Chapter 2
Biofertilizers: The Role in Sustainable Agriculture

Ishfaq Ul Rehman, Tajamul Islam, Abid Hussain Wani, Irfan Rashid, Ishfaq Ahmad Sheergojri, Maajid Mehraj Bandh, and Summia Rehman

Abstract The global rise in the human population presents a significant challenge to the world's food security. There is a huge gap between production and consumption (7.2 million tonnes nutrient deficit) due to the expanding population and agricultural land's shrinking over time. Therefore, crop production must be significantly boosted in the next few decades to meet the growing population's food demand. Chemical fertilizers have been extensively used to enable the crop outputs to bridge the lacunae between production and consumption, which ultimately seriously damaged both the natural ecosystems and human health. Therefore, biofertilizers' exploitation is, to a certain extent, considered a substitute for chemical fertilizers in the agricultural industry because of their significant potential to improve food production and safety. Biofertilizers are substances that include cells of different varieties of beneficial microorganisms that could become critical components of advanced nutrient management. Organisms typically used as constituents of biofertilizers are nitrogen fixers (N fixer), phosphorus solubilizers (P-solubilizer) and potassium solubilizers (K-solubilizer) or a mixture of fungi and moulds. These possible biofertilizers play a vital role in the production and sustainability of soils and safeguard the environment by being eco-friendly and cost-effective for producers.

Keywords Biofertilizer · Sustainability · Chemical fertilizers · Agriculture · Food security

---

I. U. Rehman (✉) · T. Islam · A. H. Wani · I. Rashid · I. A. Sheergojri · S. Rehman
Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

M. M. Bandh
Department of Zoology, University of Kashmir, Srinagar, Jammu and Kashmir, India

S. A. Bandh (ed.), *Sustainable Agriculture*,
https://doi.org/10.1007/978-3-030-83066-3_2

2.1 Introduction

Since the evolution of the human race, agriculture has been a primary survival tool for human generations. The agriculture sector generates food, fodder and other non-wood products on which a significant fraction of the world's population relies (Hervé et al., 2016; Kaur et al., 2018, 2018b). Given the population explosion, we need to set up appropriate plans and protocols to promote sustainable agriculture to meet our demands (Bhardwaj et al., 2014; Singh et al., 2014). Traditional methods are sensu stricto just to the farmer's families and the local village communities as it only engages food and feed production at the domestic level (Jehangir et al., 2017; Pandey, 2018). However, with the advent of innovative technologies, the production of agriculture output per hectare increases. Sustainable agriculture is a sensu latu concept to grow crops to their threshold limit while simultaneously protecting the environment (Barragán-Ocaña & Del-Valle-Rivera, 2016). There is a stochastic change in agricultural practice methodology as people have been paying more attention to safeguarding the environment while working to amplify the farm yield. Various hormones, fertilizers and even innovative approaches to fertigation are being used to increase crop production (Campos et al., 2019; Umesha et al., 2018a). Though yield may be amplified with increased application of synthetic chemicals, the overdose of synthetic fertilizers would diminish the utility of living conditions through pollutant and biomagnification or ecological amplification (Uosif et al., 2014). But that would compromise environmental sustainability. So, without compromising the future generation's needs, the current generation could attain sustainability in the agricultural sector by using eco-friendly products and environmentally sound technologies (Calabi-Floody et al., 2018; Umesha et al., 2018b; Wang et al., 2015).

Biofertilizer is one such product that helps us in achieving sustainable agriculture. Biofertilizers are the amalgamation of live or latent cells of competent phosphate-solubilizing strains, N_2-fixing or cellulolytic microorganisms, mainly used to apply to seeds and seedlings, etc. (Agarwal et al., 2018; García-Fraile et al., 2015). They play a significant role in escalating soil fertility by fixing atmospheric nitrogen and converting it into usable products. They also promote root growth by producing necessary hormones and antimetabolites and help in soil mineralization and nutrient decomposition (A, B., Ak, M., M, G., G, G., P, P., … B, J., 2009; Kumar et al., 2017). They are economical and can be used as supplements to synthetic fertilizers. Microflora like bacteria, fungi and blue-green algae are used as the principal ingredients of biofertilizers. To improve their shelf-life, these should be packed in material like peat and lignite powder. This way, biofertilizers have an utmost significance in sustaining agriculture and a safe environment (Agarwal et al., 2018). They can be grouped into different categories (Kumar et al., 2017) based on their service in sustainable agriculture (Table 2.1).

Table 2.1 Categories of biofertilizers

S. no.	Biofertilizers	Examples
1.	**Nitrogen fixing**	*Frankia*, *Anabaena*, *Rhizobium* (symbiotic)
		Anabaena, *Azotobacter*, *Clostridium* (free-living)
		Azospirillum (associative symbiotic)
2.	**Phosphorus mobilizing**	*Glomus* sp., *Gigaspora* sp., *Scutellospora* sp. and *Sclerocystis* sp. (arbuscular mycorrhiza)
		R. solani (orchid mycorrhiza)
		Laccaria sp., *boletus* sp., *Pisolithus* sp., *amanita* sp. (ectomycorrhiza)
		Pezizellaericae
3.	**Phosphorus solubilizing**	*Bacillus circulans*, *B. megaterium var. phosphaticum*, *B. subtilis*, *P. striata* **(bacteria)**
		Aspergillus awamori, *Penicillium* sp. **(Fungi)**
4.	**Biofertilizers (micronutrients)**	*Bacillus* sp. (for zinc and silicate Solubilizers)
5.	**Rhizobacteria (plant growth promoting)**	*P. fluorescens* (promoting plant growth)

2.1.1 *Rhizobium*

It is the most extensively studied genus to carrying the function of N_2 fixation (Odame, 1997). This genus's strains *are* symbiotically associated with leguminous crops, the essential food components. Apart from the ingredient of meals, legumes possess the potential to improve soil health via N_2 fixation (Laranjo et al., 2014), with different strains of this genus.

2.1.2 *Azospirillum*

Genus Azospirillum – a free-living genus – fixes the atmospheric nitrogen at a rate of 20–40 kg $ha^{-1}y^{-1}$ (Bashan, 1993). Strains of this genus are used as biofertilizers in various economically important crops like corn, rice, wheat, etc., which are (Döbereiner, 1997; Reinhold & Hurek, 1989; Sundaram et al., 1988). There is a proven fact that there is an increase in agricultural production and soil properties by applying *Azospirillum* strains Motsara et al. (1995).

2.1.3 *Azotobacter*

Azotobacter is an important genus promoting the synthesis of active secondary compounds like heteroxins, vitamins, gibberellins, etc. and thus significantly improves plants' root growth. This genus's species show intolerance to fluctuations of pH, salts and temperature (Jaga & Singh, 2010; Rao, 1986). Growth and crop yield of Triticum aestivum have increased with the augmentation of *Azotobacter* species (Ei-Lattief, 2016). Along with some yeast strains, it shows many improvised results (Ahmed et al., 2011). Some well-known methods of application of *Azotobacter* species are seed sipping and seedling root dipping.

2.1.4 Phosphorus-Solubilizing and Phosphorus-Mobilizing Microbes

Biofertilizers containing P-solubilizing and phosphorus-mobilizing microbes can make the accumulated phosphates readily available for plant growth progress (Goldstein, 1986). PSB also alters the status of soil nutrient structure (Blake, 1993).

2.2 Biofertilizers: Why their Need Is Inevitable?

In contemporary times there is a trend of environmental hazards and threats to sustainable agriculture due to the extensive use of chemical fertilizers. Given this, biofertilizers' continued application proves very economical, eco-friendly, efficient and productive to marginal and small farmers over chemical fertilizers. There are primarily two reasons which push the agriculturists for frequent use of biofertilizers:

- Usage of biofertilizers is a front runner in increased crop productivity.
- Increased usage of chemical fertilizer augments the damage in soil texture with accompanying environmental problems.

2.3 How Biofertilizers Work

Bacteria, fungi and other microorganisms, though distributed heterogeneously, are omnipotent in the world. The microbes that are present in the rhizosphere and can promote growth and development are accordingly termed as plant growth-promoting bacteria (PGPB). These days several PGPBs are available as biofertilizers at a commercial scale (Calvo et al., 2014). PGPB plays a very prominent role in plant growth and soil fertility maintenance in the following ways (Fig. 2.1):

1. Under certain stress conditions, PGPBs may produce and supply important hormones like auxins, cytokinin and gibberellin, which directly regulate plant growth. PGPBs also aid plants by providing essential elements like nitrogen (N) and phosphorous (P) and enhance potassium (K) intake, etc. Since these activities promote plant growth directly, they are called direct ways.

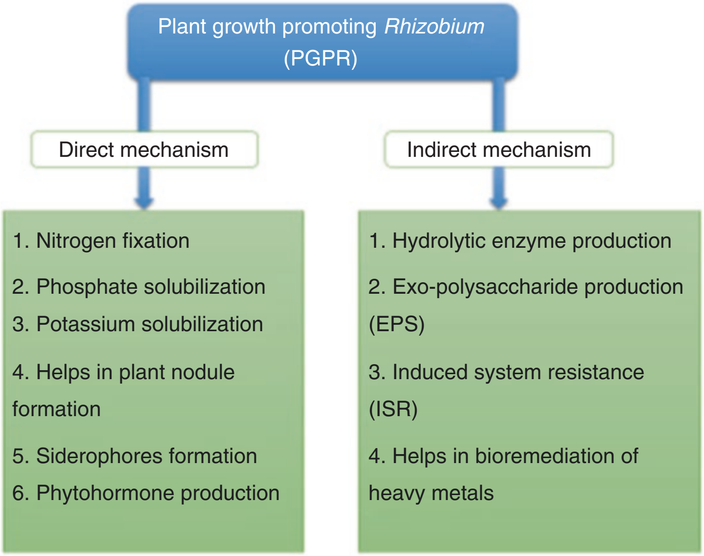

Fig. 2.1 Direct and indirect mode of action

2. PGPBs also promote plants' growth indirectly via different pathways, e.g. protecting against the deleterious effects of plant pathogens (Gamalero et al., 2009).

2.3.1 Direct Way

Nitrogen (N_2) fixation is the best-studied direct way of growth promotion in plants by PGPBs. Nitrogen belongs to the category of essential nutrient element for plants. Though the atmosphere contains 78% nitrogen as dinitrogen (N_2), plants cannot take up and use it in this form. The plant available forms (PAFs) of nitrogen are ammonia and nitrates mainly produced by microorganisms via biological nitrogen fixation (BNF). Plants can assimilate the nitrates and ammonia via assimilation pathways, i.e. ammonium assimilation and nitrate assimilation, respectively (Tairo & Ndakidemi, 2013). The nitrogen-fixing microorganisms (also called diazotrophs) possess a unique enzyme complex known as dinitrogenase which acts on atmospheric nitrogen and converts it into ammonia (Smith et al., 2013). Diazotrophs can be free-living and symbiotic. The symbiotic category includes *Rhizobiaceae* members that share a symbiosis with plants belonging to *Leguminosae* (Ahemad & Khan, 2012a, 2012b, 2012c, 2012d).

Symbiotic nitrogen-fixing rhizobacteria collectively called *Rhizobia*, e.g. *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azorhizobium* and *Mesorhizobium*, belong to the *Rhizobiaceae* (*Alphaproteobacteria*) family. They create a symbiotic relationship with their hosts (legumes) by infecting their roots. A complex interplay of chemical signalling between the host and symbiont is required to establish this relationship, which results in the root nodule formation *Rhizobia* resides intracellularly as symbiont (Allito et al., 2015). Simultaneously, the non-symbiotic nitrogen-fixing rhizobacteria form a non-obligatory relationship with the non-leguminous plants (Verma et al., 2010). All diazotrophs carry nitrogen fixation by a complex molybdenum-iron dinitrogenase system, consisting of dinitrogenase reductase with a cofactor of Fe (iron) and dinitrogenase with Fe and Mo (molybdenum) as its cofactors (Smith et al., 2013). However, many free-living bacteria like *A. vinelandii* contain iron-iron or vanadium-iron cofactors in response to molybdenum depletion. Ferredoxin reduces dinitrogenase reductase, which in turn reduces dinitrogenase, followed by reduction of dinitrogen (N_2) to ammonia (NH_3) (Santi et al., 2013). The genes responsible for nitrogen fixation are called Nif genes found in free-living and symbiotic nitrogen fixers (Black et al., 2012). *Nif* genes consist of two types of structural and regulatory genes. The former is responsible for Fe protein activation, biosynthesis of Fe-Mo cofactor and donation of electrons, and the latter accountable for enzyme functionality and synthesis (Ahemad & Kibret, 2014).

Maximum legume plants develop de novo lateral root organs to accommodate the symbiotic *Rhizobium*, called “root nodules”. The process of development of root nodules in legumes is an essential feature associated with nitrogen fixation. It involves de-differentiation of differentiated root cortical cells following bacterial infection to the roots. The de-differentiated cells then differentiate into root nodules harbouring the nitrogen-fixing microbes (Suzaki et al., 2015). The schematic representation of plant-bacteria interaction has been presented in Fig. 2.2.

For the proper formation of nodules, two regulatory events, viz. infection of bacteria in epidermis and organogenesis of the cortex’s nodule (Suzaki & Kawaguchi, 2014), must be well synchronized. Nod factors produced by rhizobia are chemically lipochoto-oligosaccharides which initiate the symbiotic relation between the

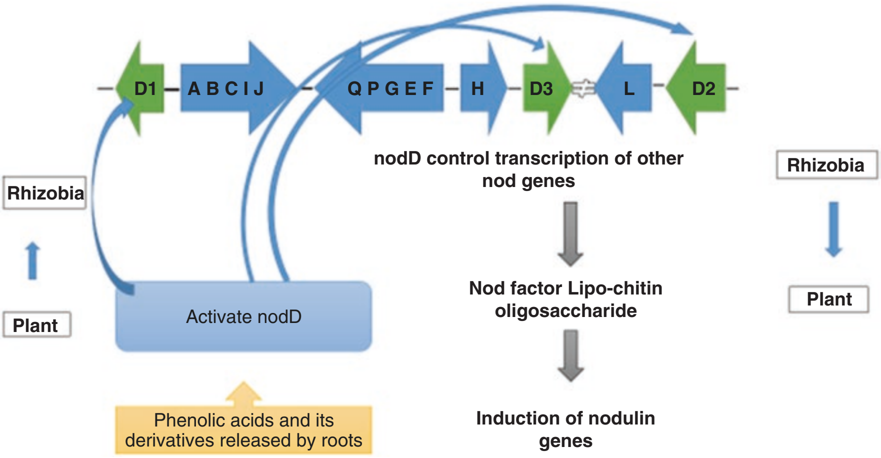

Fig. 2.2 Diagrammatic representation of plant-bacteria interaction

rhizobium and host plants (Maillet et al., 2011). The amount of plant ethylene has been reported to increase after the infection with *Rhizobium* spp., which prevents further rhizobial disease and nodule development (Abeles et al., 2012). Several rhizobial strains restrict the increase in ethylene production by synthesizing “rhizobitoxine”, a small molecule that inhibits the function of enzyme 1-aminocyclopropane-1-carboxylate (ACC) synthase – the main regulatory enzyme in the ethylene biosynthesis pathway (Nascimento et al., 2012). The limit on ethylene production because of rhizobitoxine causes an increase in the number of nodules formed on host plant roots and enhances symbiosis (Vijayan et al., 2013). Some rhizobial strains decrease the ethylene concentration by producing the enzyme ACC deaminase, which breaks down some ACC before its conversion to ethylene. This ethylene reduction results in increased formation of nodules and plant biomass by 25–40% (Zahir et al., 2011). About 10% of rhizobial strains in the field naturally have ACC deaminase, so the number of nodules formed by *Rhizobia* strains without ACC deaminase can be enhanced through transformation via genetic engineering (Glick, 2014). The same approach was used in the Sinorhizobium meliloti strain lacking this enzyme which was transformed with the ACC deaminase gene from *Rhizobium leguminosarum* bv. *viciae*. This transformation reportedly increased the number of nodules significantly by approximately 35% and the biomass of alfalfa by 40% compared to the control of wild strain (Glick, 2012, 2015).

Phytohormones produced and supplied by plant-associated microflora can stimulate growth and development in the host plant by modulating its endogenous hormone levels (Gray, 2004; Van Loon, 2007). Auxins (indole-3-acetic acid), gibberellins (GAs) and cytokinins are among the most significant plant growth regulators produced by associated microbes. It is reported that 80% of associated rhizospheric microbes of different crops synthesize auxins as their secondary metabolites (Ahemad & Khan, 2011). They do so through the tryptophan-dependent and tryptophan-independent pathways. The following three tryptophan-dependent auxin synthesis pathways are known:

(i) Indole-3-pyruvic acid (IPyA) pathway present in *Rhizobium*, *Bradyrhizobium* and *Azospirillum*
(ii) Indole-3-acetamide (IAM) pathway found in certain pathogenic bacteria such as *Pseudomonas syringae* and *Agrobacterium tumefaciens*
(iii) Tryptamine pathway found in species like *Bacillus megaterium* and *Bacillus licheniformis*

IAA from a rhizobacterial source has been recognized as the primary causal molecule of pathogenesis or phytostimulation (Ahemad & Khan, 2012b; Mahanty et al., 2017). In addition to IAA, cytokinin modulation is reported to be involved in phytostimulation. For example, enhancement of seedling growth in *Arabidopsis thaliana* and *Proteus vulgaris* has been reported via cytokinin synthesis by *Bacillus megaterium* (Ortíz-Castro et al., 2008). Diverse genera of bacteria like *Azospirillum*, *Bacillus*, *Klebsiella*, *Proteus*, *Pseudomonas*, *Xanthomonas*, etc. include well-characterized cytokinin-producing species. Besides cytokinin and ethylene, gibberellin (GA) production has also been observed in plant-associated bacteria and fungi. GA-producing bacteria are used to boost seed germination rate even though bacterial GA's precise function is not understood (Goswami et al., 2016).

2.3.2 Indirect Way

As mentioned above, PGPB may also indirectly promote the growth of plants with which they are associated, e.g. by reducing the adverse effects of pathogenic fungi or bacteria on plant growth and development. Scientists are also promoting the use of PGPB as an eco-friendly alternative to chemical fungicides.

Antibiotics
PGPBs protect plants from many pathogen attacks by producing antibiotics acting against the pathogens (mainly fungi). They make different antibiotics under different conditions, with many of them studied in detail. Some of these antibiotic-producing strains have also been commercialized. Scientists have also modified these antibiotic-producing strains of PGPBs to produce antibiotics under laboratory conditions (Devine et al., 2017).

Cell Wall-Degrading Enzymes
Some plants defend themselves against the pathogenic fungus by producing enzymes involved in cell wall degradation, e.g. such as chitinase, which hydrolyses chitin in the fungal cell wall. Similarly, some bacteria (used as biocontrol agents) produce enzymes like cellulases, chitinases, glucanases, lipases and proteases, which can degrade many pathogenic fungi's cell walls (Kim et al., 2015). Hence PGPBs control fungal diseases and prevent yield loss which is a promising and eco-friendly way.

Hydrogen Cyanide
Many PGPBs like *Rhizobium*, *Pseudomonas* and *Bacillus* produce hydrogen cyanide to control many diseases. The lower levels of hydrogen cyanide do not allow fungal pathogens to attack plants and enhance plants' resistance against the diseases. The hydrogen cyanide works by inhibiting the cytochrome-c oxidase and its other metabolites. Some bacteria also produce antibiotics and HCN that act synergistically against fungal pathogens and prevent the development of resistant pathogenic fungi (Olanrewaju et al., 2017; Ramette et al., 2006).

2.4 Methods of Application of Biofertilizers to Crops

2.4.1 Seed Treatment

In this method, selected biofertilizers are mixed with water and gently combined with the seed mass with the help of an adhesive like gum acacia, jiggery solution, etc.; however, before sowing, the seeds are shade dried on a clean sheet or piece of cloth.

2.4.2 *Seedling Root Dip*

In this method, selected biofertilizers are mixed with water, and the seedling roots are dipped in the mixture for about 8–10 hours before transplantation. This method is usually used for transplanting crops such as rice.

2.4.3 *Soil Treatment*

Recommended biofertilizers and compost are mixed in the ratio of 1:50 by weight and kept overnight. This mixture is mixed with soil at the time of sowing seeds or transplanting the seedlings.

2.5 The Role of Biofertilizers in the Alleviation of Environmental Stresses

Plants, being sessile, are vulnerable to a plethora of stress (abiotic and biotic) at any given instant, interrupting normal metabolism seen as abnormal physiology. During stress, the peculiar features in plants are the excessive formation of reactive oxygen species (ROS), which include both free radicals and non-radical molecules. These extreme ROS molecules damage cellular lipids, hence damaging cells, and cause metabolic disorders and variations in senescence. Several plant growth-promoting rhizobacteria (PGPR) are known to help plants alleviate stress. For example, rhizobacteria maintain the cytoplasmic osmolarity under drought stress by producing various osmolytes like glycine betaine, proline, ectoine, and trehalose. The production of glycine betaine helps plants tolerate droughts, frost and salinity stresses simultaneously.

As mentioned above, several rhizobacterial species may produce growth regulators like ethylene and cytokinin, thus promoting crop plants' growth under stress. *Pseudomonas alcaligenes*, *P. aureofaciens*, *P. aurantiaca* and *P. chlororaphis* have plant hormones under unfavourable conditions in saline arid soils (Verma et al., 2017; Yadav et al., 2018). Further, alleviation of heat stress in plants by cytokinin-producing PGPB was isolated from the rhizosphere's soil (Arkhipova et al., 2007). Liu et al. (2013) also reported that a cytokinin producer, *Bacillus subtilis*, improved the tolerance to drought stress. Forchetti et al. (2010) showed that *Bacillus pumilus* and *Achromobacter xylosoxidans* which are drought-tolerant endophytic bacterial strains produce salicylic acid. Similarly, inoculation with rhizobacterial strains enhances the growth parameters of sunflower under conditions of water stress.

Inoculation of cucumber plants with bacteria like *Pseudomonas fluorescens*, *P. extremorientalis*, *Stenotrophomonas rhizophila* and *Serratia plymuthica* increases dry weight appreciably up to 62% compared to the control. The improvement in growth and salt tolerance has been reported to be the IAA production under a salt environment. Further, the fruit yield of the cucumber was also enhanced under controlled conditions (Egamberdieva, 2011). Timmusk et al. (2014) showed that wheat treatment with PGPB under drought stress increased biomass to 78% higher than untreated plants. Enhanced biomass and root architecture modifications under drought stress were reported when inoculated with PGPB strain (Bresson et al., 2014) *Phyllobacterium brassicacearum* (STM196).

2.6 Some Factors Limiting the Use of Biofertilizers

- Lack of regulatory acts and facilities regarding testing of samples: One of the potential limitations to the use of fertilizers is a scarcity of facilities provided by institutions for testing biofertilizer samples. Further, there is a lack of government involvement in this area which is a potential eco-friendly alternative to chemical pesticides. In biofertilization, future research should be focused on options available to confront the issues and propose valid frameworks for the development of eco-friendly practices that allow advancement on the efficiency and subsequent supply of product for the industry in the global economies. Furthermore, their application's technical tests must authenticate their safe use at the worldwide level.
- Biofertilizers' insufficient popularization and low level of farmer acceptance: Among farmers, biofertilizers have not gained the required popularity. However, it comes with various potential benefits for crops, especially under stresses. This non-acceptance seems to be the lack of awareness among the farmers compared to their synthetic counterparts. Other problems such as lack of timely financing, experts' involvement and biofertilizers' non-availability also hinder their popularity and acceptance.

2.7 Conclusions

Biofertilizers form a significant component of organic farming in modern agricultural practices in terms of being a sustainable alternative to chemical fertilizers, linked with various environmental hazards. However, to popularize the biofertilizers' status, increased demand and awareness about its uses are yet to be created. Biofertilizer technology, a significant part of sustainable agriculture, has to be proper for farmers' and planters' social and infrastructural situations. It should be economically feasible for all farmers, renewable, adaptable to prevailing local conditions and satisfactory from the society's cultural patterns, practically implementable and productive.

Acknowledgement The authors are thankful to the University Grants Commission for providing fellowship to corresponding author and grateful to the Department of Botany, the University of Kashmir, for sharing their facilities and those who made their literature available for the compilation of this manuscript.

References

A, B., Ak, M., M, G., G, G., P, P., … B, J. (2009). Biofertilizers: A novel tool for agriculture. *International Journal of Microbiology Research, 1*(2), 23–31. https://doi.org/10.9735/0975-5276.1.2.23-31

Agarwal, P., Gupta, R., & Gill, I. K. (2018). Importance of biofertilizers in agriculture biotechnology. *Annals of Biological Research, 9*(3), 1–3.

Ahemad, M., & Khan, M. S. (2011). Effects of insecticides on plant-growth-promoting activities of phosphate solubilizing rhizobacterium Klebsiella sp. strain PS19. *Pesticide Biochemistry and Physiology, 100*(1), 51–56. https://doi.org/10.1016/j.pestbp.2011.02.004

Ahemad, M., & Khan, M. S. (2012a). Effects of pesticides on plant growth promoting traits of Mesorhizobium strain MRC4. *Journal of the Saudi Society of Agricultural Sciences, 11*(1), 63–71. https://doi.org/10.1016/j.jssas.2011.10.001

Ahemad, M., & Khan, M. S. (2012b). Effect of fungicides on plant growth promoting activities of phosphate solubilizing Pseudomonas putida isolated from mustard (Brassica compestris) rhizosphere. *Chemosphere, 86*(9), 945–950. https://doi.org/10.1016/j.chemosphere.2011.11.013

Ahemad, M., & Khan, M. S. (2012c). Ecological assessment of biotoxicity of pesticides towards plant growthpromoting activities of pea (Pisum sativum)-specific rhizobium SP. STRAINMRP1. *Emirates Journal of Food and Agriculture*, 334–343.

Ahemad, M., & Khan, M. S. (2012d). Evaluation of plant-growth-promoting activities of rhizobacterium Pseudomonas putida under herbicide stress. *Annals of Microbiology, 62*(4), 1531–1540. https://doi.org/10.1007/s13213-011-0407-2

Ahemad, M., & Kibret, M. (2014). Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. *Journal of King Saud University – Science, 26*(1), 1–20. https://doi.org/10.1016/j.jksus.2013.05.001

Ahmed, M. A., Ahmed, A. G., Mohamed, M. H., & Tawfik, M. M. (2011). Integrated effect of organic and biofertilizers on wheat productivity in new reclaimed sandy soil. *Research Journal of Agriculture and Biological Sciences, 7*(1), 105–114.

Allito, B. B., Nana, E. M., & Alemneh, A. A. (2015). Rhizobia strain and legume genome interaction effects on nitrogen fixation and yield of grain legume: A review. *Molecular Soil Biology, 6*. https://doi.org/10.5376/msb.2015.06.0004

Arkhipova, T. N., Prinsen, E., Veselov, S. U., Martinenko, E. V., Melentiev, A. I., & Kudoyarova, G. R. (2007). Cytokinin producing bacteria enhance plant growth in drying soil. *Plant and Soil, 292*(1–2), 305–315. https://doi.org/10.1007/s11104-007-9233-5

Barragán-Ocaña, A., & Del-Valle-Rivera, M. D. C. (2016). Rural development and environmental protection through the use of biofertilizers in agriculture: An alternative for underdeveloped countries? *Technology in Society, 46*, 90–99. https://doi.org/10.1016/j.techsoc.2016.06.001

Bashan, Y. (1993). Potencial use of Azospirillum as biofertilizer. *Turrialba, 43*, 286–286.

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories, 13*(1), 66. https://doi.org/10.1186/1475-2859-13-66

Black, M., Moolhuijzen, P., Chapman, B., Barrero, R., Howieson, J., Hungria, M., & Bellgard, M. (2012). The genetics of symbiotic nitrogen fixation: Comparative genomics of 14 rhizobia strains by resolution of protein clusters. *Genes, 3*(1), 138–166. https://doi.org/10.3390/genes3010138

Blake, F. (1993) In: Cartwright (Ed.). *Organic food production. In-world Agriculture* (pp. 22–24). Hong Kong: Strerling Publication Ltd.

Bresson, J., Vasseur, F., Dauzat, M., Labadie, M., Varoquaux, F., Touraine, B., & Vile, D. (2014). Interact to survive: Phyllobacterium brassicacearum improves Arabidopsis tolerance to severe water deficit and growth recovery. *PLOS ONE, 9*(9), e107607. https://doi.org/10.1371/journal.pone.0107607

Calabi-Floody, M., Medina, J., Rumpel, C., Condron, L. M., Hernandez, M., Dumont, M., & Mora, MDLL. (2018). Smart fertilizers as a strategy for sustainable agriculture. In *Advances in Agronomy* (p. 147). Academic Press. https://doi.org/10.1016/bs.agron.2017.10.003

Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. *Plant and Soil, 383*(1–2), 3–41. https://doi.org/10.1007/s11104-014-2131-8

Campos, E. V. R., Proença, P. L. F., Oliveira, J. L., Bakshi, M., Abhilash, P. C., & Fraceto, L. F. (2019). Use of botanical insecticides for sustainable agriculture: Future perspectives. *Ecological Indicators, 105*, 483–495. https://doi.org/10.1016/j.ecolind.2018.04.038

Devine, A., Harvey, R., Min, A. M., Gilder, M. E. T., Paw, M. K., Kang, J., … McGready, R. (2017). Strategies for the prevention of perinatal hepatitis B transmission in a marginalized population on the Thailand-Myanmar border: A cost-effectiveness analysis. *BMC Infectious Diseases, 17*(1), 552. https://doi.org/10.1186/s12879-017-2660-x

Döbereiner, J. (1997). A importância da fixação biológica de nitrogênio para a agricultura sustentável. *Biotecnologia Ciência*, 2–3.

Egamberdieva, D. (2011). Survival of Pseudomonas extremorientalis TSAU20 and P. chlororaphis TSAU13 in the rhizosphere of common bean (Phaseolus vulgaris) under saline conditions. *Plant, Soil and Environment, 57*(3), 122–127. https://doi.org/10.17221/316/2010-PSE

Ei-Lattief, E. A. (2016). Use of Azospirillum and Azobacter bacteria as biofertilizers in cereal crops: A review. *International Journal of Research in Engineering and Applied Sciences (IJREAS), 6*(7), 36–44.

Forchetti, G., Masciarelli, O., Izaguirre, M. J., Alemano, S., Alvarez, D., & Abdala, G. (2010). Endophytic bacteria improve seedling growth of sunflower under water stress, produce salicylic acid, and inhibit growth of pathogenic fungi. *Current Microbiology, 61*(6), 485–493. https://doi.org/10.1007/s00284-010-9642-1

Gamalero, E., Lingua, G., Berta, G., & Glick, B. R. (2009). Beneficial role of plant growth promoting bacteria and arbuscular mycorrhizal fungi on plant responses to heavy metal stress. *Canadian Journal of Microbiology, 55*(5), 501–514. https://doi.org/10.1139/w09-010

García-Fraile, P., Menéndez, E., & Rivas, R. (2015). Role of bacterial biofertilizers in agriculture and forestry. *AIMS Bioengineering, 2*(3), 183–205. https://doi.org/10.3934/bioeng.2015.3.183

Goldstein, A. H. (1986). Bacterial solubilization of mineral phosphates: Historical perspective and future prospects. *American Journal of Alternative Agriculture, 1*(2), 51–57. https://doi.org/10.1017/S0889189300000886

Goswami, D., Thakker, J. N., & Dhandhukia, P. C. (2016). Portraying mechanics of plant growth promoting rhizobacteria (PGPR): A review. *Cogent Food and Agriculture, 2*(1). https://doi.org/10.1080/23311932.2015.1127500. PubMed: 1127500

Gray, W. M. (2004). Hormonal regulation of plant growth and development. *PLOS Biology, 2*(9), E311. https://doi.org/10.1371/journal.pbio.0020311

Hervé, M., Albert, C. H., & Bondeau, A. (2016). On the importance of taking into account agricultural practices when defining conservation priorities for regional planning. *Journal for Nature Conservation, 33*, 76–84. https://doi.org/10.1016/j.jnc.2016.08.001

Jaga, P. K., & Singh, V. (2010). Effect of biofertilizer, nitrogen and sulphur on sorghum-mustard cropping system. In *Proceedings of the National Seminar on Soil Security for Sustainable Agriculture Held at College of Ariculture, Nagypur (MS on February 27–28, 2010) "XXII SAVETOVANJE O BIOTEHNOLOGIJI"* (p. 1).

Jehangir, I. A., Mir, M. A., Bhat, M. A., & Ahangar, M. A. (2017). Biofertilizers an approach to sustainability in agriculture: A review. *International Journal of Pure and Applied Bioscience, 5*(5), 327–334. https://doi.org/10.18782/2320-7051.5011

Kaur, R., Kaur, M., & Purewal, S. S. (2018). Effect of incorporation of flaxseed to wheat rusks: Antioxidant, nutritional, sensory characteristics, and in vitro DNA damage protection activity. *Journal of Food Processing and Preservation, 42*(4), e13585. https://doi.org/10.1111/jfpp.13585

Kim, J. S., Lee, J., Lee, C. H., Woo, S. Y., Kang, H., Seo, S. G., & Kim, S. H. (2015). Activation of pathogenesis-related genes by the rhizobacterium, Bacillus sp. JS, which induces systemic resistance in tobacco plants. *Plant Pathology Journal, 31*(2), 195–201. https://doi.org/10.5423/PPJ.NT.11.2014.0122

Kumar, R., Kumawat, N., & Sahu, Y. K. (2017). Role of biofertilizers in agriculture. *Pop Kheti, 5*(4), 63–66.

Laranjo, M., Alexandre, A., & Oliveira, S. (2014). Legume growth-promoting rhizobia: An overview on the Mesorhizobium genus. *Microbiological Research, 169*(1), 2–17. https://doi.org/10.1016/j.micres.2013.09.012

Liu, J., Mehdi, S., Topping, J., Friml, J., & Lindsey, K. (2013). Interaction of PLS and PIN and hormonal crosstalk in Arabidopsis root development. *Frontiers in Plant Science, 4*, 75. https://doi.org/10.3389/fpls.2013.00075

Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., & Tribedi, P. (2017). Biofertilizers: A potential approach for sustainable agriculture development. *Environmental Science and Pollution Research International, 24*(4), 3315–3335. https://doi.org/10.1007/s11356-016-8104-0

Motsara, M. R., Bhattacharyya, P., & Srivastava, B. (1995). Biofertiliser technology, marketing and usage: A sourcebook-cum-glossary. *Fertiliser Development and Consultation Org.*

Odame, H. (1997). Biofertilizer in Kenya: Research, production and extension dilemmas. *Biotechnology and Development Monitor, 30*, 20–23.

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*(11), 197. https://doi.org/10.1007/s11274-017-2364-9

Ortíz-Castro, R., Valencia-Cantero, E., & López-Bucio, J. (2008). Plant growth promotion by Bacillus megaterium involves cytokinin signaling. *Plant Signaling and Behavior, 3*(4), 263–265. https://doi.org/10.4161/psb.3.4.5204

Pandey, G. (2018). Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. *Environmental Technology and Innovation, 11*, 299–307. https://doi.org/10.1016/j.eti.2018.06.012

Ramette, A., Moënne-Loccoz, Y., & Défago, G. (2006). Genetic diversity and biocontrol potential of fluorescent pseudomonads producing phloroglucinols and hydrogen cyanide from Swiss soils naturally suppressive or conducive to Thielaviopsis basicola-mediated black root rot of tobacco. *FEMS Microbiology Ecology, 55*(3), 369–381. https://doi.org/10.1111/j.1574-6941.2005.00052.x

Rao, D. L. N. (1986). Nitrogen fixation in free living and associative symbiotic bacteria. In *Soil microorganisms and plant growth* (pp. 116–140). Oxford and IBH Publishing.

Reinhold, B., & Hurek, T. (1989). Location of diazotrophs in the root interior with special attention to the kallar grass association. In *Nitrogen Fixation with Non-Legumes* (pp. 209–218). Springer.

Santi, C., Bogusz, D., & Franche, C. (2013). Biological nitrogen fixation in non-legume plants. *Annals of Botany, 111*(5), 743–767. https://doi.org/10.1093/aob/mct048

Singh, S., Singh, B. K., Yadav, S. M., & Gupta, A. K. (2014). Potential of biofertilizers in crop production in Indian agriculture. *American Journal of Plant Nutrition and Fertilization Technology, 4*(2), 33–40. https://doi.org/10.3923/ajpnft.2014.33.40

Smith, B. E., Richards, R. L., & Newton, W. E. (Eds.). (2013). *Catalysts for nitrogen fixation: Nitrogenases, relevant chemical models and commercial processes, 1*. Springer Science+Business Media.

Sundaram, S., Arunakumari, A., & Klucas, R. V. (1988). Characterization of azospirilla isolated from seeds and roots of turf grass. *Canadian Journal of Microbiology, 34*(3), 212–217. https://doi.org/10.1139/m88-040

Tairo, E. V., & Ndakidemi, P. A. (2013). Possible benefits of rhizobial inoculation and phosphorus supplementation on nutrition, growth and economic sustainability in grain legumes. *American Journal of Research Communication, 1*(12), 532–556.

Timmusk, S., Abd El-Daim, I. A., Copolovici, L., Tanilas, T., Kännaste, A., Behers, L., … Niinemets, Ü. (2014). Drought-tolerance of wheat improved by rhizosphere bacteria from harsh environments: Enhanced biomass production and reduced emissions of stress volatiles. *PLOS ONE, 9*(5), e96086. https://doi.org/10.1371/journal.pone.0096086

Umesha, S., Manukumar, H. M., & Chandrasekhar, B. (2018a). Sustainable agriculture and food security. In *Biotechnology for sustainable agriculture* (pp. 67–92). Woodhead Publishing.

Umesha, S., Singh, P. K., & Singh, R. P. (2018b). Microbial biotechnology and sustainable agriculture. In *Biotechnology for sustainable agriculture* (pp. 185–205). Woodhead Publishing.

Uosif, M. A. M., Mostafa, A. M. A., Elsaman, R., & Moustafa, E. S. (2014). Natural radioactivity levels and radiological hazards indices of chemical fertilizers commonly used in Upper Egypt. *Journal of Radiation Research and Applied Sciences, 7*(4), 430–437. https://doi.org/10.1016/j.jrras.2014.07.006

Van Loon, L. C. (2007). Plant responses to plant growth-promoting rhizobacteria. *European Journal of Plant Pathology. Dordrecht: Springer, 119*(3), 243–254. https://doi.org/10.1007/s10658-007-9165-1

Verma, P., Yadav, A. N., Kumar, V., Singh, D. P., & Saxena, A. K. (2017). Beneficial plant-microbes interactions: Biodiversity of microbes from diverse extreme environments and its impact for crop improvement. In *Plant-microbe interactions in agro-ecological perspectives* (pp. 543–580). Springer.

Verma, J. P., Yadav, J., Tiwari, K. N., & Singh, V. (2010). Impact of plant growth promoting rhizobacteria on crop production. *International Journal of Agricultural Research*, *5*(11), 954–983. https://doi.org/10.3923/ijar.2010.954.983

Wang, H. Y., Liu, S., Zhai, L. M., Zhang, J. Z., Ren, T. Z., Fan, B. Q., & Liu, H. B. (2015). Preparation and utilization of phosphate biofertilizers using agricultural waste. *Journal of Integrative Agriculture, 14*(1), 158–167. https://doi.org/10.1016/S2095-3119(14)60760-7