Chapter 10
Phosphate Solubilizing Microorganisms: Multifarious Applications

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Abstract Phosphorus is a key element for plant growth and development. Phosphate sources are available in soil present in both forms organic as well as inorganic. Due to its highly reactive nature, phosphate forms insoluble complex with several metal ions (Fe, Al, and Ca) and becomes unavailable for plant uptake and thus acts as a major limiting factor. Phosphate solubilizing microorganisms (PSMs) such as bacteria, fungi, and actinomycetes possess the ability to solubilize insoluble phosphate and convert into available form as orthophosphate ions thereby helping in plant growth, crop yield, and simultaneously improve soil health. In addition, these PSMs also play major role in various other key activities of environmental significance. A few such activities include ecological restoration, heavy metal decontamination and immobilization, promoting sustainable agricultural practices in saline-alkaline and other unsuitable soils. Overall, these PSMs are evolving as worthy candidates with multifarious application for environmental sustainability. This chapter covers several aspects of phosphate solubilization and mobilization by PSMs in the soil and further describes several other beneficial applications of these PSMs.

Keywords Phosphorus · Phosphatase · Phytase · PSM · Solubilization

10.1 Introduction

Phosphorus (P) is the second most essential macronutrient for plant growth and development after nitrogen and it accounts for around 0.2% of plant dry weight (Lin et al. 2006; Sharma et al. 2013). Phosphorus plays very crucial roles in several of the metabolic processes such as synthesis of biomolecules, energy transfer reactions, photosynthesis, cell division, plasma membrane components, signaling molecules, nucleic acid components, flowers and seeds formation, enzyme activities regulation

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by phosphorylation of serine, histidine, aspartate, threonine, and tyrosine amino acids (Raghothama 1999). Plants absorb P as phosphate anions (HPO_4^{2-} or $H_2PO_4^{-}$) from soil (Rodriguez and Fraga 1999). However, these phosphate anions are highly reactive in the soil and immediately form complex compound with metals ions like Ca^{2+}, Al^{3+}, and Fe^{3+}; and their precipitation reaction depends on pH of the soil. In acidic soils, phosphate anions react with oxides and hydroxides of Al and Fe and form insoluble complexes whereas in alkaline soils Ca reacts with these phosphate anions and fixes the available P (Igual et al. 2001). Due to high reactivity of these phosphate anions with metal cations, most soils are deficient in available P for the plant uptake thus making it to act as a limiting factor for plant growth and development in tropical and subtropical regions (Richardson 2001). To cope with this P limitation, farmers apply synthetic fertilizer but approximately 70–90% of applied P fertilizers get precipitated rapidly after their application in the soil (Mikanova and Novakova 2002). Consequently, overuse of chemical fertilizer causes nutrient imbalance and puts a burden on arable land which is a serious concern.

Soil microbiomes play essential role in P cycle. The P cycle in the biosphere is considered as open or sedimentary because there are neither gaseous intermediary forms nor any interchange between soil and air. This P cycle takes place by means of oxidation and reduction of phosphorus compounds in which oxidation state of phosphorus ranges from phosphine (−3) to phosphate (+5) (Ohtake et al. 1996; Behera et al. 2014). PSMs eventually increase the availability of soluble phosphate in the soil and boost plant growth and development by enhancing the efficacy of biological nitrogen fixation or enhancing the availability of other trace element such as iron and zinc and by producing plant growth promoting regulators (Ponmurugan and Gopi 2006). In the recent past, these PSMs have been explored for their various other potentials like that of heavy metal removal, ecological restoration, organic pollutant clean-up, and others. In this chapter, we focus on several aspects of phosphate solubilization and mobilization by PSMs in the soil and extend our discussion further to several other beneficial applications of these PSMs.

10.2 Phosphorus in Soil

Soil is a dynamic system and an ecological niche of various biological activities. The inorganic phosphate (Pi) available for biosynthetic purposes depends not only on the total amount of P in the environment but also on its availability as well as solubility. Phosphorus is one of the most important macronutrients for plant growth and development. The concentration of soluble P in soil is generally very low, normally at level of 1 ppm or less (Goldstein 1994). Mineral forms of P are represented in soil primarily by minerals such as apatite, hydroxyapatite, and oxyapatite and their main characteristic is insolubility, though they can be solubilized under suitable conditions and become available for uptake by microorganisms and plants. In soil, P exists in both organic and inorganic form. In cultivated soil around 70–80% of P exist in inorganic form applied in the form of P fertilizers (Foth and Foth 1990). Organic forms of P may constitute 30–50% of the total P in most soil, although its concentration may vary from as low as 5% to as high 95% (Paul and Clark 1988). Organic form of P exists mainly as inositol phosphate (soil phytate) accounting for approximately 50% of the total organic P. It is most stable form of organic P in the soil and is synthesized by microorganisms and plants. The other organic P forms include phosphomonoesters, phosphodiesters, phospholipids, phosphotriesters, and nucleic acids.

10.3 Phosphate Solubilizing Microorganisms

Diverse types of microorganisms are the major players in various processes that are linked with transformation of soil P and thus are an integral part of the soil P cycle. Soil microorganisms play very crucial role in making the availability of P from inorganic and organic pool of the total soil P by solubilization and mineralization (Hilda and Fraga 1999). Evidences of naturally occurring rhizospheric PSMs date back to 1903 (Khan et al. 2007). Microorganisms involved in phosphate solubilization consist of mycorrhizal fungi, bacteria, and actinomycetes, among the microbial population in soil, phosphate solubilizing bacteria (PSB) constitute 1–50%, while phosphate solubilizing fungi (PSF) are only 0.1–0.5% in solubilization potential (Chen et al. 2006). A considerably higher number of PSB are present in the rhizospheric soil than in non-rhizospheric soil (Raghu and Mac Rae 1966). The PSMs found in the plant rhizosphere are reported to be metabolically more active (Vazquez et al. 2000). Population of PSB in soil depends on its physical and chemical properties, organic matter, and P content (Kim et al. 1998). Strains from bacterial genera *Pseudomonas*, *Bacillus*, *Rhizobium*, *Enterobacter* along with *Penicillium* and *Aspergillus* from fungi are the most powerful phosphate solubilizers (White la 2000). Bacteria such as *Bacillus megaterium*, *Bacillus circulans*, *Bacillus subtilis*, *Bacillus polymyxa*, *Bacillus sircalmous*, *Pseudomonas striata*, and *Enterobacter* are referred as most important phosphate-solubilizing strains (Kucey et al. 1989). Among the soil bacterial populations, ectorhizospheric strains from *Pseudomonas* and *Bacillus* and endosymbiotic rhizobia have been observed as effective phosphate solubilizers (Igual et al. 2001). A fungus *Arthrobotrys oligospora* has also been reported for its ability to solubilize the phosphate rocks (Duponnois et al. 2006).

10.4 Need of Phosphate Solubilizing Microorganism

Chemical phosphatic fertilizers are made by a highly energy-intensive process that consumes energy worth US $4 billion per annum in order to fulfill the global needs (Goldstein et al. 1993). Further almost 75–90% of applied phosphatic fertilizers are precipitated by certain metal ions due to complex formation in the soil and it has been estimated that the precipitated phosphates in agricultural soils are sufficient to sustain crop production worldwide for nearly 100 years (Goldstein et al. 1993). Microorganisms are reported to play very crucial role in soil P cycle and relocating P between different soil P pools (Prasad et al. 2018). Hence it is evident to explore sources of phosphate solubilizers. Under different soil and agro-climatic conditions, these PSMs have proved to be an economical alternative to the more expensive chemical phosphatic fertilizers with greater agronomic utility (Ngalimat et al. 2021). The PSMs increase the availability of usable form of phosphate and can improve plant growth and soil health by producing other plant growth promoting substances, increasing biological N-fixation and enhancing the availability of other important trace element like iron and zinc (Ponmurugan and Gopi 2006; Nath et al. 2018).

10.5 Mechanisms of Phosphate Solubilization

There are various mechanisms such as production of low molecular weight organic acids, lowering of pH through H^+ extrusion, production of inorganic acids, and secretion of different enzymes like phosphatases, phytases, and phosphonatases for solubilizing the insoluble phosphate by PSMs. The various ways of phosphate solubilization by PSMs are summarized in Fig. 10.1. Based on the source of insoluble P, the phosphate solubilization mechanism can be categorized into two categories, i.e., inorganic P solubilization and organic P solubilization (Surange et al. 1995; Dutton and Evans 1996; Nahas 1996).

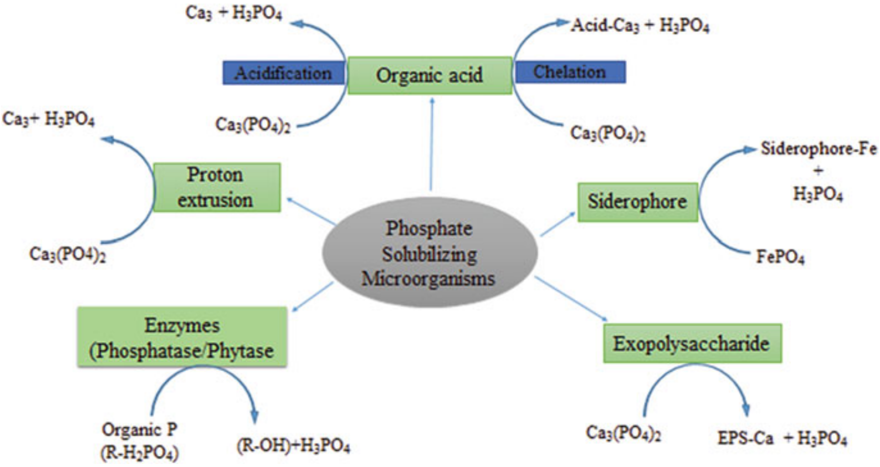

Fig. 10.1 Various mechanisms of phosphate solubilization by phosphate solubilizing microorganisms

10.5.1 Inorganic Phosphate Solubilization

The principal mechanisms of inorganic phosphate solubilization involve production of low molecular weight organic acids (Sperber 1957; Goldstein 1995; Buch et al. 2008). The organic acids produced by PSMs include acetic acid, malic acid, oxalic acid, succinic acid, citric acid, gluconic acid, 2-ketogluconic acid, tartaric acid, and many more (Kalayu 2019). The secretion of these organic acids by the microbial cells brings about acidification of its surroundings. These organic acids produced are consequently changed into ionic forms liberating proton (H^+) which replaces the metal cations like Fe^{3+}, Al^{3+}, and Ca^{2+} from the insoluble phosphate complex and makes available the soluble phosphate for plant uptake; or sometimes carboxylic anions chelate cations and release phosphate anion (Rodriguez and Fraga 1999; Hwangbo et al. 2003; Chen et al. 2006; Lin et al. 2006; Park et al. 2009; Kumar and Rai 2015; Prasad et al. 2018). Among the various organic acids produced by PSMs, gluconic acid and keto-gluconic acid are considered as major ones for P solubilization by the lowering of pH in the rhizosphere. The pH of rhizosphere is also supposed to be lowered through production of proton/bicarbonate release and gaseous (CO_2/O_2) exchange. The bacterial strains which produce the above-mentioned as well as several other organic acids are reported to belong to *Pseudomonas* (Park et al. 2009), *Enterobacter* (Hwangbo et al. 2003; Kumar et al. 2014), and *Burkholderia* (Lin et al. 2006). Based on several studies where cloning and characterization of the genes involved in organic acids production has been carried out, it had been concluded that genes involved directly or indirectly in the synthesis of organic acid or regulation of the expression of genes responsible for organic acid synthesis are also responsible for inorganic phosphate solubilization (Rodriguez et al. 2006; Buch et al. 2010; Chhabra et al. 2013). Some researchers also believe that proton translocation ATPase play an important role in P mineralization as it helps in proton extrusion to the outer surface as well as proton exchange for cation uptake (Illmer and Schiner 1995). The organic acids produced by PSMs in the medium can be identified and measured by using high performance liquid chromatography technique (Park et al. 2009; Kumar and Rai 2015). Furthermore, the other mechanism of inorganic P solubilization takes place as a result of nitrogen assimilation (nitrate formation), evolution of carbon dioxide, and oxidation of sulfur. These processes lead to the formation of nitric acid, carbonic acid, and sulfuric acid (Sperber 1957). However, the efficiency and their impact on release of bound P in soils seem to be less than organic acid production. The concept of organic acid production and phosphate solubilization hardly have any correlation between the concentration of organic acid and amount of solubilized phosphate in the culture medium hence acidification could not be the sole mechanism of inorganic phosphate solubilization (Parks et al. 1990). Solubilization of calcium phosphate has been reported to occur even in the absence of organic acid (Illmer and Schiner 1992). Furthermore, siderophores and exopolysaccharide synthesized by PSMs bring out locked phosphate into soluble form mainly by charge-related interaction (Yi et al. 2008; Sharma et al. 2013). As can be seen from above interpretations the organic

Table 10.1 Principal organic acids by phosphate solubilizing microorganisms for phosphate solubilization

PSMs	Organic acid	References
Bacteria		
Arthrobacter sp.	Malonic acid, oxalic acid	Banik and Dey (1982)
Enterobacter intermedium	2-ketogluconic acid	Zaidi et al. (2009)
Azospirillum sp.	Citric acid, fumaric acid succinic acid, gluconic acid	Kalayu (2019)
Enterobacter ludwigii	Acetic acid, gluconic acid, succinic acid	Tahir et al. (2013)
Pseudomonas cepacia	Gluconic acid, 2-ketogluconic acid	Zaidi et al. (2009)
Bacillus firmus	Oxalic acid	Banik and Dey (1982)
Bacillus megaterium	Gluconic acid	Chen et al. (2006)
Pseudomonas fluorescence	Citric acid, malic acid, tartaric acid, gluconic acid	Zaidi et al. (2009)
Fungus		
Aspergillus flavus	Citric acid, gluconic acid, oxalic acid, succinic acid	Rashid et al. (2004)
Aspergillus foetidus	Citric acid, gluconic acid, oxalic acid, succinic acid, tartaric acid	Zaidi et al. (2009)
Aspergillus japonicus	Citric acid, gluconic acid, oxalic acid, succinic acid, tartaric acid	Zaidi et al. (2009)
Penicillium sp.	Citric acid, gluconic acid, glycolic acid, malic acid, oxalic acid, succinic acid	Sane and Mehta (2015)
Penicillium radicum	Gluconic acid	Fenice et al. (2000)
Penicillium rugulosum	Citric acid, gluconic acid	Reyes et al. (2002)

acid as well as chelating and reducing molecules produced by PSMs are the key factors responsible for inorganic phosphate solubilization and these organic acids are also utilized as an alternate source of energy by PSMs resulting in the improved biomass yield (Buch et al. 2010; Kumar and Rai 2015). Table 10.1 shows various organic acids produced different PSMs.

10.5.2 Organic Phosphate Solubilization

The process of solubilization of organic phosphate is also known as mineralization of organic phosphate. The mineralization of organic phosphate is performed by different types of enzymes mainly phosphatases, phytases, and phosphonatases.

10.5.3 Phosphatase

Phosphatase (Phosphohydrolase) is an enzyme that acts by hydrolyzing phosphoester and phosphoanhydride bonds of organic matter. Phosphatase enzymes are classified into two types on the basis of their optimum pH: alkaline phosphatase ($pH > 7$) and acidic phosphatase ($pH < 6$). Their predominance is determined by pH of soil; in acidic soil acid phosphatases are predominant while in neutral and alkaline soil alkaline phosphatases are predominant (Rodriguez and Fraga 1999; Sharma et al. 2013). Table 10.2 shows some of the PSMs reported to exhibit acid and alkaline phosphatase activities.

10.5.4 Phytase

Phytase is an enzyme which acts on inositol phosphate component of phytate and releases utilizable phosphate. Phytate is the major source of inositol phosphate and accounts for more than 50% of organic phosphate form present in the soil (Rodriguez et al. 2006; Prasad et al. 2018). Phytate is synthesized by microorganism, plant seeds, and pollen grains (Rodriguez and Fraga 1999). Primarily phytases were used to improve animal nutrition; nevertheless, the contemporary approach may be the use of phytase secreting PSMs to improve plant growth and development (Richardson and Simpson 2011). *Arabidopsis* plants genetically engineered with phytase gene from *Aspergillus niger* were capable to procure phosphate from phytate. The growth and P content of the plants were equivalent to those plants supplied with soluble phosphate (Richardson and Simpson 2011). Table 10.3 enlists several of the phytase producing PSMs.

Table 10.2 List showing PSMs with phosphatase activity

Enzyme	Microorganism	References
Acid phosphatase	*Emericella rugulosa*	Yadav and Tarafdar (2007b)
	Serratia marcescens	Hameeda et al. (2006)
	Chaetomium globosum	Hameeda et al. (2006)
	Serratia marcescens	Ryu et al. (2005)
	P. fluorescens	Ryu et al. (2005)
	Burkholderia cepacia	Unno et al. (2005)
	Pseudomonas sp.	Richardson et al. (2001)
	Enterobacter aerogenes	Thaller et al. (1995)
	Enterobacter cloacae	Thaller et al. (1995)
	Citrobacter freundii	Thaller et al. (1995)
Alkaline phosphatase	*Bacillus flexus*	Patel (2016)
	Bacillus megaterium	Priya et al. (2014)
	E. coli	Bhattacharjee et al. (2018)

Table 10.3 List showing PSMs with phytase activity

Enzyme	Microorganism	References
Phytase	*Discosia* sp.	Rahi et al. (2009)
	Rhizobacteria	Hariprasad and Niranjana (2009)
	Rhizobacteria	Patel et al. (2010)
	Serratia marcescens	Hameeda et al. (2006)
	Pseudomonas sp.	Hameeda et al. (2006)
	Emericella rugulosa	Yadav and Tarafdar (2007a)
	Bacillus mucilaginous	Li et al. (2007)

10.5.5 Phosphonatases

Phosphonatases and C-P lyases hydrolyze C-P bond of organo-phosphonates and release phosphate (Rodriguez et al. 2006; Prasad et al. 2018). However, phosphonatases are not the major contributors in soil due to limited availability of their substrates (Rodriguez et al. 2006).

10.6 Application of Phosphate Solubilizing Microorganisms

There are several very important applications of PSMs in the arena of agriculture and allied activities. The PSMs play considerable role in the various ways such as plant growth and development promoters, salinity tolerance, drought tolerance, heavy metal tolerance, soil health repair, and ecological restoration in the management of agriculture (Malla et al. 2004; Prasad et al. 2018; Chhabra 2019). A few such applications of PSMs are discussed below.

10.6.1 Phosphate Solubilizing Microorganisms as Plant Growth Promoters

There are many PSMs present in soil but their numbers are not enough to compete with other microorganisms commonly found in rhizosphere, therefore the amount of phosphate released by these PSMs are generally not in enough quantity which is required by plants for better growth and development. Therefore, inoculation with selected microorganisms at a much higher concentration than that normally found in soil is necessary to harness the benefit of their phosphate solubilizing ability for plant yield increment (Singh and Kapoor 1998; Peix et al. 2001; Bharadwaj et al. 2008; Babu et al. 2015). The effectiveness of PSMs under natural conditions depends on its ability to persist and proliferate in the soil. In general, the density or population of applied PSM decreases rapidly upon introduction into soil due to various environmental factors (Ho and Ko 1985). The various factors that affect the survival of the inoculant PSM include abiotic and biotic factors. Abiotic factors include features such as soil composition, physiological condition, temperature and soil moisture (Bashan et al. 1995; Prasad et al. 2018). The biotic factors such as competition, predation, and root growth are the ones that facilitate substrate availability to the inoculated microorganisms (Mendes et al. 2013). These PSMs enhance plant growth and yield by two mechanisms, i.e., direct and indirect mechanism. The direct mechanism of growth promotion involves making the availability of nutrient by phosphate solubilization, N-fixation, and production of phytohormones (Rodriguez and Fraga 1999; Sharma et al. 2013; Chhabra 2019). Indirect mechanism of growth promotion involves synthesis of antibiotics and siderophores which help in prevention of deleterious effects of pathogenic microorganism (Rodriguez and Fraga 1999; Sharma et al. 2013; Chhabra and Dowling 2017). Several researches have been conducted to evaluate the biofertilization ability of different PSMs to enhance crop productivity in different parts of the world. Growth and crop production of mung bean was increased with the inoculation of *Bacillus circulans* (Singh and Kapoor 1998), common bean with *Burkholderia cepacia* (Peix et al. 2001), potato with *Pseudomonas*, *Stenotrophomonas*, *Arthrobacter*, *Microbacterium*, and *Pantoea* (Bharadwaj et al. 2008; Babu et al. 2015). Enhanced production of peanut (Dey et al. 2004), chickpea (Zaidi et al. 2003), radish (Antoun et al. 1998), maize (Hameeda et al. 2008; Kaur and Reddy 2014), rice (Vasudevan et al. 2002), tomato (Ghosh et al. 2015), and sugarcane (Sundara et al. 2002) has also been demonstrated with the use of different PSMs as biofertilizers.

10.6.2 Phosphate Solubilizing Microorganisms in Ecological Restoration and Phosphorus Cycling

Degraded ecosystems are characterized by extremely low levels of soil nutrients including P (Li 2006). Restoring these ecosystems requires the recovery of soil P cycling (Huang et al. 2012). Microbes play an integral role in soil P cycling, as they mediate bioavailable soil P (Rodriguez and Fraga 1999; Richardson and Simpson 2011). A global meta-analysis of 173 terrestrial studies revealed that plant responses in terrestrial ecosystems to P addition were not significantly different from those to N addition (Elser et al. 2007). Despite such an observation, substantial variations in plant responses to P and/or N addition were found between sub-habitats (e.g., forest, grassland, tundra, and wetland) within terrestrial environments (Elser et al. 2007), indicating that whether the soil is more limited to P or N is dependent on the specific ecosystem considered. Further, another global meta-analysis of 50 terrestrial studies showed that the plant responses in terrestrial ecosystems to P addition were more pronounced under elevated than under ambient N, indicating that P limitation in terrestrial ecosystems will become more pronounced under increasing atmospheric N deposition in the future (Li et al. 2016). Therefore, mitigating terrestrial P

Table 10.4 List of PSMs with active role in ecological restoration

Microorganism	Process	References
Arthrobacter sp.	P cycling	Banik and Dey (1982)
Enterobacter intermedium	P cycling	Zaidi et al. (2009)
Azospirillum sp.	P cycling	Kalayu (2019)
Enterobacter ludwigii	P cycling	Tahir et al. (2013)
Pseudomonas cepacia	P cycling	Zaidi et al. (2009)
Bacillus firmus	P cycling	Banik and Dey (1982)
Bacillus megaterium	P cycling	Chen et al. (2006)
Pseudomonas fluorescence	P cycling	Zaidi et al. (2009)

limitation is increasingly recognized as a major priority in ecosystem management and restoration (Penuelas et al. 2013). A set of PSMs-derived enzymes, such as acid phosphatase, alkaline phosphatase, phytase, phosphonatase, and C-P lyase are able to release free orthophosphate ions from recalcitrant organic P forms (Rodriguez and Fraga 1999; Richardson and Simpson 2011) and a variety of organic acids, including citric acid, formic acid, gluconic acid, malic acid, oxalic acid, are involved in the microbial solubilization of recalcitrant inorganic P forms (Rodriguez and Fraga 1999; Richardson and Simpson 2011). Several of the PSMs involved in ecological restoration are listed in Table 10.4.

10.6.3 Phosphate Solubilizing Microorganisms in Sustainable Agriculture

Mostly the challenge of P deficiency in agriculture is addressed by the application of P fertilizers. However, the majority of the applied phosphatic fertilizer is not available to plants and the addition of inorganic fertilizers in excess of the amount that is commonly employed to overcome this effect can lead to environmental problems such as groundwater contamination and waterway eutrophication (Kang et al. 2011). It is therefore of great interest to investigate management strategies that are capable of improving phosphate fertilization efficiency, increase crop yields, and reduce environmental pollution caused by phosphate drainage from the soil. Soil microorganisms enhance plant nutrient acquisition. They are involved in a wide range of biological processes including the transformation of insoluble soil nutrients (Babalola and Glick 2012). Several PSMs are capable of solubilizing and mineralizing insoluble soil phosphorus for the growth of plants. In the natural environment, numerous PSMs in the soil and rhizosphere are effective at releasing phosphate from bound soil phosphate through solubilization and mineralization (Bhattacharyya and Jha 2012). Several salt-tolerant or halophilic soil microorganisms which also exhibit the ability to solubilize insoluble phosphate holds promises for facilitation and development of saline-alkali soil-based agriculture (Zhu et al. 2011). The inoculation of soil or crop with PSMs is therefore a promising strategy for the improvement of

Table 10.5 List of PSMs involved in promotion of sustainable agriculture

PSM	Test crop	Result	References
Aspergillus niger	Wheat	Improved growth	Xiao et al. (2013)
Serratia sp.	Wheat	Increased growth	Swarnalakshmi et al. (2013)
Aspergillus awamoriS29	Mung bean	Increased plant growth, total P content, and plant biomass	Jain et al. (2012)
Azotobacter chroococcum and *Bacillus subtilis*	Wheat	Enhanced productivity of wheat	Kumar et al. (2014)
P. favisporus TG1R2	Soybeans	Increased dry biomass	Fernandez et al. (2011)

plant absorption of phosphate and thereby reducing the use of chemical fertilizers that have a negative impact on the environment (Alori et al. 2012). Mobilization of soil inorganic phosphate and increasing its bioavailability for plant use by harnessing soil PSM promotes sustainable agriculture, improves the fertility of the soil, and hence increases crop productivity. Various PSMs which imparted positive effects on crop production and promoted sustainable agriculture are listed in Table 10.5.

10.6.4 Phosphate Solubilizing Microorganisms in Immobilization of Heavy Metals

Soil contaminated with heavy metals has become a severe problem in many parts of the world (Li et al. 2014). Heavy metals are naturally occurring ingredient of the earth's crust (Pan et al. 2016); however, there are various anthropogenic activities, like ore mining, e-waste recycling, and sewage irrigation that had greatly increased the concentrations of heavy metals in the soil. Exposure of human to soil-heavy metals mainly includes the leaching of heavy metals from soil into water and the consumption of edible plants grown in the contaminated soil (Cao et al. 2009). Addition of different kinds of phosphate-containing compound into contaminated soil to immobilize heavy metals (like Pb, Zn, Cu, and Cd) has been well documented because of the formation of highly insoluble metal–phosphate precipitates (Liang et al. 2014), especially Pb–phosphate minerals, pyromorphites [$Pb_5(PO_4)_3X$, where $X = Cl^-, OH^-, F^-$], which are the most thermodynamically stable and insoluble Pb minerals over a broad pH and EC range. The efficiency of phosphate addition-induced heavy metals immobilization depends on the solubility of both the heavy metals and the added phosphate (Park et al. 2011a). Although soluble phosphate compounds like sodium-, potassium-, and ammonium phosphates having high water solubility had been widely applied to remediate heavy metals contamination and had achieved high immobilization efficiency, they are relatively more expensive than insoluble phosphate compounds and are more prone to cause eutrophication (Park et al. 2011a, b). In soils, PSMs could produce organic acids and phosphate enzymes

Table 10.6 Heavy metals immobilizing PSMs

Microorganism	Heavy metals	References
Achromobacter xylosoxidans Ax10	Cu	Ma et al. (2009)
Azotobacter chroococcum HKN5, *Bacillus megaterium* HKP-1, *Bacillus mucilaginosus HKK-1*	Pb and Zn	Wu et al. (2006)
Bacillus sp. PSB10	Cr	Wani and khan (2010)
Bacillus subtilis SJ-101	Ni	Zaidi et al. (2006)
Pseudomonas sp. M6, *Pseudomonas jessenii* M15	Ni, Cu, and Zn	Rajkumar and Freitas (2008)

to enhance the solubilization of insoluble phosphate compounds (Chen et al. 2006), and hence, PSMs have been widely used as inoculants to increase soil available phosphate contents and thus act as a good heavy metal immobilizer (Rodriguez and Fraga 1999). Microbial-immobilized remediation technology refers to using soil microorganisms to immobilize heavy metals, causing heavy metals to precipitate or be adsorbed and fixed in the soil, reducing their absorption by plants (Han et al. 2018). PSMs are capable of producing siderophore which is a metal-binding ligand molecule and chelates with several heavy metals such as cadmium, nickel, lead, arsenic, and many others that can help in adsorbing or absorbing these heavy metals from the soil and minimize the toxic effect of heavy metal accumulation by immobilizing them (Ma et al. 2009). Heavy metal-immobilizing bacteria have been widely studied and applied as excellent heavy metal passivators. Heavy metal-immobilizing PSMs not only immobilize heavy metals, alter the existing state of heavy metals in soil, and reduce the absorption of heavy metals by crops, but also promote the growth of crops and improve the quality of crops (Zhao et al. 2019). PSMs increased the growth and heavy metal resistance of vegetables by producing indole acetic acid (IAA), siderophores, 1-aminocyclopropane-1-carboxylate deaminase, and arginine decarboxylase (Teng et al. 2019). Table 10.6 enlists some of the heavy metal immobilizing microorganisms. To cope with stress caused by heavy metals, microorganisms have evolved mechanisms to overcome toxicity, including metal reduction, cell permeability reduction, and extracellular isolation (Noisangiam et al. 2011).

10.7 Conclusion

The current overuse of synthetic phosphatic fertilizers poses greater threats to the environment and also creates soil nutrient imbalance. Therefore, the application of PSMs is an eco-friendly and economically viable and efficient approach for the utilization of fixed phosphate present in the soil. Application of PSMs on one hand reduces the agricultural input cost by curtailing the use of highly priced synthetic fertilizers and on the other gives a more organic and natural crop yield. These PSMs with their additional qualities like that of heavy metal and salinity tolerance hold great potential for future of environmental sustainability.

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