American Journal of BioScience
2022; 10(2): 61-68
http://www.sciencepublishinggroup.com/j/ajbio
doi: 10.11648/j.ajbio.20221002.14
ISSN: 2330-0159 (Print); ISSN: 2330-0167 (Online)

Phosphate Solubilizing Bacteria in Optimizing Phosphorous Acquisition and Crop Production

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To cite this article:
Mamo Bekele, Wubayehu Gebremedhin. Phosphate Solubilizing Bacteria in Optimizing Phosphorous Acquisition and Crop Production. *American Journal of BioScience*. Vol. 10, No. 2, 2022, pp. 61-68. doi: 10.11648/j.ajbio.20221002.14

Received: February 14, 2022; **Accepted**: March 18, 2022; **Published**: March 23, 2022

Abstract: Phosphorous is a key essential element for overall plant life cycles and today its availability in the soil is a great challenge due to quick fixation in different soil types. Today the only solution on the hands of farmers is using chemical fertilizer. However, synthetic fertilizer have numerous negative impacts on environment, soil fertility depletion, human healthy and the microbial diversity and ecology. Using microorganisms as bio-fertilizers would be the viable complementary option for the livelihood of farmers and the environment. Those microbes speed up the microbial process immediately after directly added to soil or through seed treating as bio fertilizer and growing their population. This process facilitates the nutrient uptake of plant which is available for the targeted objectives. Groups of bacteria such as *Pseudomonas, Bacillus, Rhizobium* and *Enterobacter* etc. are the main phosphate solubilizing microbes through production of organic acid production and known as bio-fertilizer for cereal crops. However, still there are little awareness and huge knowledge gap on the importance of those microbes on their contribution for agricultural inputs. This review articles therefore summarizes the different mechanisms on how phosphate solubilizing bacteria make available inert phosphorous and information related with phosphate solubilizing bacteria.

Keywords: Bacteria, Biofertilizer, Microorganism, Phosphorous Fixation

1. Introduction

Phosphorous is an essential element which is irreversible and a building block of our life and have numerous function (energy metabolism, nucleic acid and protein synthesis, kinase regulation) [1]. It also involved in metabolic processes of plant, as photosynthesis, energy transfer, signal transduction, macromolecular biosynthesis and respiration [2]. Phosphorous deficiency affect i) decrease crop yield production in agriculture through different mechanisms, ii) affect genetic role of cell in DNA strand, and iii) cause disease to mankind due to phosphorous deficiency in the body. Soil is the primary source of phosphorous and taken up by plant. However, only 0.1% of phosphorous can be utilized by plants, rendering available phosphorous a restrictive factor for plant growth [3, 4]. From Phosphate fertilizer added to soil for crop production, (75-90%) precipitate by metallic cation and are extremely reactive, become fixed through interactions with $Ca^{2}C$, $Fe^{3}C$, and $Al^{3}C$ ions in the soil to form insoluble phosphate salt complexes [5, 6].

The realization of all these potential problems associated with chemical P fertilizers together with the enormous cost involved in their manufacture, has led to the search for environmental compatible and economically feasible alternative strategies for improving crop production in low or P-deficient soils [7]. The utilization of microorganism with the goal at enhancing nutrient availability for plants is a significant practice and is essential for agriculture [8]. Hence, Phosphate solublizing microbes are an eco-friendly and a novel approach of keeping world food security [9].

This microorganism influence the plant growth in different mechanism directly through solubilizing unavailable phosphorous and indirectly through attacking pathogenic mechanism, initiating plant growth hormones and decaying organic matter and changing soil physicochemical properties

[10]. This all process boosts the agricultural yield product and keeps world food security and makes the environment safe. Today, the human interest is focused on yield through application of synthetic phosphate fertilizer and the knowhow for the contribution of microbes is at very limited stage. In case, atmospheric nitrogen fixing microbes especially rhizobia as a bio-fertilizer for leguminous crops currently are in good progress. Although microbial-based bio formulations that increase plant performance are greatly needed [11], bio-fertilizer for the case of cereal crops to minimize the application of synthetic phosphate fertilizer is the research gap in today's world. Therefore, the aim of this review articles was focused on the knowledge sharing about the contribution of phosphate solubilizing bacteria on the growth of plant and the impact on the grain yield production.

2. Phosphorous Fixation

The term phosphorous fixation is used to describe reactions that eliminate accessible phosphate from the soil solution into the soil solid phase [12] through phosphate sorption on the surface of soil minerals and precipitation of phosphate by free Al^{3+} and Fe^{3+} in the soil solution [13].

Therefore, soil phosphorous becomes fixed and available P levels have to be supplemented on most agricultural soils by adding synthetic P fertilizers, which not only represent a major cost of agricultural production but also inflict adverse environmental impacts on overall soil health and degradation of terrestrial, freshwater and marine resources [14].

3. Factors Affecting the Availability of Phosphorous in the Soil

Although there are abundant phosphorous in soils, in both organic and inorganic forms, its availability is restricted as it occurs mostly in insoluble forms. The phosphorous content in average soil is about 0.05% (w/w) but only 0.1% of the total P is available to plant because of poor solubility and its fixation in soil [15]. Availability of phosphorus to plants uptake is influenced by different factors i.e., soil pH, soil compaction, soil aeration, soil moisture, temperature, texture and organic matter of soils, crop residues, extent of plant root systems, minerals already present in the soil and root exudates secretions and available soil microbes [16]. In the case of acidic soils, phosphorous fixation is occurred by soluble form of Fe, Mn and free oxides and hydroxides of aluminum. But, in alkaline soils soluble phosphate ions quickly react with calcium to form a sequence of products of decreasing solubility [17]. The low availability of phosphorus in saline soil is attributed to its fixation with calcium, aluminum and iron that is then unavailable to plants [18].

Therefore, soil P dynamics is characterized by physicochemical (sorption-desorption) and biological (immobilization-mineralization) processes. Large amount of P applied as fertilizer enters in to the immobile pools through precipitation reaction with highly reactive Al^{3+} and Fe^{3+} in acidic, and Ca^{2+} in calcareous or normal soils [19, 20]. Hence, phosphate solubilizing microbes are a critical solution where phosphorus nutrient are regarded as a limiting nutrient in agricultural soils.

4. Mechanism of Phosphate Solublization

Phosphorus solubilizing is carried out by a large number of saprophytic bacteria and fungi through various mechanisms including acting on sparingly soluble soil phosphates, mainly by chelation-mediated mechanisms [21], organic acid production and proton extrusion [22]. Organic acid and mineral acids, alkaline phosphatases, phytohormones and H^+ protonation [23] anion exchange, chelation and production of siderophores are entirely promote phosphorous solublization in soil [24]. Secretions of organic acids from phosphate solublizing bacteria are potentially playing a crucial role for the mechanism of solubilization through dissolving insoluble soil phosphorous [25].

Inorganic Phosphorous is solublizing by the action of organic and inorganic acids secreted by phosphate solublizing bacteria in which hydroxyl and carboxyl groups of acids chelate cations (Al, Fe, and Ca). These acids acidify phosphate conjugate bases increasing their solubility as a result of the reduction of soil pH, while also chelating metals [26]. They also dissolve the soil phosphorous through production of low molecular weight organic acids mainly gluconic and keto gluconic acids [27, 28], in addition to lowering the pH of rhizosphere. The pH of rhizosphere is lowered through biotical production of proton / bicarbonate release (anion / cation balance) and gaseous (O_2/CO_2) exchanges. Peishi et al. [29] also suggested that production of key acids, such as propionic acid and oxalic acid, is especially important for the main mechanism used by PSM for dissolving phosphorus in saline environments.

Role of organic acids in mineral phosphate solublizing is escorted through medium acidification [30]. Accordingly, the availability of the phosphorous to the plant is enhanced when the organic and inorganic acids convert tricalcium phosphate to di and mono basic phosphates. Based on their potential type and species, different phosphate solublizing bacteria produce various potential. The type of organic acid produced and their amounts differ with different organisms.

Additionally, there are also numerous organic acids which were identified for the purpose of solubilizing phosphate such that oxalic acid, acetic acid, turturic acid and etc. [31]. Among the organic acids secreted by those microbes, aliphatic acids have the potential to solubilize soil phosphorous [32]. Phosphate solubilizing microbes are also known to produce acidity by CO_2 evolution (carbonic acid); this kind of acidification was observed in solubilizing of calcium phosphates. Certain of phosphate solubilizing bacteria, under anaerobic conditions release H_2S which reacts with insoluble ferric phosphate to yield solubilized ferrous sulphate. Microbial biomass assimilates soluble P, and prevents it from adsorption or fixation [33]. Phosphate solublizing bacteria are also solubilizing phosphorous through the production of siderophores [34]. The secretion of phenolic compounds and humic substances is also reported [35].

5. Factors Affecting Phosphate Solublizing Bacteria in the Soil

P-solublizing is a complex phenomenon, which depends on many factors such as nutritional, physiological and growth conditions of the culture [36]. Larger populations of phosphate solublizing bacteria are found in agricultural and range land soils [37].

Population of PSB also depends on different soil properties and affected by physical and chemical properties, organic matter, and P content and cultural activities. These physicochemical properties of soil inhibit the metabolic activities of organism. The concentration of iron ore, temperature, and C and N sources greatly influence the P solublizing potentials of these microbes. Among the various nutrients used by these microorganisms, ammonium salts has been found to be the best N source followed by asparagine, sodium nitrate, potassium nitrate, urea and calcium nitrate [38].

Application of phosphate fertilizer also negatively affect the microbial activities in the soil includes inhibition of substrate-induced respiration by streptomycin sulphate (fungal activity) and actidione (bacterial activity) and microbial biomass carbon (C) [39]. Similarly, the application of triple superphosphate has shown a substantial reduction in microbial respiration and metabolic quotient (qCO_2) [40].

Pesticides may adversely affect the proliferation of beneficial soil microorganisms and their associated biotransformation in the soil through inactivation of nitrogen-fixing and phosphorus solubilizing microorganisms [41]. Microbial organic compound mineralization and associated biotransformation such as nutrient dynamics and their bioavailability are more or less adversely affected by pesticides [42]. Although the pesticides used in low concentration, they affect the growth of soil microorganisms, chemical and biological properties, biochemical activity [43]. However, the effect of pesticides on soil microorganisms and their activity depend upon the type of pesticides used, quantities and soil conditions [44].

6. Effects of Phosphate Solublizing Bacteria on Growth and Yields of Different Crops

Phosphate solublizing bacteria increase crop yield through modification of plant root properties [45]. Improving biological nitrogen fixation is an additional importance of phosphate solubilizing bacteria in encouragements of plant growth [46]. According to the research findings [47], pseudomonas species are the principal phosphate solubilizing bacteria and also enhance nutrient availability, increase nodule number, dry weight, and improve yield and yield components of soybean. They also improved the seedling length of *Cicer arietinum* [48] and increased sugarcane yield by 12.6% [49], could also boost yields of many crops apple, maize, soybean, sugar beet, chickpea and peanut [50-55].

Phosphate solublizing bacteria have a multifunctional goal in plant growth and biosynthesis in addition to availing phosphorous to plant. They also have value in making essential growth promoting hormone substance, initiate the availability of atrmospheric nitrogen, make available trace essential elements and generally facilitate plant growth [56]. Additionally, they have also important as biocontrol through facilitating iron (siderophores), antibiotics and providing protection to plants against soil borne pathogens [57-59]. Accordingly, these microbial communities when used singly [60] or in combination with other rhizosphere microbes have shown substantial measurable effects on plants in conventional agronomic soils [61]. PSM isolated from soils can produce IAA and can increase the extension of roots in the soil, thus causing phosphorus to become more available to the roots and therefore, phosphate solublizing bacteria, promoting plant growth under saline conditions [62, 29]. Phosphate solublizing bacteria has important role in the secretion of extra polysaccharides and these extra polysaccharides important in improving salt stress through binding to Na^+ and decrease sodium ion uptake by plants [63].

Phosphate solublizing bacteria specially *Pseudomonas* genus can produce sidosphore and used to improve uptake of iron ion by plant under saline stress [64, 29]. Root associated microbes, including endophytes, closely cooperate with each other and can mediate important physiological processes, especially nutrient acquisition and plant fitness to abiotic stresses [65, 66].

The beneficial effects of PSB involve boosting key physiological processes, including water and nutrient uptake, photosynthesis, and source-sink relationships that promote growth and development [67]. The distinctive characteristics of PSB are they must be able to colonize the root, they must survive and multiply in microhabitats associated with the root surface, in competition with other microbiota, at least for the time needed to express their plant promotion/ protection activities and they must promote plant growth [68, 69].

Use of PSMs can increase crop yields up to 70 percent [70]. Combined inoculation of arbuscular mycorrhiza and PSB give better uptake of both native P from the soil and P coming from the phosphatic rock [71, 72]. Phosphate solublizing bacteria enhanced the seedling length of *Cicer arietinum* [48], while co-inoculation of PSB and PGPR reduced P application by 50% without affecting corn yield. Sole application of bacteria increased the biological yield, while the application of the same bacteria along with mycorrhizae achieved the maximum grain weight.

Phosphate solublizing bacteria also improve the uptake of other essential elements such as nitrogen, and potassium and also used as biocontrol agents of phytopathogenic fungi, synthesizing phytohormones in the root zone and rhizoplane, resulted in promote plant growth and development [73].

7. Synergy of PSB with Other Microbes in the Soil

Some phosphate-solublizing bacteria behave as mycorrhizal helper bacteria and interact with arbuscular mycorrhizae (AM) by releasing phosphate ions in the soil, which causes a synergistic interaction that allows for better exploitation of poorly soluble P sources [74]. Therefore, the phosphorous solublizing by this system can easily uptake through mycorrhizae-mediated bridge between roots and surrounding soil that allows nutrient translocation from soil to plants [75]. Toro et al. [76] also demonstrated that phosphate solublizing bacteria associated with AM improved mineral nitrogen and phosphorous accumulation in plant tissues. Other research findings also suggested that Arbuscular mycorrhizal fungi (AMF) and phosphate solublizing *Pseudomonas* bacteria (PSB) could potentially interact synergistically because PSB solublizing phosphate into a form that AMF can absorb and transport to the plant [77]. Although AMF can only exploit soluble P sources and much P in the soil is in an insoluble form, the capacity of AMF to transport P to the plant, can adds' up to 70% of total P plant uptake, is well known [78]. Synergistic effects between nitrogen fixing bacteria and phosphate solublizing bacteria were obvious; co-inoculations with nitrogen fixing bacteria enhanced the accumulation of available P and greater performance in plant growth promotion [79].

Grain yield of wheat (*Triticum aestivum* L. is increased due to application of phosphate solubilizing bacteria biofertilizer *Pseudomonas* and *Bacillus* species through improving availability of phosphorous nutrient in the soil, the plant easily access it [80]. Integrated application of phosphorous solubilizing bacteria and inorganic phosphate fertilizer improve grain yiled of wheat upto 30-40% times when compared to phosphorous fertilizer alone [81].

8. Types of Phosphate Solublizing Bacteria

In agricultural soil, the populations of phosphate solubilizing bacteria are the dominant which account for 1 to 50% whereas the fungi populations constitute small amount only 0.1 to 0.5% [82]. Among the soil bacterial communities ectorhizospheric strains from *Bacillus* and *Pseudomonas* [61] and endosymbiotic rhizobia have been described as effective phosphate solubilizers [83]. Strains from bacterial genera *Pseudomonas, Bacillus, Rhizobium* and *Enterobacter* and *Aspergillus* and *Penicillium* from fungal genera [84] are the most powerful phosphate solubilizers [21]. In the same manner, Sharma et al. [4] also reported that *Pseudomonas, Mycobacterium, Micrococcus, Bacillus, Flavobacterium, Rhizobium, Mesorhizobium and Sinorhizobium* are best phosphate solublizing strains involved in phosphate solublizing bacteria.

The bacteria species used for phosphate solublizer in the agricultural activity are listed that *Phyllobacterium, Chryseobacterium, Gordonia, Rhodococcus, Arthrobacter* [82]. There were bacteria species which have dual purpose i.e., initiating phosphorous availability to plant through dissolving unavailable phosphorous and fixing atmospheric inert nitrogen into ammonia and used up by host plant. These type of activity is carried out by *Rhizobium leguminosarum*, *R. leguminosarum* bv. *Viciae* and *Rhizobium* species nodulating *Crotalaria* species [85-87] improved solublizing phosphates by mobilizing inorganic and organic phosphorus.

Microorganisms have been isolated using cultural procedures with species of *Pseudomonas* and *Bacillus* bacteria [15] and *Aspergillus* and *Penicillium* fungi being predominant [88]. These organisms are ubiquitous but vary in density and mineral phosphate solublizing ability from soil to soil or from one production system to another. In soil phosphorous solublizing bacteria constitute 150% and fungi 0.1 to 0.5% of the total respective population. They are generally isolated from rhizosphere and nonrhizosphere soils, rhizoplane, phyllosphere, and rock P deposit area soil and even from stressed soils [7].

Bacillus and *Pseudomonas* spp. are the most frequent genus of phosphate solublizing and were able to dissolve insoluble phosphorus, thereby increasing the available phosphorus content in soil [89]. Moreover, *Enterobacter*, *Streptomycetes* and *Providencia rettgeri* spp. were phosphates solublizer in saline soil and the latter genus was reported for the first time as a phosphate solubilizer [29]. However, the phosphorus-solublizing ability of *Streptomyces* is low and indicates that bacterial agents are more suitable for use as PSMs.

Bacteria from genera such as *Achromobacter, Agrobacterium, Bacillus, Enterobacter, Erwinia, Escherichia, Flavobacterium, Mycobacterium, Pseudomonas* and *Serratia* are highly efficient in solubilising unavailable complexed phosphate into available inorganic phosphate ion [90]. *Rhizobia*, including *R. leguminosarum*, *R. meliloti, Mesorhizobium mediterraneum, Bradyrhizobium* sp. and *B. japonicum* are the potential phosphate solubilizers [91-93]. Through nitrifying bacteria and *Thiobacillus, nitric* acid and sulphuric acids (organic acids and inorganic acids respectively) produced during the oxidation of nitrogenous or inorganic compounds of sulfur which react with calcium phosphate and convert them into soluble forms [6].

9. Current Trends and Future Prospects of Phosphate Solublizing Bacteria in Ethiopia

The successful implementation of phosphate solublizing bacteria as bio-fertilizer has already been demonstrated in the fields by various workers, to a limited extent in different world countries. In Ethiopia, the application of phosphorous nutrient for crop production is still focused on chemical fertilizer. Moreover, the different agricultural experts in the country only limited to boosting the country production and productivity in any direction for cereal crops, vegetable crops, industrial crops and etc. As an indicator, bacteria strain as inoculants for different crop production is an appreciating starting research done by Ethiopian researcher. Hence, Gizaw B, et al. [94] reported that Phichia *norvegensis and Cryptococcus albidus var aerius* were superior in phosphate solubilization and recommended as bio fertilizers for teff productivity. Additionally, Muleta D et al. [95] also suggested that Pseudomonas spp. and two Erwinia species and a P. chlororaphis strain isolated from coffee Arabica in southwestern Ethiopia and recommended as higher organic acid producer which capable of solublize fixed phosphorous in the soil and have traits for extending the use of indigenous microbes as microbial biofertilisers. Similarly phosphate solublizing microbes from rhizosphere of fababean, teff at flowering stage, coffee Arabica, tef at seedling stage, white lupin were also recommended [96-100].

Although significant studies related to PSM and their roles in sustainable agriculture have been done across the globe as well as in Ethiopia, field evaluation, biofertilizer based large scale crop yield production technique remains in its infancy stage and the research result still not feasible at field condition.

Future research should focus on isolation of PSB, characterization, authentication, large scale demonstration, managing plant–microbe interactions, particularly with respect to their mode of actions and adaptability to conditions under extreme environments for the benefit of plants and finally ways and means for their better utilization in the farmers' fields to ensure conservation of our environments. Furthermore, scientists need to address certain issues, like how to improve the efficacy of bio-fertilizers, what should be an ideal and universal delivery system, how to stabilize these microbes in soil systems, and how nutritional and root exudation aspects could be controlled in order to get maximum benefits from PSM application.

10. Conclusion

Phosphorous is an essential macronutrient with huge challenge in the soil by its active fixation. This leads the minutes uptake of by plants in available forms and disturb overall metabolic activity of crops finally low grain yield in terms of quality and quantity. However, world population is increasing from time to time and needs concrete attention on how to keep the world food security. Therefore, to increase human demand considerable production of grain yield is imperative and the final decision we have is still using inorganic phosphate fertilizer. Though these options have beneficial effects, immediate phosphorous fixation during application, cost of production, transportation and availability to resource poor farmers, and finally hazardous to the environment and nutrient depletion is the other majestic problem. Furthermore, several times, these inorganic fertilizers are not accessible or too expensive for resource-poor famers. Hence, there is a strong need for novel, effective, affordable, integrated and durable strategies for crop yield improvement. To meet these challenges researcher have better give attention towards PSB from all location and soil types to solve farmers problems for accessing bio-fertilizer which is cost effective, environmentally friend approach even maintaining the soil fertility for the coming generation and human health as well instead of chemical fertilizer. Hence, researchers will have explore the potential rhizospheric microbes (soil and plant micro biomes) as an effective, generic and environmentally-sound approach to improve crop productivity in the country and even better to avail the isolated phosphate solublizing bacteria using the previous result for resource poor farmers.

References

[1] Nesme, T., Metson, G. S., and Bennett, E. M. Global P flows through agricultural trade. Glob. Environ. Change. 2018; 50: 133–141.

[2] Pradhan, A., Pahari, A., Mohapatra, S., & Mishra, B. B. Phosphate-Solubilizing Microorganisms in Sustainable Agriculture: Genetic Mechanism and Application. In *Advances in Soil Microbiology: Recent Trends and Future Prospects*. Springer, Singapore. 2017; (pp. 81-97).

[3] Lambers, H., and Plaxton, W. C. P: back to the roots. Annu. Plant Rev. 2018; 48, 3–22.

[4] Sharma, S. B., Sayyed, R. Z., Trivedi, M. H. & Gobi, T. A. Phosphate solublizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *Springer Plus*. 2013; 2: 587.

[5] Schnug, E., & Haneklaus, S. H. The enigma of fertilizer phosphorus utilization. In *Phosphorus in Agriculture: 100% Zero*. Springer, Dordrecht. 2016; (pp. 7-26).

[6] Khan, M. S., Zaidi, A., & Wani, P. A. Role of phosphate-solubilizing microorganisms in sustainable agriculture—a review. Agron. Sustain. Dev, 2007; *27* (1): 29-43.

[7] Zaidi A, Khan MS, Ahemad M, Oves M, Wani PA. Recent Advances in Plant Growth Promotion by PhosphateSolubilizingMicrobes. In Microbial Strategies for Crop Improvement. Edited by: Khan MS. Berlin Heidelberg: SpringerVerlag; 2009; 2350.

[8] Backman, P. A., Sikora R. A. Endophytes: an emerging tool for biological control. Biol. Control. 2008; 26: 1-3.

[9] Alori, E. T., Glick, B. R., & Babalola, O. O. Microbial phosphorus solubilization and its potential for use in sustainable agriculture. *Front Microbial.*, 2017; *8*: 971.

[10] Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., & Smith, D. L. Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Front. Plant Sci*, 2018; *9*: 1473.

[11] Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y., & Dhiba, D. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Front. Microbial.* 2018; *9*: 1606.

[12] Barber SA: Soil nutrient bioavailability. Wiley, New York: A mechanistic approach; 1995.

[13] Havlin J, Beaton J, Tisdale SL, Nelson W: Soil fertility and fertilizers. An introduction to nutrient management. Upper Saddle River, NJ: Prentice Hall; 1999.

[14] Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Wackhamer D: Forecasting agriculturally driven global environmental change. Sci. 2001; (5515): 281-284.

[15] Illmer P, Schinner F. Solubilization of inorganic phosphates by microorganisms isolated from forest soil. Soil. Biol. Biochem. 1992; 24: 389–95.

[16] Gopalakrishnan, S., Sathya, A., Vijayabharathi, R., Varshney, R. K., Laxmipathi Gowda, C. L., and Krishnamurthy, L. Plant growth promoting rhizobia: challenges and opportunities. *Biotech.* 2015; 5: 355–377.

[17] Toro, M. Phosphate solubilizing microorganisms in the rhizosphere of native plants from tropical savannas: An adaptive strategy to acid soils? In *First International Meeting on Microbial Phosphate Solubilization.* Springer, Dordrecht. 2007; (pp. 249-252).

[18] Sashidhar B, Podile AR Mineral phosphate solubilization by rhizosphere bacteria and scope for manipulation of the direct oxidation pathway involving glucose dehydrogenase. J. Appl. Microbiol. 2010; 109: 1–12.

[19] Gyaneshwar, P., G. N. Kumar, L. J. Parekh and P. S. Poole. Role of soil microorganisms in improving P nutrition of plants. Plant Soil. 2002; 245: 83-93.

[20] Hao, X., C. M. Cho, G. J. Racz and C. Chang. Chemical retardation of phosphate diffusion in an acid soil as affected by liming. Nutr. Cycl. Agroecosys. 2002; 64: 213-224.

[21] Whitelaw, M. A. Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv. Agron. 2000; 69: 99-151.

[22] Surange, S., A. G. Wollum, N. Kumar and C. S. Nautiyal. Characterization of *Rhizobium* from root nodules of leguminous trees growing in alkaline soils. Can. J. Microbiol. 1995; 43: 891- 894.

[23] Xiao, Y., Wang, X., Chen, W. & Huang, Q. Isolation and identification of three potassium-solubilizing bacteria from rape rhizospheric soil and their effects on ryegrass. *Geomicrobiol. J*. 2017; 1–8.

[24] Sugihara, S., Funakawa, S., Kilasara, M. & Kosaki, T. Dynamics of microbial biomass nitrogen in relation to plant nitrogen uptake during the crop growth period in a dry tropical cropland in Tanzania. *Soil Sci. Plant Nut.* 2010; 56: 105–114.

[25] Vyas P, Gulati A. Organic acid production in vitro and plant growth promotion in maize under controlled environment by phosphate-solublizing fluorescent *pseudomonas*. BMC Microbiol. 2009; 9: 174.

[26] Wei Y, Zhao Y, Shi M, Cao Z, Lu Q, Yang T, Fan Y, Wei Z. Effect of organic acids production and bacterial community on the possible mechanism of phosphorus solubilization during composting with enriched phosphate-solubilizing bacteria inoculation. Bioresour Technol. 2018; 247: 190–199.

[27] Goldstein, A. H. Recent progress in understanding the molecular genetics and biochemistry of calcium phosphate solubilization by Gram-negative bacteria. Biol. Agri. Hort. 1995; 12: 185-193.

[28] Deubel, A., Gransee and W. Merbach. Transformation of organic rhizodeposits by rhizoplane bacteria and its influence on the availability of tertiary calcium phosphate. J. Plant Nutr. Soil Sci. 2000; 163: 387-392.

[29] Peishi Qi., Huanhuan Jiang., Tong Wang., Mian Wang., Mingna Chen., Na Chen., Lijuan Pan., and Xiaoyuan Chi. Isolation and characterization of halotolerant phosphate-solubilizing microorganisms from saline soils. springer *Nature*, 2018; 8 (461): 1-8.

[30] Halder AK, Mishra AK, Bhattacharyya P, Chakrabartty PK. Solubilization of rock phosphate by *Rhizobium* and *Bradyrhizobium.* J Gen Appl Microbiol 1990; 36: 81–92.

[31] Ahmed N, Shahab S. Phosphate solubilization: Their mechanism genetics and application. Int. J. Microbiol. 2011; 9: 4408-4412.

[32] Mahidi SS, Hassan GI, Hussain A, Faisul-ur-Rasool. Phosphorus availability issue-Its fixation and role of phosphate solubilizing bacteria in phosphate solubilization-Case study. Res. J. Agric. Sci. 2011; 2: 174-179.

[33] Khan, M. S., Zaidi, A., Wani, P. A., Oves, M. Role of plant growth promoting rhizobacteria in the remediation of metal contaminated soils. *Environ Chem. Lett.* 2009; 7 (1): 1–19.

[34] Vassilev AM, Vassileva M. Microbial solubilization of rock phosphate on media containing agro-industrial wastes and effect of the resulting products on plant growth and P uptake. Plant Soil. 2006; 287: 77–84.

[35] Patel DK, Archana G, Kumar GN. Variation in the nature of organic acid secretion and mineral phosphate solubilization by Citrobacter sp. DHRSS in the presence of diverent sugars. Curr. Microbiol. 2008; 56: 168–174.

[36] Reyes, I., Bernier, L., Simard, R., Antoun, H.,. Effect of nitrogen source on solubilization of different inorganic phosphates by an isolate of Pencillium rugulosum and two UV-induced mutants. FEMS Microbiol. Ecol. 1999; 28: 281–290.

[37] Yahya, A. and S. K. A. Azawi. Occurrence of phosphate solubilizing bacteria in some Iranian soils. Plant Soil 1998; 117: 135-141.

[38] Ahuja, A., Ghosh, S. B., & D'souza, S. F. Isolation of a starch utilizing, phosphate solubilizing fungus on buffered medium and its characterization. *Bioresour Technol*, 2007; *98* (17): 3408-3411.

[39] Bolan NS, Currie LD, Baskaran S (1996) Assessment of the influence of phosphate fertilizers on the microbial activity of pasture soils. Biol. Fertil. Soils 21: 284–292.

[40] Chandini TM, Dennis P. Microbial activity, nutrient dynamics and litter decomposition in a Canadian Rocky Mountain pine forest as affected by N and P fertilizers. For Ecol Manage 2002; 159: 187–201.

[41] Sarfraz Hussain,., Tariq Siddique., Muhammad Saleem., Muhammad Arshad., and Azeem Khalid. Impact of Pesticides on Soil Microbial Diversity, Enzymes, and Biochemical Reactions. Adv. Agron. 2009; 102: 160-200.

[42] Demanou, J., Monkiedje, A., Njine, T., Foto, S. M., Nola, M., Serges, H., Togouet, Z., and Kemka, N. Changes in soil chemical properties and microbial activities in response to the fungicide Ridomil gold plus copper. Int. J. Environ. Res. Public Health 2004; 1, 26–34.

[43] Cycon, M; Piotrowska-seget, Z. and J. Kozdro, J. Response of indigenousmicroorganisms to a fungicidal mixture of mancozeb and dimethomorph added to sandy soils. Int. Biodeterior. Biodegradation 2010; 64: 316-323.

[44] Subhani, A; El-ghamry, A; Changyong, H and Jianming, Xu. Effects of Pesticides (Herbicides) on Soil Microbial Biomass - A Review. Pakistan J. Biolog. Sci, 2000; 3: 705-709.

[45] Mahanta D, Rai RK, Dhar S, Varghese E, Raja A, Purakayastha TJ. Modification of root properties with phosphate solubilizing bacteria and arbuscular mycorrhiza to reduce rock phosphate application in soybean-wheat cropping system. Ecol. Eng 2018; 111: 31– 43.

[46] Ponmurugan P, Gopi C. *In vitro* production of growth regulators of phosphatase activity by phosphate solubilizing bacteria. Afr. J. Biotechnol. 2006; 5: 348-350.

[47] Son HJ, Park GT, Cha MS, Heo MS. Solubilization of insoluble inorganic phosphates by a novel salt and pH tolerant *Pantoea agglomerans* R-42 isolated from soybean rhizosphere. Bioresour. Technol. 2006; 97: 204-210.

[48] Sharma K, Dak G, Agrawal A, Bhatnagar M, Sharma R. Effect of phosphate solubilizing bacteria on the germination of *Cicer arietinum* seeds and seedling growth. J. Herb Med. Toxicol. 2007; 1: 61-63.

[49] Sundara B, Natarajan V, Hari K. Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugarcane yields. Field Crops Res. 2002; 77: 43-49.

[50] Aslantas R, Cakmakci R, Sahin F. Effect of plant growth promoting rhizobacteria on young apple tree growth and fruit yield under orchard conditions. Sci. Hortic. 2007; 111: 371-377.

[51] Hameeda B, Harini G, Rupela OP, Wani SP, Reddy G. Growth promotion of maize by phosphate-solubilizing bacteria isolated from composts and macrofauna. Microbiol. Res. 2008; 163: 234-242.

[52] Fernandez LA, Zalba P, Gomez MA, Sagardoy MA. Phosphate solubilization activity of bacterial strains in soil and their effect on soybean growth under greenhouse conditions. Biol. Fertil. Soils 2007; 43: 805-809.

[53] Sahin F, Cakmakci R, Kantar F. Sugar beet and barely yields in relation to inoculation with N_2-fixing and phosphate solubilizing bacteria. Plant Soil 2004; 265: 123-129.

[54] Akhtar MS, Siddiqui ZA. Effects of phosphate solubilizing microorganisms and *Rhizobium* sp. on the growth, nodulation, yield and root-rot disease complex of chickpea under field condition. Afr. J. Biotechnol. 2009; 8: 3489-3496.

[55] Taurian T, Anzuay MS, Angelini JG, Tonelli ML, Luduena L, Pena D, Inanez F, Fabra A. Phosphate-solubilizing peanut associated bacteria: screening for plant growth-promoting activities. Plant Soil. 2010; 329: 421-431.

[56] Mittal V, Singh O, Nayyar H, Kaur J, Tewari R. Stimulatory effect of phosphate solubilizing fungal strains (*Aspergillus awamori and Penicillium citrinum*) on the yield of chickpea (*Cicer arietinum* L. cv. GPF2). Soil Biol. Biochem. 2008; 40: 718-727.

[57] Wani PA, Khan MS, Zaidi A. Co-inoculation of nitrogen fixing and phosphate solubilizing bacteria to promote growth, yield and nutrient uptake in chickpea. Acta Agron. Hung. 2007a; 55: 315-323.

[58] Lipping Y, Jiatao X, Daohong J, Yanping F, Guoqing L, Fangcan L. Antifungal substances produced by *Penicillium oxalicum* strain PY-1-potential antibiotics against plant pathogenic fungi. World J. Microbiol. Biotechnol. 2008; 24: 909-915.

[59] Hamdali H, Hafidi M, Virolle MJ, Ouhdouch Y. Rock phosphate solubilizing Actinimycetes: Screening for plant growth promoting activities. World J. Microbiol. Biotechnol. 2008; 24: 2565-2575.

[60] Chen Z, Ma S, Liu LL. Studies on phosphorus solubilizing activity of a strain of phospho bacteria isolated from chestnut type soil in China. Bioresour. Technol. 2008; 99: 6702-6707.

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

[62] Bahadur I, Maurya BR, Meena VS, Saha M, Kumar A, Aeron A. Mineral release dynamics of tricalcium phosphate and waste muscovite by mineral-solubilizing rhizobacteria isolated from indogangetic plain of India. Geomicrobiol J 2016; 34: 454–466.

[63] Qurashi AW, Sabri AN. Bacterial exopolysaccharide and biofilm formation stimulate chickpea growth and soil aggregation under salt stress. Br J Microbiol 2012; 43: 1183–1191.

[64] Sadgir MD, Totawar MV, Shinde SB. Assessment of phosphate solubilizing activity of different fungal and bacterial isolates. Int J Plant Sci 2016; 11: 40–46.

[65] Berg, G., Alavi, M., Schmidt, C. S., Zachow, C., Egamberdieva, D., Kamilova, F., Lugtenberg, B.,. Biocontrol and osmoprotection for plants under saline conditions. In: de Bruijn, Frans J. (Ed.), Molecular Microbial Ecology of the Rhizosphere. Wiley-Blackwell, USA, 2013.

[66] Abd_Allah, E. F., Hashem, A., Alqarawi, A. A., Bahkali, A. H and Alwhibi M. S. Enhancing growth performance and systemic acquired resistance of medicinal plant Sesbania sesban (L.) Merr using arbuscular mycorrhizal fungi under salt stress. Saudi J. Biol. Sci. 2015; 22: 274–283.

[67] llangumuran, G., Smith, D. L. Plant Growth Promoting Rhizobacteria in Amelioration of Salinity Stress: A Systems Biology Perspective. *Front. Plant Sci*. 8: 1-14.

[68] Kloepper, J. W. (1994). Plant growth-promoting rhizobacteria (other systems) In: *Azospirillum*/ Plant Associations (Okon, Y, ed.). Boca Raton, FL, USA: CRC Press, pp 2017; 111-118.

[69] Lucy M., Reed, E., Glick, B. R. Applications of free living plant growth promoting rhizobacteria. *Antonie Van Leeuwenhoek*. 2004; 86 (1): 1–25.

[70] Verma, L. N. Biofertiliser in agriculture. In: P. K. Thampan (ed.) Organics in soil health and crop production. Peekay Tree Crops Development Foundation, Cochin, India. pp. 1993; 152-183.

[71] Goenadi, D. H., Siswanto and Y. Sugiarto. Bioactivation of poorly soluble phosphate rocks with a phosphorus-solubilizing fungus. Soil Sci. Soc. Am. J. 2000; 64: 927-932.

[72] Cabello, M., G. Irrazabal, A. M. Bucsinszky, M. Saparrat and S. Schalamuck. Effect of an arbuscular mycorrhizal fungus, *G. mosseae* and a rock-phosphate-solubilizing fungus, *P. thomii* in *Mentha piperita* growth in a soiless medium. J. Basic Microbiol. 2005; 45: 182-189.

[73] Khasa, Y. P., Babbal & Adivitiya. Microbes as Biocontrol Agents. In *Probiotics and Plant Health* (pp. Springer Singapore. 2017; 507-552).

[74] Frey-Klett P, Pierrat JC, Garbaye J. Location and survival of mycorrhiza helper *Pseudomonas fluorescens* during establishment of ectomycorrhizal symbiosis between *Laccaria bicolor* and Douglas fir. Appl. Environ Microbiol 1997; 63: 139–44.

[75] Jeffries P, Barea JM. Bioeochemical cycling and arbuscular mycorrhizas in the sustainability of plant-soil system. In: Gianinazzi S, Schüepp H, editors. Impact of Arbuscular Mycorrhizas on Sustainable Agriculture and Natural Ecosystems. Basel, Switzerland: Birkhäuser Verlag, 1994; pp. 101–15.

[76] Toro M, Azcón R, Barea JM. Improvement of arbuscular mycorrhiza development by inoculation of soil with phosphate-solubilizing rhizobacteria to improve rock phosphate bioavailability (32P) and nutrient cycling. Appl. Environ. Microbiol. 1997; 63: 4408–12.

[77] Ordonez YM, Fernandez BR, Lara LS, Rodriguez A, Uribe-Vélez D, Sanders IR. Bacteria with Phosphate Solubilizing Capacity Alter Mycorrhizal Fungal Growth Both Inside and Outside the Root and in the Presence of Native Microbial Communities. PLoS ONE 2016; 11 (6).

[78] Smith SE, Read DJ. The mycorrhizal symbiosis. San Diego, USA: Academic Press 2008.

[79] Xiangxiang Fu, Zhikang Wang and Ziyun Chen. Integrated Effects of Co-Inoculation with Phosphate-Solubilizing Bacteria and N_2-Fixing Bacteria on Microbial Population and Soil Amendment Under C Deficiency Int. J. Environ. Res. Public Health, 2019; 16, 2442.

[80] Afzal A, Ashraf A, Saeed A, Asad, Farooq M. Effect of phosphate solubilizing microorganisms on phosphorus uptake, yield and yield traits of wheat (*Triticum aestivum* L.) in rainfed area. Int. J. Agric. Biol. 2005; 7: 1560-8530.

[81] Afzal A, Bano A. Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (*Triticum aestivum* L.). Int. J. Agric. Biol. 2008; 10: 85-88.

[82] Chen YP, Rekha PD, Arun AB, Shen FT, Lai WA, Young CC. Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl. Soil Ecol. 2006; 34: 33-41.

[83] Igual JM, Valverde A, Cervantes E, Velazquez E. Phosphate solubilizing bacteria as inoculants for agriculture: use of updated molecular techniques in their study. Agronomie 2001; 21: 561-568.

[84] Xiao CQ, Chi RA, Li XH, Xia M, Xia ZW. Biosolubilization of rock phosphate by three stress-tolerant fungal strains. Appl. Biochem. Biotechnol. 2011; 165: 719-727.

[85] Abril, A., Zurdo-Pineiro, J. L., Peix, A., Rivas, R., & Velázquez, E. Solubilization of phosphate by a strain of Rhizobium leguminosarum bv. trifolii isolated from Phaseolus vulgaris in El Chaco Arido soil (Argentina). In *First international meeting on microbial phosphate solubilization* Springer, Dordrecht. 2007; (pp. 135-138).

[86] Alikhani, H. A., Saleh-Rastin, N., & Antoun, H. Phosphate solubilization activity of rhizobia native to Iranian soils. In *First international Meeting on microbial phosphate solubilization* Springer, Dordrecht. 2007; (pp. 35-41).

[87] Sridevi M, Mallaiah KV, Yadav NCS Phosphate solubilization by *Rhizobium* isolates from *Crotalaria species*. J. Plant Sci. 2007; 2: 635-639.

[88] Wakelin, S. A., Warren, R. A., Harvey, P. R., & Ryder, M. H. Phosphate solubilization by Penicillium spp. closely associated with wheat roots. *Biol Fertil Soils* 2004; *40* (1), 36-43.

[89] Pirhadi, M., Enayatizamir, N., Motamedi, H., & Sorkheh, K. Impact of the soil salinity on diversity and community of sugarcane endophytic plant growth promoting bacteria (Saccharum officinatum L. var. CP48). *Appl Ecol Environ*, 2018; *16*: 725-739.

[90] Goldstein, A. H. Bioprocessing of rock phosphate ore: essential technical considerations for the development of a successful commercial technology. In *Proceedings of the 4th international fertilizer association technical conference, IFA, Paris* 2000; 220).

[91] Vessey, K. J. Plant growth promoting rhizobacteria as biofertilizers. *Plant Soil*. 2003; 255 (2): 571–586.

[92] Egamberdiyeva, D., Qarshieva, D., & Davranov, K. Growth and yield of soybean varieties inoculated with Bradyrhizobium spp in N-deficient calcareous soils. *Biol. Fert. Soils*. 2004; *40* (2): 144-146.

[93] Rodriguez Rodríguez, H., Fraga, R., Gonzalez, T., Bashan, Y. Genetics of phosphate solubilisation and its potential applications for improving plant growth-promoting bacteria. *Plant Soil*. 2006; 287: 15-21.

[94] Gizaw, B., Tsegay, Z., Tefera, G., & Aynalem, E. Phosphate Solubilizing Yeast Isolated and Characterized from Teff Rhizosphere Soil Collected from Gojam; Ethiopia. *J Bacteriol Mycol Open Access*, 2017; *5* (1): 00120.

[95] Muleta, D., Assefa, F., Börjesson, E., & Granhall, U. Phosphate-solubilising rhizobacteria associated with Coffea arabica L. in natural coffee forests of southwestern Ethiopia. *Journal of the Saudi Society of Agricultural Sciences*, 2013; *12* (1): 73-84.

[96] Keneni, A., Assefa, F., & Prabu, P. C. Isolation of phosphate solubilizing bacteria from the rhizosphere of faba bean of Ethiopia and their abilities on solubilizing insoluble phosphates. *Journal of Agricultural Science and Technology*, 2010; *12* (1): 79-89.

[97] Tsegaye, Z., Yimam, M., Bekele, D., Chaniyalew, S., & Assefa, F. Characterization and Identification of Native Plant Growth-Promoting Bacteria Colonizing Tef (Eragrostis Tef) Rhizosphere During the Flowering Stage for A Production of Bio Inoculants. *Biomedical Journal of Scientific & Technical Research*, 2019; *21* (5), 16444-16456.

[98] Teshome, B., Wassie, M., & Abatneh, E. Isolation, screening and biochemical characterization of Phosphate-solubilizing rhizobacteria associated with Coffea arabica L. 2017; 8: 188.

[99] Tsegaye, Z., Gizaw, B., Tefera, G., Feleke, A., Chaniyalew, S., Alemu, T., & Assefa, F. Isolation and biochemical characterization of Plant Growth Promoting (PGP) bacteria colonizing the rhizosphere of Tef crop during the seedling stage. *Biomed J Sci & Tech Res*, 2019; *14* (2), 1586-1597.

[100] Haile, D., Mekbib, F., & Assefa, F. Isolation of phosphate solubilizing bacteria from white lupin (Lupinus albus L.) rhizosphere soils collected from Gojam, Ethiopia. *J Fertil Pestic*, 2016; *7* (2).