3 Is PGPR an Alternative for NPK Fertilizers in Sustainable Agriculture?

Éva Laslo and Gyöngyvér Mara

3.1 Sustainable Agriculture and Environmental Problems of Current Fertilizing Methods

Agricultural production as a user of natural resources has a significant influence on the state of the environment. In agricultural practice, focus has shifted to its environmental impact and effect on the population's wellbeing and living standards. This concept of sustainable agriculture was formulated as the main challenge globally. The rapid population growth of the earth has given rise to major concerns about the food supply. It is expected that the global population will increase from 7.2 to 9.6 billion by 2050. If the consumption habits remain unchanged, the lands used for crop production and production efficiency have to be increased. This phenomenon gives rise to concern about maintaining the world ecosystem functions and services. The solution relies on the development and innovation of sustainable agriculture, which achieves crop production without polluting the environment and causing damage. The origin of the word "sustain," is derived from the Latin word *sustinere*, having the meaning of maintain, long-term support or permanence.

Considering agriculture, sustainable farming systems describe the management systems that are able to maintain their productivity and their benefits to society for an indefinite period of time. This agricultural system must be a resource preserver, socially encouraging, economically competitive, and environmentally friendly (Valkó 2017).

The phrase "Sustainable agriculture" became known in literature in the 1980s, when the Worldwatch Institute published a work on sustainable societies. In 1990, the Senate of the United States Congress introduced the Sustainable Agriculture Research and Education Act, which dealt with developing technical guides for

É. Laslo · G. Mara (✉)
Faculty of Economics, Socio-Human Sciences and Engineering,
Department of Bioengineering, Sapientia Hungarian University of Transylvania,
Miercurea Ciuc, Romania
e-mail: maragyongyver@uni.sapientia.ro

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low-input sustainable agricultural production methods and initiation of a national training program in sustainable agriculture. It was defined that sustainable agriculture comprises crop and livestock production in an integrated system with site-specific application and durability. Regarding the definition, this system provides humanity with food. It contributes to the enhancement of environmental quality, natural resources, and society. The nonrenewable materials are used as effectively as possible, combining the natural biological cycles and controls. It also maintains the economic viability of agricultural operations (Gold 2016).

One of the concerns of modern agricultural practice is ecological worry. This includes the deterioration of soil productivity, desertification, water pollutants, such as fertilizers, eutrophication, etc. In sustainable agroecosystems, it is emphasized to keep the natural resource base and to depend on the minimum use of artificial inputs outside the agricultural system (Itelima et al. 2018).

The supply of necessary nutrients is one of the major challenges of agricultural production. The traditional chemical forms of fertilizers used in plant production result in significant growth of the crops. In general, farmers use an overdose of fertilizers to maximize crop production. Approximately 50–70% of conventional fertilizers used are lost in the environment, and the consequences are the negative impact on the environment (eutrophication, water and soil contamination) and health. For example, the nitrite with other pollutants can disturb the nervous system, cause heart diseases, and different types of cancer. The fertilizer industry uses a very high amount of energy for the production of these compounds (Singh et al. 2017).

Common practice for enhancement of cultivated crop production is the use of different forms of fertilizer. For the N supply, urea, ammonium nitrate, diammonium phosphate, etc., are used (Hermary 2007). The exaggerated treatment of plants with N fertilizers contributes to the increase of root biomass. Owing to this fact, a high absorption of the other nutrients can occur, resulting in a lack of micronutrients in the soil. Because nitrate is absorbed by plants in the fast growing stage, the soil may release significant amounts of it. This results in nitrogen loss. Another negative impact of N fertilizer is on global warming, due to the ammonia and NOx gases. It was shown that the use of various fertilizers (P_2O_5, K_2O, urea) for cereal crops resulted in leaching NO_3^-, loses of phosphorus, nitrogen, and ammonia volatilization.

Phosphorus is an essential macronutrient and also one of the major limiting factors in crop production. A large amount of phosphorus exists in soils in an immobilized form that is unavailable for plants, and therefore chemical fertilization is used. P fertilizer is taken out from P-rich rock in the form of phosphate, which is a finite resource (Karamesouti and Gasparatos 2017). It was evaluated that 5.7 billion hectares of land throughout the world are deficient in P, which underlines the importance of phosphorus as a limiting factor (Granada et al. 2018). Owing to the high rate of added phosphorus immobilization in soil from fertilization in agricultural, routinely, twice as much or more P fertilizers are used than needed. It was also estimated that annual P utilization will increase yearly by 2.5% (Sattari et al. 2012). Besides the fact that fertilizers are expensive and need finite resources, they are also harmful to the environment, soil structure, properties, composition, and microbiota (White 2008). As an alternative solution, natural phosphate rocks used in combination with phosphate solubilization bacteria (PSB) under field conditions can be used as P fertilizers (Kaur and Reddy 2015).

Globally, potassium represents the seventh most abundant element that occurs in the earth's crust. The different forms of potassium in the soil are: mineral K, exchangeable K, non-exchangeable K, and dissolved K^+ ions. From this, plants can reach only 1–2% in the form of solution and exchangeable K. This mineral is essential for plants because it is involved in different growth and development mechanisms and takes part in cell membrane function. The forms of potassium found as minerals are potassium sulfate or chloride. In agricultural production, it is used as potassium sulfate, in most cases under the name of potash or arcanite. The negative impact of the use of the mined form is that it can easily leach. The consequence of K leaching is its accumulation in different aquatic ecosystems harboring the vegetation (Meena et al. 2016).

In agricultural practice, the expanded use of chemical fertilizers has contributed to the deterioration of water and soil and caused irreversible impacts on the biosphere too. Many researchers emphasize that the solution lies in sustainable resource management. One possible measure is the use of biofertilizers to reduce the negative impact of synthetic manures. These microbial products can contribute to plant nutrient acquisition without the depletion of natural resources (Verma et al. 2018).

3.2 Role of Bacteria in Nutrient Management of Plants

3.2.1 Plant Nutrition Requirements

There are 13 essential mineral elements divided into major elements and micronutrients based on the concentration needed by the plant. The majority of elements are primarily taken up by the root transport system in ionic form, other elements, such as C, H, and O from water and air.

Nitrogen is found in both organic and inorganic form in plants, with predominantly organic prevalence, comprising amino-acids, enzymes, nucleic acids, chlorophyll, and alkaloids. Nitrogen in inorganic form (NO_3^-) can accumulate in plant tissues. The nitrogen content of plants varies between 0.5% and 5% of the dry weight. N is available for root absorption either as NO_3^- or NH_4^+. NO_3^- moves in the soil basically by mass flow, while NH_4^+ by diffusion, and they are absorbed at the root surface. Uptake of NO_3^- stimulates the uptake of cations, while uptake of NH_4^+ restricts cations.

Phosphorus is the component of phospholipids, proteins, nucleic acids, adenosine triphosphate (energy providing molecule), and phytin. The phosphorus content of plants varies between 0.1% and 0.5% of the dry weight, and it is present in soil in organic (50–70% of total P content, in the form of phytin) and inorganic (30–50% of total P content, in the form of Al, Fe, and Ca phosphates) form. It is available for root absorption in $H_2PO_4^-$ and HPO_4^{2-} anionic forms, moves in the soil primarily by diffusion and root hair abundance increases the opportunity of P uptake (Lambers et al. 2006).

Potassium has as major function in the plant water status and cell turgor pressure maintenance and is involved in stomatal functioning. It is also required for carbohydrate accumulation and translocation as well as for enzyme activation. The potassium content of plants varies between 0.5% and 5% of dry weight. Potassium moves in the soil mostly by diffusion and partially by mass flow, and it is absorbed as K^+ cation. The root density and soil oxygen has a notable effect on its uptake.

3.2.2 Plant Main Mechanisms of Nutrient Acquisition

The uptake of soil nutrients is affected by several factors, such as soil properties and nutrient content, plant root properties (size, architecture, morphology, substance release), and rhizosphere microorganisms. Plant roots forage for nutrients. Transport from soil to root is realized through mass flow, diffusion or root interception. The uptake of nutrients occurs through membrane transporter proteins on the root surface. Owing to the continuous uptake, nutrient concentration on the root surface is decreased, generating a concentration gradient from soil to root surface. Plants differ in nutrient uptake capacity, but there is a clear correlation between root hair development and plant nutritional level in the case of nitrate, phosphate, and potassium; the uptake being facilitated by root length and volume. Different mechanisms play a role in N, P, and K uptake (Jungk 2001).

Nitrogen from soil is available for plants in organic (urea, amino acids, and small peptides) and inorganic (nitrate and ammonium) form, but the organic forms contribute to plant N nutrition only in special environments, and therefore the inorganic forms are considered universal. The acquisition of nitrogen depends on the root architecture and uptake activity through plasma membrane. High affinity transporters and low affinity transporters are located in the plasma membrane, serving nutrient uptake. The two types of transporters were developed because of the large variation in nitrate concentration, low affinity when external nitrate concentration is high and high affinity when nitrate concentration is low in the cell external environment. Nitrate uptake is realized through NPF (nitrate transporter 1/peptide transporter family) and NRT2 (nitrate transporter 2) transporter proteins. NPF transporter proteins have low affinity for nitrate, whereas NRT2 transporter proteins are high affinity transporters (Pii et al. 2015). The members of the latter protein family for nitrate transport require another NAR2 protein. Experimental data shows that, in the case of Arabidopsis plants, NRT2 transporters (consisting of seven different genes) accounted for 95% of high-affinity nitrate influx; some of the proteins being involved in nitrate uptake from soil (*AtNRT2.4* and *AtNRT2.5* genes were expressed), whereas others in apoplastic transport (*AtNRT2.1* gene was expressed) (Kiba and Krapp 2016).

Ammonium transport is mediated by the AMT transporter superfamily encoding high affinity ammonium transporters. In Arabidopsis, six AMT genes exist, three encoding transporters that absorb ammonium by a direct route from soil and one encoding apoplastic transporter (Kiba and Krapp 2016).

The nutrient uptake can also be modulated by root growth and development, when under mild nitrogen limitation the increased absorptive surface and scavenging root system make it possible for the plants to adapt to nutrient availability.

Phosphorus is obtained in the form of inorganic phosphate (Pi) in the form of several cations (PO_3^{-4}, HPO_2^{-4}, H_2PO^{-4}) depending on the pH. The most easily accessed form of P for plants is H_2PO^{-4}. Inorganic phosphate uptake is an energy mediated process realized through phosphate/H^+ symporter. These membrane proteins are included in phosphate transporter (PT), among which the PHT1 family (phosphate transporter 1) is the most studied (Nussaume et al. 2011). PHT1 are highly expressed in roots and comprise nine members in *Arabidopsis thaliana*. Phosphate transporter genes are transcriptionally induced under Pi starvation condition (Gu et al. 2016).

Potassium is essential for many physiological processes in the plants; therefore, the concentration in the cytosol is maintained within the 100–200 mM range. Potassium is absorbed as K^+ anion through high and low affinity mechanisms depending on external concentration. In the case of high external potassium concentration, K^+ uptake is passive and is realized through membrane channels, whereas in the case of low external potassium concentration, the high affinity uptake is mediated by H^+/K^+ symporter (Nieves-Cordones et al. 2014). These two systems were described in *Arabidopsis thaliana*, where the passive membrane transport is realized through the inward-rectifier K^+ channel (AKT1), whereas in the case of low K^+ concentration the high affinity K^+ transporter (AtHAK5) is involved in potassium uptake (Ródenas et al. 2017). In the case of high external K^+ concentration, it was observed that non-selective cation channels sensitive to Ca^{2+}can also contribute to potassium uptake.

3.2.3 Role of PGP Bacteria in Plant Nutrient Management

Nitrogen, phosphorus, and potassium uptake by roots is strictly dependent on their availability in soil. Plant roots in addition to water and nutrient uptake also synthetize and secrete diverse compounds called root exudates that act as chemical attractants for soil microbes. These chemical compounds regulate the rhizosphere microbial community. The biogeochemical cycles of major nutrients are mainly managed by microbial processes. The rhizosphere bacteria therefore affect the nutritional and physiological status of plants (Ahemad and Kibret 2014; Sahu et al. 2018).

Rhizobacteria can alter nitrogen availability in soil through several processes, such as soil organic matter decomposition, atmospheric N_2 fixation, nitrification, and denitrification. Owing to the fact that the total nitrogen in soil is present mainly in organic form (90%), which is unavailable to the plants, the role of the rhizosphere bacteria in soil organic matter mineralization is important. Proteins, nucleic acids, and other organic compounds containing N are decomposed and transformed into the plant available form as ammonia through the process called ammonification.

Another microbial process that plays a role in plant nitrogen management is the biological nitrogen fixation by diazotrophs, when the atmospheric N_2 is turned into plant-utilizable forms. The biological nitrogen fixation can be realized by free-living diazotrophs (*Cyanobacteria, Proteobacteria, Archaea,* and *Firmicutes*) not associated with plants and by symbiotic diazotrophs (*Rhizobium* and *Bradyrhizobium* in the case of legumes, *Frankia*, *Nostoc, Azolla* in the case of non-legumes). In the biological nitrogen fixation process, the atmospheric N_2 is transformed into ammonia by the microorganisms using the nitrogenase enzyme system, found in both free-living and symbiotic systems. Nitrogenase genes (*nif*) are found in a cluster of seven operons, including structural genes, regulatory genes for the synthesis of enzymes, and others important for functioning, encoding 20 different proteins (Saha et al. 2017).

Nitrification processes are realized by *Nitrosococcus* and *Nitrobacter* bacteria that transform soil ammonia into a plant available form in nitrite (NO_2^-) and nitrate (NO_3^-). Through denitrification, nitrites and nitrates are converted by denitrifying bacteria (for example *Pseudomonas, Paracoccus, Alcaligenes, Bacillus*) back to gaseous form (NO_x). The presence of NO_x in the soil can trigger plant growth and development and also has a positive impact on root acquisition processes (Takahasi and Morikawa 2014).

Rhizobacteria, besides nutrient mobilization, can also enhance the nutrient uptake of the plant. In the case of maize, a single inoculation with *Bacillus sp*., *Acinetobacter sp.,* and *Klebsiella sp*. notably increased the N uptake of the plant; in early growth, the majority of N was assimilated from soil urea source, while in later growth through N fixation (Kuan et al. 2016). *Achromobacter sp*. were also reported as enhancers of NO_3^- uptake in *Brassica napus*. In *Arabidopsis thaliana* seedlings, the inoculation with *Phyllobacterium brassicacearum* increased the NO_3^- uptake in the first period, but decreased after 7 days. Data regarding the role of PGP rhizobacteria in altering NO_3^- uptake across the root plasma membrane are still contradictory. Information about the role of plant growth promoting rhizobacteria on the plant acquisition of NH_4^+ and urea is scarce. In the case of *Cucurbita moschata,* it was observed that the plants supplemented with NO_3^+, NH_4^+, and NO_3NH_4 and inoculated with bio-inoculant (Bionutrients AG 8-1-9, containing the mixture of *Bacillus subtilis, B. amyloliquefaciens, B. pumilus, B. licheniformis,* and *Saccharomyces cerevisiae*) showed an increase in biomass and N, P, K, and Mn concentration in leaves (Tchiaze et al. 2016).

Phosphorus is present in soil as phosphates in organic form as phytic acid and inorganic form bound to Fe, Al, and Ca that reduces its solubility. In addition, the application of fertilizers applied as inorganic phosphates are 75% immobilized in soil, and therefore they cannot solve the plant nutritional problem (Tóth et al. 2014). Less than 5% of soil P is taken up by plants in the form of HPO_4^{2-} and H_2PO_4. Phosphate solubilizing bacteria (PSB) provide soluble phosphate for plants mainly due to the presence of low molecular weight organic acids (gluconic acid, citric acid), whereas plants supply bacteria with carbon compounds for their growth. Low molecular weight organic acids through ligand exchange desorb phosphate, and once released it is available for plants. Besides the increased phosphate availability, PGP rhizobacteria can enhance the phosphate uptake of the plants by stimulating the plasma membrane H^+-ATP-ase in plant roots (Pii et al. 2015). Soil microbes beside organic acids can also produce enzymes, such as phosphatases and phytases, in soil releasing phosphates. Soil bacteria belonging to *Aerobacter, Acinetobacter, Acromobacter, Agrobacterium, Azospirillum, Azotobacter, Bacillus, Burkholderia, Enterococcus, Enterobacter, Erwinia, Flavobacterium, Micrococcus, Pantoea, Pseudomonas, Rhizobium,* and *Serratia* genera were described as having phosphate solubilizing activity (Anzuay et al. 2015; Pii et al. 2015).

Potassium uptake can be modified by K-solubilizing microbes that excrete low molecular organic acids, mainly citric, oxalic, tartaric, succinic acids, but production of ferulic, coumaric, syringic, and malic acid was also reported. Organic acids dissolute K+ from minerals by lowering pH (acidolysis) and forming metal-organic complexes with Si^{4+} ion and bringing the K into solution. Biofilms, capsular polysaccharides, polymers, and low molecular weight ligands produced by soil microbiota are able to mobilize potassium through the weathering process (Ahmad et al. 2016).

Since molecular fingerprinting is used in microbial community analysis, the ability of plants to select species specific microbiome was demonstrated (Pii et al. 2015). The composition of root exudates (low and high molecular weight organic compounds) varies among plant species and with environmental factors. These exudates (mainly low molecular weight) are an accessible C source for microbes and act as chemoattractants, and therefore the microbes are more abundant in the root proximity. Plant and bacteria communicate in the rhizosphere through complex signals, and as a result of this communication, the type of relationship is settled (detrimental, neutral or beneficial). In this context, rhizosphere bacteria that play an important role in plant nutrient acquisition processes depend on plant species and genotype, plant-microbe communication, and environmental conditions (Miransari 2014; Rosier et al. 2018).

3.3 PGPR as Bio Inoculants in Practical Use

In integrated nutrient management, the use of bio-inoculants is spreading. Bio-inoculants are based on selected bacterial strains that increase access to the inaccessible nutrient for plant growth and development. They also contribute to the improvement of soil sustainability and productivity and are, therefore, considered a tool for green agriculture. It was reported that the market of microbial inoculants worldwide will increase from $440 million in 2012 to $1295 million by 2020 (Owen et al. 2015). Microbial inoculants are applied to host plant surface, seed or soil. After colonizing the environment, they can exert their effect. Depending on their mechanism – contributing to the availability of nutrients – they can be grouped as nitrogen fixers (N-fixer), potassium and phosphorus solubilizers. In agricultural systems, different bacterial formulations are applied as bio-inoculants based on nitrogen fixing and phosphorus and potassium solubilizing microorganisms. It was revealed that single strains also exert beneficial effects, but mixed inoculants are more productive and effective.

Through biological nitrogen fixation, different microorganisms use their complex enzyme systems to transform atmospheric N into an assimilable N form, such as ammonia. The efficiency of this process is affected by different factors, such as climatic, soil or host genotype or the complex host bacteria interaction. It was revealed that the efficiency of legume–rhizobia symbiosis with approximately 13–360 kg N/ha is higher than the non-symbiotic systems, where the measured values range between 10 and 160 kg N/ha. Many experiments focused on measuring the amount of fixed nitrogen in different plant species, for example, in groundnut the fixed N varied between 126 and 319 kg N/ha, in soybean 3–643 kg N/ha, in pigeon pea 77–92 kg N/ha, in cowpea between 25 and 100 kg N/ha, in green gram 71–74 kg N/ha, and in black gram 125–143 kg N/ha (Gopalakrishnan et al. 2015).

Nitrogen fixing biofertilizers are grouped as free-living bacteria, for example *Azotobacter*, *Bejerinkia, Clostridium, Klebsiella, Anabaena,* and *Nosto*c. Bacteria from *Rhizobium, Frankia, Anabaena,*and *Azollae* genera belong to the symbiotic group, whereas bacteria from *Azospirillum* genera belong to the associative symbiotic species. Atmospheric nitrogen fixation is one of their direct plant promotion effects. These bacterial formulations in most cases are crop specific (Bhat et al. 2015).

The genus of *Azospirillum* belong to the family Spirilaceae. Their contact with plants is based on associative symbiosis. Host plants are those that possess the C4-dicarboxyliac pathway of photosynthesis. They are proposed for the inoculation of maize, sugarcane, sorghum, and pearl millet. These bacterial species were also detected in the rhizosphere of different plants, such as rice, maize, sugarcane, pearl millet, vegetables, and plantation crops. There are reports of applying them as biofertilizer for diverse crops, such as barley, castor, cotton, coffee, coconut, jute, linseeds, maize, mustard, oat, rice, rubber, sesame, sorghum, sugar beets, sunflower, tobacco, tea, and wheat (Bhat et al. 2015).

It was detected that these bacteria are able to fix nitrogen to 20–40 kg/ha. A worldwide improved inoculation effect was determined in the case of *A.lipoferum* and *A.brasilense*. *Azospirillium brasilense* with *Rhizobium meliloti* plus 2,4D exerted beneficial effects on wheat, improving the harvested grain's N, P, and K content (Askary et al. 2009). In the case of maize, *A. lipoferum* CRT1, a commercial isolate, showed a positive effect on sugar metabolism (Rozier et al. 2017). It was reported that *A. brasilense* Ab-V5, besides influencing the photosynthesis metabolism in maize, also positively influenced the nitrogen supply under nitrogen limiting conditions (Calzavara et al. 2018).

From the family *Azotobacteriaceae: A. vinelandii, A. beijerinckii, A. insignis,* and *A. macrocytogenes* are the most known species. These bacterial species take part in the global nitrogen cycle due to their role in atmospheric nitrogen fixation. *Azotobacter sp*. are able to fix atmospheric nitrogen in the rhizospheric relationship with maize and wheat. It was shown that the application of *Azotobacter sp.* strains in mustard and wheat increased the plant growth rate, yield, and nitrogen level. In the case of *Brassica juncea,* the inoculation with *Azotobacter chroococcum* contributed to the stimulation of plant growth, whereas in *Fagopyrum esculentum* the inoculation with *Azotobacter aceae* contributed to nitrogen assimilation (Gouda et al. 2018).

It was also reported that *Azotobacter vinelandii* has a synergistic effect with *Rhizobium sp*., promoting the formation of nodules on the roots of different leguminous plants, such as soybean, pea, and clover (Gopalakrishnan et al. 2015). Bio-inoculants based on *Pseudomonas* species were also reported as having an effect on nitrogen assimilation. Rice seedlings inoculated with *Pseudomonas stutzeri* A15 showed 1.5- and threefold higher shoot length and root dry weight contrary to the control plants. It was proposed that this bacterial strain contributed to the nitrogen fixation (Pham et al. 2017).

Another form of nitrogen supply to plants is based on *Rhizobium*–legume symbiosis. That is a host dependent complex biochemical relationship. It was remarked on the global market that in 2012 the prevalent biofertilizers were rhizobium-based formulations (Bhardwaj et al. 2014).

Biofertilizers can also be used for the phosphorus supply of crop plants. The result of the phosphate mobilizing and solubilizing biofertilizers is the increase of the P mobilization in soil, where the soluble form of this nutrient is low. Different microorganisms were reported to have the ability to solubilize phosphorus. These include bacterial species belonging to genera *Arthrobacter, Bacillus, Beijerinckia, Burkholderia, Enterobacter, Erwinia, Flavobacterium, Mesorhizobium, Microbacterium, Rhizobium, Rhodococcus, Pseudomonas,* and *Serratia*. The above mentioned phosphorus solubilizing bacteria used as bio-inoculants improved the plant growth and yield in agricultural soils. Beyond bacterial strains, there are also microscopic fungi with phosphate mobilization capacity belonging to the *Aspergillus, Fusarium, Penicillium,* and *Sclerotium* genera. This type of biofertilizer is defined as a broad spectrum biofertilizer (Alori et al. 2017). It was revealed that the plant growth promoting effect was associated with phosphate solubilization in *Triticum aestivum* treated with *Azotobacter chroococcum*, in *Camellia sinensis* inoculated with *Bacillus megaterium*, and in *Cucumis sativus* treated with *Bacillus megaterium var. phosphaticum*. *Enterobacter agglomerans* used as an inoculant for *Solanum lycopersicum* showed phosphate solubilization effect. Co-inoculation of *Bradyrhizobium japonicum* with different phosphate mobilizing bacteria, such as *Pseudomonas chlororaphis* and *Pseudomonas putida,* resulted in phosphate solubilization in *Glycine max* (Gouda et al. 2018).

In many studies, it was shown that the applied phosphate solubilizing bacteria, beyond increasing phosphorus uptake of plants, contributed to the improvement of plant yield. Plant growth was detected in the case of wheat inoculated with *Serratia sp.*, in sweetleaf inoculated with *Burkholderia gladioli,* and in maize treated with *Burkholderia cepacia* (Alori et al. 2017).

Total weight and length of Chinese cabbage was increased by *Pseudomonas aeruginosa*. Rice shoot length was increased with the application of *Bacillus thuringiensis*. Productivity of wheat was achieved by the application of *Azotobacter chroococcum* and *Bacillus subtilis* (Singh et al. 2017). The phosphorus mobilizing *Rhizobium tropici* CIAT899 in beans contributed to the enhancement of nodule number and mass, and it also increased the shoot dry weight and the root growth.

The existing form of potassium in soil is insoluble rock or silicate. Numerous plant growth promoting bacteria, due to organic acid production, are able to release potassium in an accessible form to plants. The potassium solubilizer bacteria include, for example, *Bacillus edaphicus, B. ferrooxidans, B. mucilaginosus, B. megaterium var. phosphaticum, B. subtilis, Burkholderia sp., Enterobacter hormaechei, Paenibacillus sp.,* and *Pseudomonas sp* (Meena et al. 2016). As part of the soil bacterial community, they have a key role in the potassium cycle. These bacteria are used in potassium solubilizing or mobilizing biofertilizers. It is revealed that the result of potassium solubilizing and mobilizing biofertilizer consists of the weathering reaction of potassium bearing minerals from natural available sources. The efficiency of bio-inoculants is influenced by different factors, such as the potassium solubilization mechanism, applied strains, nutritional status of soil, minerals, and other environmental conditions (Etesami et al. 2017).

The use of these microorganisms in greenhouse or in field conditions as seed or seedling inoculants resulted in the increase of germination percentage, plant growth, and yield. The enhancement of K uptake by plants was also shown. In different plants, such as cotton, rape, eggplant, peanut, maize, sorghum, wheat, Sudan grass, potato, tomato, and tea, the growth promotion was detected due to the beneficial effect of microorganisms (Etesami et al. 2017).

A beneficial effect of *Bacillus mucilaginosus* strain RCBC13 on tomato plant was observed, resulting in an increase of 125% in biomass. The potassium and phosphorus uptake was more than 150% compared to uninoculated plants (Etesami et al. 2017). In two field experiments, the potassium-solubilizing *Bacillus cereus* and *Pseudomonas sp*. contributed to the improvement of potassium uptake, and this nutrient use efficiency also enhanced the tomato yield (Etesami et al. 2017). In wheat, *Bacillus sp.* significantly increased the N, P, and K content and the yield compared to the uninoculated control. Field experiments in hot pepper inoculated with the phosphate solubilizers *Bacillus megaterium* and *Bacillus mucilaginosus* resulted in beneficial effects on photosynthesis, biomass harvest, and fruit yield (Sindhu et al. 2016). In the case of rice plants, the grain yield resulted from a sample inoculated with a potassium solubilizer microorganism increased from 4419 to 5218 kg/ha.

It was reported that the efficiency of bacterial strains with potassium mobilizing or solubilizing capacity as bio-inoculants was higher when they were used in combination with soil minerals, such as mica, feldspar, or rock phosphate (Meena et al. 2016).

Numerous bacterial strains were reported as having beneficial effects on plants due to the improvement of nutrient uptake of plants. By using the potential of these bacterial strains, either in single or in complex formulations, a decrease in chemical fertilizer utilization can be achieved, suiting the requirements of an environmentally friendly and sustainable agricultural production.

References

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

Ahmad M, Nadeem SM, Naveed M, Zahir ZA (2016) Potassium-solubilizing bacteria and their application in agriculture. In: Meena V, Maurya B, Verma J, Meena R (eds) Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2776-2_21

Alori ET, Glick BR, Babalola OO (2017) Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Front Microbiol 8:971–979. https://doi.org/10.3389/fmicb.2017.00971

Anzuay MS, Ludueña LM, Angelini JG, Fabra A, Taurian T (2015) Beneficial effects of native phosphate solubilizing bacteria on peanut (*Arachis hypogaea* L) growth and phosphorus acquisition. Symbiosis 66:89–97. https://doi.org/10.1007/s13199-015-0337-z

Askary M, Mostajeran A, Amooaghaei R, Mostajeran M (2009) Influence of the co-inoculation Azospirillum brasilense and rhizobium meliloti plus 2,4-D on grain yield and N, P, K content of *Triticum aestivum* (Cv. Baccros and Mahdavi). Am-Eurasian J Agric Environ Sci 5(3):296–307

Bhardwaj D, Ansari MW, Sahoo RK, Tuteja NV (2014) Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb Cell Factories 13:66. https://doi.org/10.1186/1475-2859-13-66

Bhat T, Ahmad L, Ganai MA, Shams-Ul-Haq KOA (2015) Nitrogen fixing biofertilizers; mechanism and growth promotion: a review. J Pure Appl Microbiol 9:1675–1690

Calzavara AK, Paiva PHG, Gabriel LC, Oliveira ALM, Milani K, Oliveira HC, Bianchini E, Pimenta JA, de Oliveira MCN, Dias-Pereira J, Stolf-Moreira R (2018) Associative bacteria influence maize (*Zea mays* L.) growth, physiology and root anatomy under different nitrogen levels. Plant Biol 20:870–878. https://doi.org/10.1111/plb.12841

Etesami H, Emami SE, Alikhani HA (2017) Potassium solubilizing bacteria (KSB): mechanisms, promotion of plant growth, and future prospects – a review. J Soil Sci Plant Nutr 17:897–911
Gold MV (2016) Sustainable agriculture: the basics. In: Etingoff K (ed) Sustainable agriculture and food supply scientific, economic and policy enhancements. Apple Academic Press, Oakville
Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Gowda CLL, Krishnamurthy L (2015) Plant growth promoting rhizobia: challenges and opportunities. 3 Biotech 5:355–377. https://doi.org/10.1007/s13205-014-0241-x
Gouda S, Kerry RG, Das G, Paramithiotis S, Shin HS, Patra JK (2018) Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiol Res 206:131–140. https://doi.org/10.1016/j.micres.2017.08.016
Granada CE, Passaglia LMP, de Souza EM, Sperotto RA (2018) Is phosphate solubilization the forgotten child of plant growth-promoting rhizobacteria? Front Microbiol 9:2054. https://doi.org/10.3389/fmicb.2018.02054
Gu M, Chen A, Sun S, Xu G (2016) Complex regulation of plant phosphate transporters and the gap between molecular mechanisms and practical application: what is missing? Mol Plant 9:396–416. https://doi.org/10.1016/j.molp.2015.12.012
Hermary H (2007) Effects of some synthetic fertilizers on the soil ecosystem
Itelima JU, Bang WJ, Sila MD, Onyimba IA, Egbere OJ (2018) A review: biofertilizer – a key player in enhancing soil fertility and crop productivity. Microbiol Biotechnol Rep 2:73–83. https://doi.org/10.26765/DRJAFS.2018.4815
Jungk A (2001) Root hairs and the acquisition of plant nutrients from soil. J Plant Nutr Soil Sci 164:121–129. https://doi.org/10.1002/1522-2624(200104)
Karamesouti M, Gasparatos D (2017) Sustainable management of soil phosphorus in a changing world. In: Rakshit A, Abhilash P, Singh H, Ghosh S (eds) Adaptive soil management: from theory to practices. Springer, Singapore. https://doi.org/10.1007/978-981-10-3638-5_9
Kaur G, Reddy MS (2015) Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics. Pedosphere 25:428–437. https://doi.org/10.1016/s1002-0160(15)30010-2
Kiba T, Krapp A (2016) Plant nitrogen acquisition under low availability: regulation of uptake and root architecture. Plant Cell Physiol 57:707–714. https://doi.org/10.1093/pcp/pcw052
Kuan KB, Othman R, Abdul Rahim K, Shamsuddin ZH (2016) Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilisation of maize under greenhouse conditions. PLoS One 11:e0152478. https://doi.org/10.1371/journal.pone.0152478
Lambers H, Shane MW, Cramer MD, Pearse SJ, Veneklaas EJ (2006) Root structure and functioning for efficient acquisition of phosphorus: matching morphological and physiological traits. Ann Bot 98(4):693–713. https://doi.org/10.1093/aob/mcl114
Meena VS, Bahadur I, Ram B, Ashok M, Meena RK, Meena SK (2016) Potassium-solubilizing microorganism in evergreen agriculture: an overview. In: Meena V, Maurya B, Verma J, Meena R (eds) Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2776-2_1
Miransari M (2014) Plant growth promoting rhizobacteria. J Plant Nutr 37:2227–2235. https://doi.org/10.1080/01904167.2014.920384
Nieves-Cordones M, Alemán F, Martínez V, Rubio F (2014) K^+ uptake in plant roots. The systems involved, their regulation and parallels in other organisms. J Plant Physiol 171:688–695. https://doi.org/10.1016/j.jplph.2013.09.021
Nussaume L, Kanno S, Javot H, Marin E, Pochon N, Ayadi A, Nakanishi TM, Thibaud M-C (2011) Phosphate import in plants: focus on the PHT1 transporters. Front Plant Sci 2:83. https://doi.org/10.3389/fpls.2011.00083
Owen D, Williams AP, Griffith GW, Withers PJA (2015) Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition. Appl Soil Ecol 86:41–54. https://doi.org/10.1016/j.apsoil.2014.09.012

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

Pii Y, Mimmo T, Tomasi N, Roberto T, Cesco S, Crecchio C (2015) Microbial interactions in the rhizosphere: beneficial influences of plant growth-promoting rhizobacteria on nutrient acquisition process. A review. Biol Fertil Soils 51:403–415. https://doi.org/10.1007/s00374-015-0996-1

Ródenas R, García-Legaz MF, López-Gómez E, Martínez V, Rubio F, Ángeles Botella M (2017) $NO_3{}^-$, $PO_4{}^{3-}$ and $SO_4{}^{2-}$ deprivation reduced LKT1-mediated low-affinity K^+ uptake and SKOR-mediated K^+ translocation in tomato and Arabidopsis plants. Physiol Plant 160(4):410–424. https://doi.org/10.1111/ppl.12558

Rosier A, Medeiros FHV, Bais HP (2018) Defining plant growth promoting rhizobacteria molecular and biochemical networks in beneficial plant-microbe interactions. Plant Soil 428:35–55. https://doi.org/10.1007/s11104-018-3679-5

Rozier C, Hamzaoui J, Lemoine D, Czarnes S, Legendre L (2017) Field-based assessment of the mechanism of maize yield enhancement by Azospirillum lipoferum CRT1. Sci Rep 7:7416–7427. https://doi.org/10.1038/s41598-017-07929-8

Saha B, Saha S, Das A, Bhattacharyya PK, Basak N, Sinha AK, Poddar P (2017) Biological nitrogen fixation for sustainable agriculture. In: Meena V, Mishra P, Bisht J, Pattanayak A (eds) Agriculturally important microbes for sustainable agriculture. Springer, Singapore. https://doi.org/10.1007/978-981-10-5343-6_4

Sahu A, Bhattacharjya S, Mandal A, Thakur JK, Atoliya N, Sahu N, Manna MC, Patra AK (2018) Microbes: a sustainable approach for enhancing nutrient availability in agricultural soils. In: Meena V (ed) Role of rhizospheric microbes in soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-0044-8_2

Sattari SZ, Bouwman AF, Giller KE, van Ittersum MK (2012) Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proc Natl Acad Sci 109:6348–6353. https://doi.org/10.1073/pnas.1113675109

Sindhu SS, Parmar P, Phour M, Sehrawat A (2016) Potassium-solubilizing microorganisms (KSMs) and its effect on plant growth improvement. In: Meena V, Maurya B, Verma J, Meena R (eds) Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2776-2_13

Singh RP, Kumar S, Sainger M, Sainger PA, Barnawal D (2017) Eco-friendly nitrogen fertilizers for sustainable agriculture. In: Rakshit A, Abhilash P, Singh H, Ghosh S (eds) Adaptive soil management: from theory to practices. Springer, Singapore. https://doi.org/10.1007/978-981-10-3638-5_11

Takahashi M, Morikawa H (2014) Nitrogen dioxide is a positive regulator of plant growth. Plant Signal Behav 9:e28033. https://doi.org/10.4161/psb.28033

Tchiaze AI, Taffouo VD, Fankem H, Kenne M, Baziramakenga R, Ekodeck GE, Antoun H (2016) Influence of nitrogen sources and plant growth-promoting rhizobacteria inoculation on growth, crude fiber and nutrient uptake in squash (*Cucurbita moschata* Duchesne ex Poir.). Not Bot Horti Agrobot 44:53–59. https://doi.org/10.15835/nbha44110169

Tóth G, Guicharnaud R-A, Tóth B, Hermann T (2014) Phosphorus levels in croplands of the European Union with implications for P fertilizer use. Eur J Agron 55:42–52. https://doi.org/10.1016/j.eja.2013.12.008

Valkó G (2017) A fenntartható mezőgazdaság indikátorrendszerének kialakítása az Európai Unió tagországaira vonatkozóan. Központi Statisztikai Hivatal, Budapest, pp 19–31

Verma RK, Sachan M, Vishwakarma K, Upadhyay N, Mishra, RK, Tripathi DK, Sharma S (2018) Role of PGPR in sustainable agriculture: molecular approach toward disease suppression and growth promotion. In: Meena V (ed) Role of rhizospheric microbes in soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-0044-8_9

White PJ (2008) Efficiency of soil and fertilizer phosphorus use: reconciling changing concepts of soil phosphorus behaviour with agronomic information. In: Syers JK, Johnston AE, Curtin D (eds) Experimental agriculture 45(01). Food and Agricultural Organization of the United Nations, Rome, p 108. https://doi.org/10.1017/S0014479708007138