassum B., Abd-Allah E.F. (2019a): Cadmium stress tolerance in plants and role of beneficial soil microorganisms. In: Phyto and Rhizo Remediation. Singapore, Springer: 213–234.

Hashem A., Tabassum B., Abd-Allah E.F. (2019b): *Bacillus subtilis*: A plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi Journal of Biological Sciences, 26: 1291–1297.

Hassan M.K., McInroy J.A., Kloepper J.W. (2019): The interactions of rhizodeposits with plant growth-promoting rhizobacteria in the rhizosphere: A review. Agriculture, 9: 142. doi. 10.3390/agriculture9070142

Hassan T.U., Bano A., Naz I. (2017): Alleviation of heavy metals toxicity by the application of plant growth promoting rhizobacteria and effects on wheat grown in saline sodic field. International Journal of Phytoremediation, 19: 522–529.

Heidarzadeh N., Baghaee-Ravari S. (2015): Application of *Bacillus pumilus* as a potential biocontrol agent of Fusarium wilt of tomato. Archives of Phytopathology and Plant Protection, 48: 841–849.

Igiehon N.O., Babalola O.O. (2017): Biofertilizers and sustainable agriculture: Exploring arbuscular mycorrhizal fungi. Applied Microbiology and Biotechnology, 101: 4871–4881.

Igiehon N.O., Babalola O.O. (2018): Below-ground-above-ground plant-microbial interactions: Focusing on soybean, rhizobacteria and mycorrhizal fungi. Open Microbiology Journal, 12: 261. doi: 10.2174/1874285801812010261

Igiehon N.O., Babalola O.O., Aremu B.R. (2019): Genomic insights into plant growth promoting rhizobia capable of enhancing soybean germination under drought stress. BMC Microbiology, 19: 159. doi: 10.1186/s12866-019-1536-1

Jha C.K., Saraf M. (2015): Plant growth promoting rhizobacteria (PGPR): A review. Journal of Agricultural Research and Development 5: 108–119.

Jiang C.J., Liu X.L., Liu X.Q., Zhang H., Yu Y.J., Liang Z.W. (2017): Stunted growth caused by blast disease in rice seedlings is associated with changes in phytohormone signaling pathways. Frontiers in Plant Science: 8: 1558. doi: 10.3389/fpls.2017.01558

Jog R., Pandya M., Nareshkumar G., Rajkumar S. (2014): Mechanism of phosphate solubilization and antifungal activity of *Streptomyces* spp. isolated from wheat roots and rhizosphere and their application in improving plant growth. Journal of Microbiology, 160: 778–788.

Kaouthar F., Ameny F.K., Yosra K., Walid S., Ali G., Faical B. (2016): Responses of transgenic Arabidopsis plants and recombinant yeast cells expressing a novel durum wheat manganese superoxide dismutase TdMnSOD to various abiotic stresses. Journal of Plant Physiology, 198: 56–68.

Karimi A., Khodaverdiloo H., Rasouli-Sadaghiani M.H. (2018a): Microbial-enhanced phytoremediation of lead contaminated calcareous soil by *Centaurea cyanus* L. Clean – Soil, Air, Water, 46: 1700665. doi: 10.1002/clen.201700665

Karimi N., Zarea M.J., Mehnaz S. (2018b): Endophytic *Azospirillum* for enhancement of growth and yield of wheat. Environmental Sustainability, 1: 149–158.

Khan N., Bano A. (2016): Modulation of phytoremediation and plant growth by the treatment with PGPR, Ag nanoparticle and untreated municipal wastewater. International Journal of Phytoremediation, 18: 1258–1269.

Kim I.H., Choi J.H., Joo J.O., Kim Y.K., Choi J.W., Oh B.K. (2015): Development of a microbe-zeolite carrier for the effective elimination of heavy metals from seawater. Journal of Microbiology and Biotechnology, 25: 1542–1546.

Kuan K.B., Othman R., Rahim K.A., Shamsuddin Z.H. (2016): Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilisation of maize under greenhouse conditions. PloS One, 11:e0152478. doi: 10.1371/journal.pone.0152478

Kumar A., Bahadur I., Maurya B., Raghuwanshi R., Meena V., Singh D., Dixit J. (2015): Does a plant growth-promoting rhizobacteria enhance agricultural sustainability. Journal of Pure and Applied Microbiology, 9: 715–724.

Kumar A., Meena V.S., Roy P., Kumari R. (2019): Role of *Rhizobia* for sustainable agriculture: Lab to land. In: Plant Growth Promoting Rhizobacteria for Agricultural Sustainability. Singapore, Springer: 129–149.

Kumar M., Gupta N., Ratn A., Awasthi Y., Prasad R., Trivedi A., Trivedi S.P. (2020): Biomonitoring of heavy metals in river Ganga water, sediments, plant, and fishes of different trophic levels. Biological Trace Element Research, 193: 536–547.

Kumar S. (2016): *Paenibacillus lentimorbus* inoculation enhances tobacco growth and extenuates the virulence of *Cucumber mosaic virus*, PLoS One 11: e0149980. doi: 10.1371/journal.pone.0149980

Lawal T.E, Babalola O.O .(2014): Relevance of biofertilizers to agriculture. Joural of Human Ecology, 47: 35–43.

Liang H., Bilon N., Hay M.T. (2015): Analytical methods for pesticide residues in the water environment. Journal of Water and Environmental Research, 87: 1923–1937.

Liu D., Li K., Hu J., Wang W., Liu X., Gao Z. (2019): Biocontrol and action mechanism of *Bacillus amyloliquefaciens* and *Bacillus subtilis* in soybean phytophthora blight. Interna-

https://doi.org/10.17221/130/2020-PPS

tional Journal of Molecular Sciences, 20: 2908. 10.3390/ijms20122908

Liu D. (2017): Promotion of iron nutrition and growth on peanut by *Paenibacillus illinoisensis* and *Bacillus sp.* strains in calcareous soil. Brazilian Journal of Microbiology, 48: 656–670.

Lobo C.B., Tomás M.S.J., Viruel E., Ferrero M.A., Lucca M.E. (2019): Development of low-cost formulations of plant growth-promoting bacteria to be used as inoculants in beneficial agricultural technologies. Microbiological Research, 219: 12–25.

Ma Y., Rajkumar M., Rocha I., Oliveira R.S., Freitas H. (2015): Serpentine bacteria influence metal translocation and bioconcentration of *Brassica juncea* and *Ricinus communis* grown in multi-metal polluted soils. Frontiers in Plant Science, 5: 757. doi: 10.3389/fpls.2014.00757

Magauzi R. (2011): Health effects of agrochemicals among farm workers in commercial farms of Kwekwe District, Zimbabwe. Pan African Medical Journal, 9: 26. doi: 10.4314/pamj.v9i1.71201

Manasa K., Reddy S., Triveni S. (2017): Characterization of Potential PGPR and Antagonistic Activities of *Rhizobium* isolates from different rhizosphere. Soils Pharmacognosy and Phytochemistry 6: 51–54.

Masood S., Bano A. (2016): Mechanism of potassium solubilization in the agricultural soils by the help of soil microorganisms. In: Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi, Springer: 137–147.

Meena M., Swapnil P., Zehra A., Aamir M., Dubey MK., Goutam J., Upadhyay R. (2017): Beneficial microbes for disease suppression and plant growth promotion. In: Plant-microbe Interactions in Agro-ecological perspectives. Singapore, Springer: 395–432.

Mfilinge A., Mtei K., Ndakidemi P. (2014): Effect of *Rhizobium* inoculation and supplementation with phosphorus and potassium on growth and total leaf chlorophyll (Chl) content of Bush Bean *Phaseolus vulgaris*, L. Agricultural Science, 5: 1413–1426.

Mhlongo M.I., Piater L.A., Madala N.E., Labuschagne N., Dubery I.A. (2018): The chemistry of plant–microbe interactions in the rhizosphere and the potential for metabolomics to reveal signaling related to defense priming and induced systemic resistance. Frontier in Plant Science, 9: 112. doi: 10.3389/fpls.2018.00112

Mishra S.K. (2020): Drought tolerant *Ochrobactrum sp*. inoculation performs multiple roles in maintaining the homeostasis in *Zea mays* L. subjected to deficit water stress. Plant Physiology and Biochemistry, 150: 1–14.

Myers S.S. (2017): Climate change and global food systems: Potential impacts on food security and undernutritio. Annual Review of Public Health, 38: 259–277.

Nascimento F.X., Rossi M.J., Glick B.R. (2018): Ethylene and 1-Aminocyclopropane-1-carboxylate (ACC) in plant–bacterial interactions. Frontiers in Plant Science, 9: 114. doi: 10.3389/fpls.2018.00114

Ogawara H. (2016): Self-resistance in *Streptomyces*, with special reference to β-Lactam antibiotics. Molecules, 21: 605. doi: 10.3390/molecules21050605

Ojuederie O.B., Babalola O.O. (2017): Microbial and plant-assisted bioremediation of heavy metal polluted environments: A review. International Journal of Environmental Research and Public Health, 14: 1504. doi: 10.3390/ijerph14121504

Ojuederie O.B., Olanrewaju O.S., Babalola O.O. (2019): Plant growth-promoting rhizobacterial mitigation of drought stress in crop plants: Implications for sustainable agriculture. Agronomy. 9: 712. doi: 10.3390/agronomy9110712

Olanrewaju O.S., Glick B.R., Babalola O.O. (2017): Mechanisms of action of plant growth promoting bacteria. World Journal of Microbiology and Biotechnology, 33: 197. doi: 10.1007/s11274-017-2364-9

Omran R., Kadhem M.F. (2016): Production, purification, and characterization of bioactive metabolites produced from rare actinobacteria *Pseudonocardia alni.* Asian Journal of Pharmacetical and Clinical Research, 9: 1–9.

Paiter A., Freitas G., Pinto L., Hass L., Barreiros M., Oliveira A., Grange L. (2019): IAA production and phosphate solubilization performed by native rhizobacteria in western Paraná. Agronomy Science and Biotechnology, 5: 70–70.

Panwar M., Tewari R., Nayyar H. (2016): Native halo-tolerant plant growth promoting rhizobacteria *Enterococcus* and *Pantoea sp.* improve seed yield of mungbean (*Vigna radiata* L.) under soil salinity by reducing sodium uptake and stress injury. Physiology and Molecular Biology of Plants, 22: 445–459.

Paredes-Páliz K. (2018): Investigating the mechanisms underlying phytoprotection by plant growth-promoting rhizobacteria in *Spartina densiflor*a under metal stress. Plant Biology, 20: 497–506.

Patel P., Shah R., Joshi B., Ramar K., Natarajan A. (2019): Molecular identification and biocontrol activity of sugarcane rhizosphere bacteria against red rot pathogen *Colletotrichum falcatum.* Biotechnology Reports, 21:e00317. doi: 10.1016/j.btre.2019.e00317.

Patel T., Minocheherhomji F. (2018): Plant growth promoting rhizobacteria: Blessing to agriculture. International Journal of Pure Applied Bioscience, 6: 481–492.

Pathak P. (2018): Intestine Farnesoid X receptor agonist and the gut microbiota activate G-protein bile acid receptor-1 signaling to improve metabolism. Hepatology, 68: 1574–1588.

https://doi.org/10.17221/130/2020-PPS

Pathan S.I., Ceccherini M.T., Sunseri F., Lupini A. (2020): Rhizosphere as hotspot for plant-soil-microbe interaction. In: Carbon and Nitrogen Cycling in Soil. Singapore, Springer: 17–43.

Perez-Harguindeguy N. (2016): Corrigendum to: New handbook for standardised measurement of plant functional traits worldwide. Australian Journal of Botany, 64: 715–716.

Pinter I.F., Salomon M.V., Berli F., Bottini R., Piccoli P. (2017): Characterization of the As (III) tolerance conferred by plant growth promoting rhizobacteria to in vitro-grown grapevine. Applied Soil Ecology, 109: 60–68.

Puyen Z.M., Villagrasa E., Maldonado J., Diestra E., Esteve I., Solé A. (2012): Biosorption of lead and copper by heavy-metal tolerant *Micrococcus luteus* DE2008. Bioresource Technology, 126: 233–237.

Ramos P.L., Van Trappen S., Thompson F.L., Rocha R.C., Barbosa H.R., de Vos P., Moreira-Filho C.A. (2011): Screening for endophytic nitrogen-fixing bacteria in Brazilian sugar cane varieties used in organic arming and description of *Stenotrophomonas pavanii sp*. Nov. International Journal of Systemic and Evolution Microbiology, 61: 926–931.

Rani S., Pooja K., Pal G.K. (2018): Exploration of rice protein hydrolysates and peptides with special reference to antioxidant potential: computational derived approaches for bioactivity determination. Trend in Food Science, 80: 61–70.

Ranveer K., Gusain Y., Vivek K. (2014): Interaction and symbiosis of AM fungi, *Actinomycetes* and plant growth promoting rhizobacteria with plants: Strategies for the improvement of plants health and defense system. International Journal of Current Microbiology and Applied Science, 3: 564–585.

Ravikumar R. (2012): Growth effects of *Rhizobium* inoculation in some legume plants. International Journal of Current Science, 1: 1–6.

Rijavec T., Lapanje A, (2016): Hydrogen cyanide in the rhizosphere: Not suppressing plant pathogens, but rather regulating availability of phosphate. Frontiers in Microbiology, 7: 1785. doi: 10.3389/fmicb.2016.01785

Romero-Perdomo F., Abril J., Camelo M., Moreno-Galván A., Pastrana I., Rojas-Tapias D., Bonilla R. (2017): *Azotobacter chroococcum* as a potentially useful bacterial biofertilizer for cotton (*Gossypium hirsutum*): Effect in reducing N fertilization. Revista Argentina de Microbiologia, 49: 377–383.

Rosier A., Medeiros F.H., Bais H.P. (2018): Defining plant growth promoting rhizobacteria molecular and biochemical networks in beneficial plant-microbe interactions. Plant and Soil, 428: 35–55.

Rouphael Y., Colla G. (2020): Biostimulants in agriculture. Frontiers in Plant Science, 11: 40. doi. 10.3389/fpls.2020.00040

Roychowdhury D., Paul M., Banerjee S.K. (2014): A review on the effects of biofertilizers and biopesticides on rice and tea cultivation and productivity. International Journal of Science and Engineering Technology, 2: 96–105.

Saadani O., Fatnassi I.C., Chiboub M., Abdelkrim S., Barhoumi F., Jebara M., Jebara S.H. (2016): *In situ* phytostabilisation capacity of three legumes and their associated plant growth promoting bacteria (PGPBs) in mine tailings of northern Tunisia. Ecotoxicology and Environmental Safety, 130: 263–269.

Samago T.Y., Anniye E.W., Dakora F.D. (2018): Grain yield of common bean (*Phaseolus vulgaris* L.) varieties is markedly increased by rhizobial inoculation and phosphorus application in Ethiopia. Symbiosis, 75: 245–255.

Saraf M., Pandya U., Thakkar A. (2014): Role of allelochemicals in plant growth promoting rhizobacteria for biocontrol of phytopathogens. Microbiology Research, 169: 18–29.

Schaller G.E. (2012): Ethylene and the regulation of plant development. BMC Biology, 10: 9. doi. 0.1186/1741-7007-10-9

Shabbir R.N., Ali H., Nawaz F., Hussain S., Areeb A., Sarwar N., Ahmad S. (2019): Use of biofertilizers for sustainable crop production. In: Agronomic Crops. Place of publish, Springer: 149–162.

Shafi M.E., Khattab A.E.-N.A. (2020): Improvement of chitinase produced from chitin of desert locust by *Streptomyces halstedii* strain isolated from Jeddah, KSA. Advances in Environmental Biology, 14: 7–19.

Shah S., Ramanan V.V., Singh A., Singh A.K. (2018). Potential and Prospect of Plant Growth Promoting Rhizobacteria in Lentil Scientific Lentil Production. Delhi, Satish Serial Publishing House.

Shaikh S., Sayyed R. (2015): Role of plant growth-promoting rhizobacteria and their formulation in biocontrol of plant diseases. In: Plant Microbes Symbiosis: Applied Facets. New Delhi, Springer: 337–351.

Sharma H. (2016): Physicochemical analyses of plant biostimulant formulations and characterisation of commercial products by instrumental techniques. Chemical and Biological Technologies in Agriculture, 3:13. doi. 10.1186/s40538-016-0064-6

Shen F.T., Yen J.H., Liao C.S., Chen W.C., Chao Y.T. (2019): Screening of rice endophytic biofertilizers with fungicide tolerance and plant growth-promoting characteristics. Sustainability, 11: 1133. doi: https://doi.org/10.3390/su11041133

Shoaib M. (2016): Inulin: Properties, health benefits and food applications. Carbohydrate Polymers, 147: 444–454.

Singh J., Singh P., Ray S., Rajput R.S., Singh H.B. (2019): Plant growth-promoting rhizobacteria: Benign and useful substitute for mitigation of biotic and abiotic stresses. In: Plant Growth Promoting Rhizobacteria for Sustainable Stress Management. Singapore, Springer: 81–101.

https://doi.org/10.17221/130/2020-PPS

Singh N.S., Sharma R., Parween T., Patanjali P. (2018): Pesticide contamination and human health risk factor. In: Modern Age Environmental Problems and Their Remediation. Cham, Springer: 49–68.

Sinha A., Pant K.K., Khare S.K. (2012): Studies on mercury bioremediation by alginate immobilized mercury tolerant *Bacillus cereus* cells. International Biodeterioration and Biodegradation, 71: 1–8.

Srivastava S. (2015): Bioremediation technology: A greener and sustainable approach for restoration of environmental pollution. In: Applied Environmental Biotechnology: Present Scenario and Future Trends. New Delhi, Springer: 1–18.

Stamenković S., Beškoski V., Karabegović I., Lazić M., Nikolić N. (2018): Microbial fertilizers: A comprehensive review of current findings and future perspectives. Journal of Agricultural Research, 16:e09R01. doi: 10.5424/sjar/2018161-12117

Tabassum B., Khan A., Tariq M., Ramzan M., Khan M.S.I., Shahid N., Aaliya K. (2017): Bottlenecks in commercialisation and future prospects of PGPR. Applied Soil Ecology, 121: 102–117.

Tan K., Radziah O., Halimi M., Khairuddin A., Shamsuddin Z. (2015): Assessment of plant growth-promoting rhizobacteria (PGPR) and rhizobia as multi-strain biofertilizer on growth and N_2 fixation of rice plant. Australian Journal of Crop Science, 9: 1257–1264.

Tariq M., Noman M., Ahmed T., Hameed A., Manzoor N., Zafar M. (2017): Antagonistic features displayed by plant growth promoting rhizobacteria (PGPR): A review. Journal of Plant Science and Phytopathology, 1: 38–43.

Thijs S., Sillen W., Rineau F., Weyens N., Vangronsveld J. (2016): Towards an enhanced understanding of plant-microbiome interactions to improve phytoremediation: engineering the metaorganism. Frontiers in Microbiology, 7:341. doi: 10.3389/fmicb.2016.00341

Tiwari S., Prasad V., Chauhan P.S., Lata C. (2017): *Bacillus amyloliquefaciens* confers tolerance to various abiotic stresses and modulates plant response to phytohormones through osmoprotection and gene expression regulation in rice. Frontiers in Plant Science, 8: 1510. doi. 10.3389/fpls.2017.01510

Vejan P., Abdullah R., Khadiran T., Ismail S., Nasrulhaq Boyce A. (2016): Role of plant growth promoting rhizobacteria in agricultural sustainability – A review. Molecules, 21: 573. doi: 10.3390/molecules21050573

Vishan I., Saha B., Sivaprakasam S., Kalamdhad A. (2019): Evaluation of Cd (II) biosorption in aqueous solution by using lyophilized biomass of novel bacterial strain *Bacillus badius* AK: Biosorption kinetics, thermodynamics and mechanism. Environmental Technology and Innovation, 14:100323. doi: 10.1016/j.eti.2019.100323

Vurukonda S.S.K.P., Giovanardi D., Stefani E. (2018): Plant growth promoting and biocontrol activity of *Streptomyces* spp. as endophytes. International Journal of Molecular Science, 19: 952. doi: 10.3390/ijms19040952

Walter A., Mayer C. (2019): Peptidoglycan structure, biosynthesis, and dynamics during bacterial growth. In: Extracellular Sugar-Based Biopolymers Matrices. Cham, Springer: 237–299.

Wang Q., Zhang W.J., He L.Y., Sheng X.F. (2018): Increased biomass and quality and reduced heavy metal accumulation of edible tissues of vegetables in the presence of Cd-tolerant and immobilizing *Bacillus megaterium* H3. Ecotoxicology and Environmental Safety, 148: 269–274.

Wang Y., Huang W.E., Cui L., Wagner M. (2016): Single cell stable isotope probing in microbiology using raman microspectroscopy. Current Opinion in Biotechnology, 41: 34–42.

Wani S.P., Gopalakrishnan S. (2019): Plant growth-promoting microbes for sustainable agriculture. In: Plant Growth Promoting Rhizobacteria (PGPR): Prospects for Sustainable Agriculture. Singapore, Springer: 19–45.

Yakhin O.I., Lubyanov A.A., Yakhin I.A., Brown P.H. (2017): Biostimulants in plant science: A global perspective. Frontiers in Plant Science, 7:2049. doi: 10.3389/fpls.2016.02049

Yang J.H., Zhang W.W., Zhuang Y.Q., Xiao T. (2017): Biocontrol activities of bacteria from cowdung against the rice sheath blight pathogen. Journal of Plant Diseases and Protection, 124: 131–141.

Youseif S.H., Abd El-Megeed F.H., Saleh S.A. (2017): Improvement of faba bean yield using *Rhizobium*/*Agrobacterium* inoculant in low-fertility sandy soil. Agronomy, 7: 2. doi. 10.3390/agronomy7010002

Zheng X. (2012): Coronatine promotes *Pseudomonas syringae* virulence in plants by activating a signaling cascade that inhibits salicylic acid accumulation. Cell Host, 11: 587–596.

Zhu W. (2017): Biological characterisation of the emerged highly pathogenic *Avian influenza* (HPAI) A (H7N9) viruses in humans, in Mainland China, 2016 to 2017. European Communicable Disease Bulletin, 22: 19. doi: 10.2807/1560-7917.ES.2017.22.19.30533

Received: September 4, 2020
Accepted: January 15, 2021
Published online: March 1, 2021