African Journal of Microbiology Research Vol. 6(37), pp. 6600-6605, 27 September, 2012
Available online at http://www.academicjournals.org/AJMR
DOI: 10.5897/AJMR12.889
ISSN 1996-0808 ©2012 Academic Journals

Review

Prospectus of phosphate solubilizing microorganisms and phosphorus availability in agricultural soils: A review

Buddhi Charana Walpola and Min-Ho Yoon*

Department of Bio-Environmental Chemistry, College of Agriculture and Life Sciences, Chungnam National University, Daejeon, 305-764, Korea.

Accepted 11 September, 2012

Phosphate solubilizing microorganisms (PSMs) offer an ecologically acceptable mean for converting insoluble phosphate to soluble forms making them available for plants to absorb. Several bacterial strains (*Pseudomonas*, *Bacillus*, *Rhizobium* and *Enterobacter*) and fungal strains (*Aspergillus* and *Penicillium*) have so far been recognized as powerful phosphate solubilizers. Insoluble phosphates are converted into available forms by phosphate solubilizing microorganisms via the process of acidification, chelation, exchange reactions and production of organic acid. Though phosphorus is found to be a limiting factor in many soils, application of PSMs as biofertilizers or bioconverters for solubilizing fixed phosphorus has not yet been successfully practiced. In this context, isolation, identification and characterization of soil PSMs are considered to be effective in broadening the spectrum of phosphate solubilizers available for field application.

Key words: Phosphate solubilization, insoluble phosphate, organic acid, Phosphate solubilizing microorganisms (PSMs).

INTRODUCTION

As the world population continues to increase at an alarming rate, the demands placed upon agriculture to supply future food will be one of the greatest challenges facing the agrarian communities. In order to meet this challenge, a great deal of effort focusing on the soil biological system and the agro-ecosystem as a whole is needed enabling better understand the complex processes and interactions governing the stability of agricultural lands. Phosphorus, the second most important macro-nutrient required by the plants, next to nitrogen, is reported to be a critical factor of many crop production systems, due to the fact that the limited availability in soluble forms in the soils (Xiao et al., 2011). Microbes present in the soil employ different strategies to make use of unavailable forms of phosphorus and in turn also help in making phosphorus available for plants to absorb. When phosphatic fertilizers are applied to the soil, they often become insoluble (more than 70%) and are convert into complexes such as calcium phosphate, aluminum phosphate and iron phosphate in the soil (Mittal et al., 2008). Crop plants can therefore utilize only a fraction of applied phosphorus, which ultimately results in poor crop performance. To rectify this and to maintain soil fertility status, frequent application of chemical fertilizers is needed, though it is found to be a costly affair and also environmentally undesirable (Reddy et al., 2002).

Microorganisms contribute directly and indirectly to the soil health through their beneficial or detrimental activities. Rhizospheric microorganisms mediate soil processes such as exudation of soluble compounds, storage and release of nutrients and water, nutrient mobilization and mineralization by roots and microorganisms, soil organic matter decomposition, phosphate solubilization and nitrogen fixation, nitrification, denitrification and sulfur reduction (Khan et al., 2007). The organisms possessing phosphate solubilizing ability called phosphate solubilizing organisms and they can convert the insoluble

*Corresponding author. E-mail: mhyoon@cnu.ac.kr. Tel: +82-42-821-6733. Fax: +82-42-823-9241.

phosphatic compounds into soluble forms in soil and make them available for plants to absorb (Pradhan and Sukla, 2005). Given the negative environmental impacts of chemical fertilizers and increasing costs, it is urgently needed to imply eco-friendly and cost effective agro-technologies to increase crop production. Therefore, utilization of phosphate solubilizing microorganisms is considered to be a sound strategy in improving the productivity of lands that are currently under crop production. The technique is also claimed to show the ability to restore the productivity of degraded, marginally productive and unproductive agricultural soils (Gyaneswar et al., 2002). However, utilization of phosphate solubilizing microorganisms is found to be limited, lack of knowledge among practitioners being the key reason (Prasanna et al., 2011). The present paper reviewed recent findings of phosphate solubilizing microorganisms in order to widen the understanding of different aspects of them.

PHOSPHORUS PROBLEM IN SOIL

Phosphorus (P) is considered to be one of the most essential macro-elements required for growth and development of plants (Saber et al., 2005) and it is second only to nitrogen (N). Phosphorus nutrition is associated with several key functions of the plants, which include development of roots, strengthening the stalks and stems, formation of flowers and seeds, crop maturity and quality of the production, nitrogen fixation in legumes and strengthening the plant against diseases.

Phosphorus can naturally be found in diverse forms in the soil solution. They can broadly be categorized as insoluble inorganic phosphorus and insoluble organic phosphorus. However, due to low solubility and fixation in soils, only a small fraction of phosphorus exists in soil solution (1 ppm or 0.1%), is readily available to plants. The roots take up several forms of phosphorus, out of which the greatest part is absorbed in the forms of $H_2PO_4^-$ and HPO_4^{2-} depending upon soil pH (Mahidi et al., 2011). As a consequence of continuous applications of phosphatic fertilizers at high doses, most of the agricultural soils generally contain large reserves of accumulated phosphorus (Richardson, 2004). Soon after application, a large portion of soluble inorganic phosphate applied to soil as chemical fertilizer is rapidly immobilized and becomes unavailable to plants. When the fertilizer or manure phosphate comes in contact with the soil, a series of reactions begins which make the phosphate less soluble and less available. However, the degree of fixation and precipitation of phosphorus in soil is highly dependent upon the soil conditions such as pH, moisture content, temperature and the minerals already present in the soil. In the case of acidic soils, free oxides and hydroxides of aluminium and iron play a key role in fixing phosphorus, while in alkaline soils it is fixed by calcium (Toro, 2007). Therefore, phosphorus is often regarded as a limiting nutrient in agricultural soils (Guiñazú et al., 2010).

By contrast, the total phosphorus level of soils is low, which is usually no more than one-tenth to one-fourth of nitrogen, and one twentieth of potassium (Jones and Eva, 2011). The content of phosphorus in soil varies from 200 to 2000 kg phosphorus/ha of the upper 15 cm of soil, with an average of about 1000 kg. Worldwide, 5.7 billion hectares contain very little available phosphorus for sustaining optimal crop production (Hinsinger, 2001). Unlike nitrogen, there is no large atmospheric P source that can be made biologically available phosphorus. Therefore, deficiency of phosphorus severely restricts the growth and yield of crops.

The conditions in many tropical and subtropical soils are more critical due to the fact that the acidic nature of these soils which increases the rate of sorption (fixation) and immobilization (Fankem et al., 2006). Before being absorbed by roots, a considerable amount of applied phosphorus is rapidly transformed into less available forms by forming a complex with aluminum (Al) or iron (Fe) in acid soils or with calcium (Ca) in calcareous soils (Toro, 2007). Therefore, in order to sustain the production, problems of phosphorus deficiency are needed to be arrested through the application of phosphorus fertilizers (Khan et al., 2010). The repeated and injudicious applications of these phosphorus containing fertilizers, however, lead to (1) the loss of soil fertility (Gyaneshwar et al., 2002) (2) disturbance to microbial diversity and their associated metabolic activities, and (3) reduced yield of agronomic crops (Khan et al., 2009). This has led to the search for environment-friendly and economically feasible alternative strategies for improving crop production in low or phosphorus deficient soils.

In fact, most agricultural soils are obviously having large reserves of phosphorus. However, as the greater part of them, approximately 95 to 99% is present in the form of insoluble phosphates, utilization of them by plants is virtually restricted (Pradhan and Sukla, 2005). It has been suggested that this accumulated phosphates in agricultural soils is sufficient to sustain maximum crop yields worldwide for about 100 years. Instead of making attempts to utilize these reserves, chemical fertilizers are widely used in meeting the phosphorous need of crops. However, as the fertilizer production is dependent upon fossil energy sources, continuous use of chemical fertilizers has become a matter of great concern, not only because of the diminishing availability of costly inputs but environmental concerns also. Under this background, it has obviously brought the subject of mineral phosphate solubilization in the forefront (Khan et al., 2007).

PHOSPHATE SOLUBILIZATION

Under diverse soil and agro-climatic conditions, the organisms with phosphate solubilizing abilities have proved to be an economically sound alternative to the more expensive superphosphates and posses a greater agronomic utility (Khan et al., 2007; Xiao et al., 2009). Emphasis is therefore, being placed onto the possibility of greater utilization of unavailable phosphorus forms wherein the phosphate solubilizing microbes could play a pivotal role in making soluble phosphorus available to plants (Khan et al., 2010). Inorganic forms of phosphorus are solubilized by a group of heterotrophic microorganisms excreting organic acids that dissolve phosphatic materials and/or chelate cationic partners of the phosphorus ions that is, PO_4^{3-} directly, releasing phosphorus into solution (He et al., 2002). Microorganisms involved in the solubilization of insoluble phosphorus include bacteria, fungi, actinomycetes and arbuscular mycorrhizal (AM) fungi (Khan et al., 2007; Wani et al., 2007a; Xiao et al., 2009).

Not only proving phosphorus to the plants, the phosphate solubilizing microorganisms also facilitate the growth of plants by stimulating the efficiency of nitrogen fixation, accelerating the accessibility of other trace elements and by synthesizing important growth promoting substances (Mittal et al., 2008), including siderophores (Wani et al., 2007a) and antibiotics (Lipping et al., 2008), and providing protection to plants against soil borne pathogens (Hamdali et al., 2008). Accordingly, these microbial communities when used singly (Chen et al., 2008) or in combination with other rhizosphere microbes (Wani et al., 2007b) have shown substantial measurable effects on plants in conventional agronomic soils.

As revealed by several investigations, phosphate solubilizing bacteria could increase growth and yield in several crops including walnut (Xuan et al., 2011), apple (Aslantas et al., 2007), maize (Hameeda et al., 2008), soybean (Fernandez et al., 2007), sugar beet (Sahin et al., 2004), chickpea (Akhtar and siddiqui, 2009), and peanut (Taurian et al., 2010).

PHOSPHATE SOLUBILIZING MICROORGANISMS (PSMS)

A diverse group of soil microflora was reported to be involved in solubilizing insoluble phosphorous complexes enabling plants to easily absorb phosphorous (Tripura et al., 2005). Several fungal and bacterial species, popularly called as PSMs assist plants in mobilization of insoluble forms of phosphate. PSMs are ubiquitous whose numbers vary from soil to soil. Phosphate solubilizing bacteria constitute 1 to 50 % and fungi 0.1 to 0.5 % of the total respective population in soil (Chen et al., 2006). PSMs are predominately concentrated in the rhizosphere, where they are known to be metabolically more active than those isolated from other sources (Vazquez et al., 2000). Evidence of naturally occurring rhizospheric PSMs dates back to 1903 (Khan et al., 2007). Numerous rhizosphere microorganisms possessing phosphate solubilizing activity are reported (Mittal et al., 2008). Among the soil bacterial communities ectorhizospheric strains from *Bacillus* and *Pseudomonas* (Wani et al., 2007b) and endosymbiotic rhizobia have been described as effective phosphate solubilizers (Igual et al., 2001). Strains from bacterial genera *Pseudomonas, Bacillus, Rhizobium* and *Enterobacter* and *Aspergillus* and *Penicillium* from fungal genera (Wakelin et al., 2004; Xiao et al., 20011) are the most powerful phosphate solubilizers (Whitelaw, 2000). A nematofungus *Arthrobotrys oligospora* also has the ability to solubilize the phosphate rocks (Duponnois et al., 2006).

Apart from those species, the other bacteria reported as phosphate solubilizers include *Rhodococcus, Arthrobacter, Serratia, Chryseobacterium, Gordonia, Phyllobacterium, Delftia* sp. (Chen et al., 2006), *Azotobacter, Pantoea* and *Klebsiella* (Chung et al., 2005). Furthermore, symbiotic nitrogenous rhizobia, which fix atmospheric nitrogen into ammonia and export the fixed nitrogen to the host plants, have also shown phosphate solubilization activity. For instance, *Rhizobium leguminosarum* bv. *trifolii* (Abril et al., 2007), *R. leguminosarum* bv. *Viciae* (Alikhani et al., 2007) and *Rhizobium* species nodulating *Crotalaria* species (Sridevi et al., 2007) improved solubilize phosphates by mobilizing inorganic and organic phosphorus.

MECHANISM OF PHOSPHATE SOLUBILIZATION

A diverse group of bacteria and fungi is recognized to be involved in microbial phosphate solubilization mechanisms through which insoluble forms of phosphates convert into soluble forms (HPO_4^{-2} or $H_2PO_4^-$). Acidification of the medium, chelation, exchange reactions and production of various acids has been discussed as the key processes attributed to the conversion (Chung et al., 2005; Gulati et al., 2010).

The major microbiological means by which insoluble phosphate compounds are mobilized is the production of organic acids, accompanied by acidification of the medium. The organic and inorganic acids convert tricalcium phosphate to di and mono basic phosphates with the net result of an enhanced availability of the element to the plant. The type of organic acid produced and their amounts differ with different organisms. Among them, gluconic acid and 2-ketogluconic acid seems to be the most frequent agent of mineral phosphate solubilization (Song et al., 2008). Other organic acids, such as acetic, citric, lactic, propionic, glycolic, oxalic, malonic, succinic acid, fumaric, tartaric etc. have also been identified among phosphate solubilizers (Ahmed and Shahab, 2011). Organic acids produced by PSMs can be detected by high performance liquid chromatography and enzymatic methods (Whitelaw, 2000).

The organic acids released in the culture filtrates react with the insoluble phosphate. Organic acids contribute to the lowering of solution pH as they dissociate in a pH dependent equilibrium, into their respective anion(s) and proton(s). Organic acids buffer solution pH and continue to dissociate as protons, which are consumed by the dissolution reaction (Welch et al., 2002). Efficiency of solubilization is dependent upon the strength and nature of acids. Tri and di-carboxylic acids are more effective as compared to mono basic and aromatic acids. Aliphatic acids are also found to more effective in phosphate solubilization compared to phenolic, citric and fumaric acids (Mahidi et al., 2011). Besides organic acids, inorganic acids such as nitric and sulphuric acids are also produced by the nitrifying bacteria and thiobacillus during the oxidation of nitrogenous or inorganic compounds of sulphur which react with calcium phosphate and convert them into soluble forms (Khan et al., 2007). PSMs are also known to create acidity by CO_2 evolution (carbonic acid); this type of acidification was observed in solubilization of calcium phosphates. Some PSMs, under anaerobic conditions release H_2S which reacts with insoluble ferric phosphate to yield solubilized ferrous sulphate.

These acids may also complete for fixation sites of Al and Fe insoluble oxides, on reacting with them, stabilize them and are called ‘chelates’ Chelation process is also one of the important phosphate solubilization processes (Whitelaw, 2000). Many aerobic PSMs excrete 2-ketogluconic acid which is powerful chelator of calcium and such PSMs are versatile in solubilization of various forms of hydroxyapatites, fluorapatites and aluminium phosphates. Humic and fulvic acids released during microbial degradation of plant debris are also good chelators of calcium, iron and aluminium present in insoluble phosphates (Stevenson, 2005).

Organic form of phosphatic compounds is transformed into utilizable form by PSM via process of mineralization and it occurs in soil at the expense of plant and animal remains, which contain a large amount of organic phosphorus compounds. Soil *Bacillus* and *Streptomyces* spp. are able to mineralize very complex organic phosphates by production of extracellular enzymes like phosphoesterases, phosphodiesterases, phytases and phospholipases. Immobilization of phosphorus is sometimes practiced by soil PSMs. They compete with other bacteria and even plants for the assimilation of available phosphate and in result accumulate more phosphorus than plant. This stored phosphate is released into the environment under stress conditions or after death of PSMs. Such released phosphorus is then taken up by plants or other microbes to fulfill their phosphorus requirement.

The degradability of organic phosphorus compounds depends mainly on the physico-chemical and biochemical properties of their molecules for example, nucleic acids, phosphorlipids, and sugar phosphates are easily broken down, but phytic acid, polyphosphates, and phosphonates are decomposed more slowly. However microbial action is influenced by moisture content and pH of soil, weather conditions, chemical nature, particle size and degree of solubility of phosphate form in water.

EFFECT OF PSMS ON GROWTH, YIELD AND PHOSPHORUS ECONOMY

Inoculation of plants with PSMs generally results in improved plant growth and yield, in particular, under glasshouse conditions (Khan et al., 2010; Zaidi et al., 2009). More importantly, investigations conducted under field level using wheat and maize plants have revealed that PSMs could drastically reduce the usage of chemical or organic fertilizers (Singh and Reddy, 2011). As reported by Vessey and Heisinger (2001), enhancement of plant phosphorus nutrition might be due to stimulation of root growth or elongation of root hairs by specific microorganisms, thus no direct increase in the availability of soil phosphorus is always expected. PSMs have been isolated from soil of various plants such as walnut (Xuan Yu, 2011), rice (Chaiharn and Lumyong, 2009), mustard (Chandra et al., 2007), oil palm (Fankem et al., 2006), soybean (Son et al., 2006), aubergine and chili (Ponmurugan and Gopi, 2006), and maize (Alam et al., 2002). Better crop performance was reported to be achieved from several horticultural plants and vegetables, which were successfully inoculated with PSB (Young et al., 2003). Phosphorus use efficiency in agricultural lands could effectively be improved through the inoculation of relevant PSMs, which is in fact, an integrated and sustainable mean of nutrient management of crop production systems.

Enhancement of plant growth by improving biological nitrogen fixation is another beneficial effect of microorganisms with phosphate solubilizing potential (Ponmurugan and Gopi, 2006). Son et al. (2006) have reported that number of nodules, dry weight of nodules, yield components, grain yield, nutrient availability and uptake in soybean were found to be enhanced by *Pseudomonas* spp.

According to Afzal et al. (2005), inoculation of phosphate solubilizing *Pseudomonas* and *Bacillus* species has resulted in increased phosphorus uptake followed by increased grain yield of wheat (*Triticum aestivum* L.). Single and dual inoculation along with phosphorus fertilizer resulted in 30 to 40% times increased in grain yield of wheat compared to phosphorus fertilizer alone and dual inoculation without phosphorus fertilizer improved grain yield up to 20% against sole phosphorus fertilization (Afzal and Bano, 2008). *Pseudomonas* inoculation had favorable effect on slat tolerance of *Zea mays* L. under NaCl stress (Bano and Fatima, 2009). PSB enhanced the seedling length of *Cicer arietinum* (Sharma et al., 2007), and increased sugarcane yield by 12.6% (Sundara et al., 2002).

CONCLUSION

Approximately 70 to 90% of phosphorus fertilizer applied to the soil is precipitated by Ca, Fe and Al metal cations making insoluble forms which are not efficiently taken up by plants. Inoculation of phosphate solubilizing microorganisms in soil has been shown to improve solubilization of insoluble phosphates resulting in higher crop performances. A diverse group of microorganisms has been reported to show mineral P-solubilizing ability. Mechanisms such as acidification by producing low molecular organic acids like gluconic acids, chelation and iron exchange reactions in growth environment are attributed to the phosphate solubilization by PSMs. Apart from phosphate solubilizing abilities, some of these microorganisms can benefit plant growth by several different mechanisms such as enhancing nitrogen fixation, plant hormone production etc. Although phosphorus PSMs are abundant in many of the soils, isolation, identification and selection of PSMs have not as yet been successfully commercialized, thus application is still found to be limited. Investigations on the subject are often designed to confirm a specific response of PSMs to a particular environment, thus large scale application in field level is still limited.

REFERENCES

Abril A, Zurdo-Pineiro JL, Peis A, Rivas R, Velazquez E (2007). Solubilization of phosphate by a strain of *Rhizobium leguminosarium* bv *trifolii* isolated from *Phaseolus vulgaris* in El Chaco Arido soil (Argentina). In Velazquez E, Rodriguez-Berrueco C (eds) Book Series: Developments in Plant and Soil Sciences. Springer, The Netherlands. pp.135-138.

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

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

Ahmed N, Shahab S (2011). Phosphate solubilization: Their mechanism genetics and application. Int. J. Microbiol. 9: 4408-4412.

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

Akhtar MS, Siddiqui ZA (2009). 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. 8:3489-3496.

Alam S, Khalil S, Ayub N, Rashid M (2002). *In vitro* solubilization of inorganic phosphate by phosphate solubilizing microorganism (PSM) from maize rhizosphere. Int. J. Agric. Biol. 4:454-458.

Alikhani HA, Saleh-Rastin N, Antoun H (2007). Phosphate solubilization activity of rhizobia native to Iranian soils. In: Velazquez E, Rodriguez-Berrueco C (eds) Book Series: Developments in Plant and Soil Sciences. Springer, The Netherlands. pp. 135-138.

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

Bano A, Fatima A (2009). Salt tolerance in *Zea mays* (L.) fllowing inoculation with *Rhizobium* and *Pseudomonas*. Biol. Fert. Soils 45: 405-413.

Chaiharn M, Lumyong S (2009). Phosphate solubilization potential and stress tolerance of rhizobacteria from rice soil in Nothern Thailand. World J. Microbiol. Biotechnol. 25:305-314.

Chandra S, Choure K, Chaubey RC, Maheshwari DK (2007). Rhizosphere competent *Mesorhizobium loti* MP6 induces root hair curling, inhibits *Sclerotina sclerotiorum* and enhances growth of Indian mustard (*Brassica campestris*). Br. J. Microbiol. 38:124-130.

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

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

Chung H, Park M, Madhaiyan M, Seshadri S, Song J, Cho H, Sa T (2005). Isolation and characterization of phosphate solubilizing bacteria from the rhizosphere of crop plants of Korea. Soil Biol. Biochem. 37:1970-1974.

Duponnois R, Kisa M, Plenchette C (2006). Phosphate solubilizing potential of the nematofungus *Arthrobotrys oligospora*. J. Plant Nutr. Soil Sci. 169:280-282.

Fankem H, Nwaga D, Deubel A, Dieng L, Merbach W, Etoa FX (2006). Occurrence and functioning of phosphate solubilizing microorganisms from oil palm tree (*Elaeis guineensis*) rhizosphere in Cameroon. Afr. J. Biotechnol. 5:2450-2460.

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

Guiñazú LB, Andrés JA, MFDel P, Pistorio M, Rosas SB (2010). Response of alfalfa (*Medicago sativa* L.) to single and mixed inoculation with phosphate-solubilizing bacteria and *Sinorhizobium meliloti*. Biol. Fertil. Soils 46:185-190.

Gulati A, Sharma N, Vyas P, Sood S, Rahi P, Pathania V, Prasad R (2010). Organic acid production and plant growth promotion as a function of phosphate solubilization by *Acinetobacter rhizosphaerae* strain BIHB 723 isolated from the cold deserts of the trans-Himalayas. Arch. Microbiol. 192:975-983.

Gyaneshwar P, Naresh KG, Parekh LJ, Poole PS (2002). Role of soil microorganisms in improving P nutrition of plants. Plant Soil. 245:83-93.

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

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

He ZL, Bian W, Zhu J (2002). Screening and identification of microorganisms capable of utilizing phosphate adsorbed by goethite. Comm. Soil Sci. Plant Anal. 33:647-663.

Hinsinger P (2001). Bio-availability of soil inorganic P in the rhizosphere as affected by root induced chemical changes: A review. Plant Soil 237:173-195.

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

Jones DL, Eva O (2011). Solubilization of phosphorus by soil microorganisms. EL Bunemann et al (eds). Phosphorus in action-Biological processes in soil phosphorus cycling. Soil Biol. 26: Springer, Heidelberg NY. pp. 169-198.

Khan MS, Zaidi A, Wani P (2007). Role of phosphate solubilizing microorganisms in sustainable agriculture-A review. Agron. Sustain. Develop. 27:29-43.

Khan MS, Zaidi A, Wani PA, Oves M (2009). Role of plant growth promoting rhizobacteria in the remediation of metal contaminated soils. Environ. Chem. Lett. 7:1-19.

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

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

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

Mittal V, Singh O, Nayyar H, Kaur J, Tewari R (2008). 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. 40:718-727.

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

Pradhan N, Sukla LB (2005). Solubilization of inorganic phosphate by fungi isolated from agriculture soil. Afr. J. Biotechnol. 5: 850-854.

Prasanna A, Deepa V, Balakrishna MP, Deecaraman M, Sridhar R, Dhandapani P (2011). Insoluble phosphate solubilization by bacterial strains isolated from rice rhizosphere soils from Southern India. Int. J. Soil Sci. 6:134-141.

Reddy MS, Kumar S, Babita K (2002). Biosolubilization of poorly soluble rock phosphates by *Aspergillus tubingensis* and *Aspergillus niger*. Bioresour. Technol. 84:187-189.

Richardson AE (2004). Soil microorganisms and phosphorus availability: Management in sustainable farming systems. Melbourne, Australia: CSIRO. pp. 50-62.

Saber K, Nahla l, Ahmed D, Chedly A (2005). Effect of P on nodule formation and N fixation in bean. Agron. Sustain. Dev. 25: 389-393.

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

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

Singh H, Reddy MS (2011). Effect of inoculation with phosphate solubilizing fungus on growth and nutrient uptake of wheat and maize plants fertilized with rock phosphate in alkaline soils. Eur. J. Soil. Biol. 47:30-34.

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

Song OR, Lee SJ, Lee YS, Lee SC, Kim KK, Choi YL (2008). Solubilization of insoluble inorganic phosphate by *Burkholderia cepacia* DA 23 isolated from cultivated soil. Brazil J. Microbiol. 39: 151-156.

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

Stevenson FJ (2005). Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients. John Wiley and Sons, New York.

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

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

Toro M (2007). Phosphate solubilizing microorganisms in the rhizosphere of native plants from tropical savannas: An adaptive strategy to acid soils? In: Velaquez C, Rodriguez-Barrueco E (eds) Developments in Plant and Soil Sciences. Springer, The Netherlands. Pp. 249-252.

Tripura CB, Sashidhar B, Podile AR (2005). Transgenic mineral phosphate solubilizing bacteria for improved agricultural productivity. In Microbial Diversity Current Perspectives and Potential Applications ed. Satyanarayana, T. and Johri, B.N. New Delhi, India: I. K. International Pvt. Ltd. pp. 375-392.

Vazquez P, Holguin G, Puente M, Elopez Cortes A, Bashan Y (2000). Phosphate solubilizing microorganisms associated with the rhizospere of mangroves in a semi-arid coastal lagoon. Biol. Fert. Soils 30:460-468.

Vessey JK, Heisinger KG (2001). Effect of *Penicillium bilaii* inoculation and phosphorus fertilization on root and shoot parameters of field-grown pea. Can. J. Plant Sci. 81:361-366.

Wakelin S, Warren R, Harvey P, Ryder M (2004). Phosphate solubilization by *Penicillium spp.* closely associated with wheat roots. Biol. Fert. Soils 40:36-43.

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

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

Welch SA, Taunton AE, Banfield JF (2002). Effect of microorganisms and microbial metabolites on apatite dissolution. Geomicrobiol. J. 19: 343-367.

Whitelaw MA (2000). Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv. Agron. 69:99-151.

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

Xiao CQ, Chi RA, He H, Qiu GZ, Wang DZ, Zhang WX (2009). Isolation of phosphate solubilizing fungi from phosphate mines and their effect on wheat seedling growth. Appl. Biochem. Biotechnol. 159:330-342.

Xuan Yu, Xu Liu, Tian Hui Zhu, Guang Hai Liu, Cui Mao (2011). Isolation and characterization of phosphate solubilizing bacteria from walnut and their effect on growth and phosphorus mobilization. Biol. Fertil. Soils 47:437-446.

Young CC, Shen FT, Lai WA, Hung MH, Huang WS, Arun AB, Lu HL (2003). Biochemical and molecular characterization of phosphate solubilizing bacteria from Taiwan soil. Proceeding of 2nd International Symposium on Phosphorus Dynamics in the Soil-Plant Continuum. Perth, Australia. Pp. 44-45.

Zaidi A, Khan MS, Ahemad M, Oves M (2009). Plant growth promotion by phosphate solubilizing bacteria. Acta Microbiol. Immunol. Hungarica 56:263-284.