

## Chapter 6

# Role of Phosphate-Solubilizing Actinomycetes in Plant Growth Promotion: Current Perspective

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**Abstract** Phosphorus (P), an essential plant nutrient, is a nonrenewable resource whose availability depends exclusively on mined rock phosphates. Deficiency of P in soil results in reduction in food production since all plants require an adequate supply of P for its growth and development. Even though synthetic phosphatic fertilizer has played some major roles in enhancing crop production, its excessive use has also dark sides to it where it has been found to damage the environment, destruct soil fertility, and, via food chain, seriously affect the human health. Considering the nuisance of overuse of P, there is an urgent demand by the agriculture practitioners to find nonhazardous strategy that can overcome/reduce the use of agrochemicals in agricultural practices and, hence, may preserve the very integrity of soil ecosystems. In this context, actinobacteria, a group of Gram-positive bacteria, ubiquitous in soils, are likely to play some important roles in supplying soluble P to plants by solubilizing/mineralizing complex P resources of soils. Additionally, the extracellular metabolites produced by actinomycetes may inhibit phytopathogens and, sometimes such metabolic compounds may also act as plant growth regulators. These qualities, among others, make actinobacteria an ideal candidate for developing as microbial inoculants for ultimate use in agriculture production system. The potential roles of actinomycetes as phosphate solubilizers in enhancing crop production are discussed.

**Keywords** Actinomycetes • P solubilizers • Plant growth • Biocontrol

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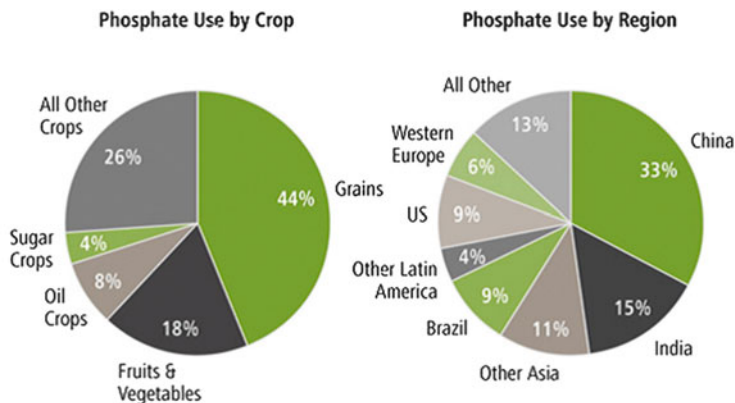
## 6.1 Introduction

Phosphorus, identified as an essential element for all life forms (Smil 2000), is the second most important plant macronutrient after N (Donahue et al. 1990). Phosphorus accounts for the biomass buildup, the energy transfer, signal transduction, macromolecular biosynthesis, photosynthesis, and respiration chain reactions (Vance et al. 2003; Fernández et al. 2007). Sadly, this highly vital element is one of the least accessible (only 0.1 % of the total soil P reserve) nutrients to the plants (Zou et al. 1992; Takahashi and Anwar 2007). Owing to the suboptimal levels of P, it is often considered a limiting factor to primary production across a diverse range of ecosystem (Elser et al. 2007) and may cause a 5–15 % loss in plant yields (Hinsinger 2001). The low availability of P in soil is primarily due to its highly reactive nature as it readily forms insoluble complexes with the soil ions. Thus, to fulfill the growing P demands for food production and to maintain a balanced fertility in soils and, hence, to achieve a low-input, sustainable eco-friendly agriculture targets, a better management of the soil P reserve is urgently needed. Many strategies have been introduced by the scientists across different regions where the role of phosphate-solubilizing microorganisms involving bacteria (Zaidi et al. 2009; Ahmad et al. 2013), fungi (Khan et al. 2010), and actinomycetes (Gangwar et al. 2012) in increasing plant yields and soil quality via P supply has been recognized. Among these, actinomycetes as P solubilizers (de Vasconcellos et al. 2010; Hamdali et al. 2012) have been less explored despite showing a better genetic and greater biodiversity potential (Pathom-Aree et al. 2006; Thangapandian et al. 2007). Also, they represent heterogeneous and abundant microbial populations and hugely affect cycling of nutrient in soil ecosystems (Elliot and Lynch 1995; Figueiredo et al. 2010). Recently, the role of actinomycetes in sustainable agriculture (Johansson et al. 2004; Strap 2011) via P supply to plants has been identified. Some other actinomycetes, for example, endophytic actinomycete (Araújo et al. 2000; Kunoh 2002; Lee et al. 2008; Qin et al. 2008), which fix atmospheric N into  $\text{NH}_3$  and export the fixed N to the host plants, have also shown PS activity (Gangwar et al. 2012). In a study, almost 44 % of the endophytic actinomycetes isolated from rice had PS activity, among which *S. lavendulae* R22 solubilized the maximum (26.5 mg/100 ml) amount of P, while *Micromonospora* R19 isolate could solubilize the minimum amount of P. Realizing the plant-growth-promoting potentials of actinomycetes which involve one or simultaneous mechanisms, here, the recent advances in P solubilization by actinomycetes and its impact on crop production are highlighted.

## 6.2 Phosphorus Status and P Dynamics in Rhizosphere: Current Perspective

Globally, rock phosphate (RP) is an abundantly available and inexpensive form of P, and therefore, about 80 % of mined RP is used for agricultural fertilizer (Tirado and Allsopp 2012). Worldwide, there is a huge RP deposit in countries such as Morocco and China, while other regions particularly Asian countries depend heavily on import of phosphates for intensive agriculture production systems. From a consumption point of view, China is the largest consumer of P fertilizers accounting for about 34 % of the total world consumption, whereas India ranks second with 19 % of global consumption (FAOSTAT 2012). Similarly, the uptake of P by plants varies greatly (Fig. 6.1). Regrettably, mining of RP and its use as fertilizers pose a serious human health risk (Zhang and Shan 2008; Pan et al. 2010; Tirado and Allsopp 2012). Considering the declining P resources, cost of P-fertilizer production, and direct or indirect human health problems due to their excessive application, scientists around the world have directed their attention toward exploring the natural and inexpensive P resources which could serve as an eco-friendly and economical alternative for chemical fertilizers in sustainable agriculture. In this context, the phosphate-solubilizing actinomycetes have provided some solutions to the expensive P problems.

Further, the chemical and biological processes in the rhizosphere play an important role in soil nutrient availability and crop productivity (Zhang et al. 2010) as presented in Fig. 6.2. Plants acquire P in the form of orthophosphate anions (mainly  $\text{H}_2\text{PO}_4^-$  and  $\text{H}_2\text{PO}_4^{-2}$ ) which they obtain from different soil P reserves including inorganic P (Pi) and organic P (Po). Broadly, on the basis of plant accessibility, soil P has been grouped as follows: (a) solution P, present in the soil solution and immediately available for plant uptake; (b) active P, adsorbed on active sites of soil yet readily available and in equilibrium with solution P; and (c) fixed P, strongly adsorbed and least soluble with slow conversions to active P over a vast period, even years (Syers et al. 2008; Shen et al. 2011). Generally, concentration of plant-available P in soil is below the critical level required for plant growth and yields (Raghothama 1999). Thus, the synthetic phosphatic fertilizer or organic manure is applied to overcome the P deficiency to plants. Of the total P applied to soils, only 15–25 % of it is available for uptake by plants and the remainder is fixed (Shen et al. 2011). The P dynamics and availability in soil is, therefore, controlled by several factors: (1) the ability of plants to form extensive root systems, (2) impact of microbial colonization onto the development of plants, (3) soil microflora affecting biogeochemical cycling of elements, and (4) physico-chemical properties of soils supporting plants and microbial life in soils.



**Fig. 6.1** Crop-wise use of phosphorus and its distribution in different countries (Source: CRU, Fertecon, IFA (Potash Corp. 2013))

### 6.3 Actinomycetes: An Ideal Candidate for Sustainable Crop Production

Actinomycetes are a ubiquitous, saprophytic, and heterogeneous group of microorganisms belonging to an extensive and diverse group of Gram-positive, aerobic, mycelial bacteria that have DNA with high %G+C content (51–73 %) with the exception of freshwater actinobacteria which has low GC content (Takisawa et al. 1993; Ghai et al. 2012). Actinomycetes inhabit both the rhizoplane and rhizosphere (Solans and Vobis 2003; Frioni 2006) and are known to play some important ecological roles in soil nutrient cycling (Elliot and Lynch 1995), probiotics (Lievin et al. 2000), bioremediation (Amoroso et al. 2013), nitrogen fixation, and deterioration and decomposition of plant and animal residues and also provide many bioactive compounds such as vitamins, enzymes, and antibiotics (de Boer et al. 2005; Busti et al. 2006; Prapagdee et al. 2008; Genilloud et al. 2011). Apart from their beneficial impact, actinomycetes also cause some harmful effects such as they cause diseases and spoil different useful materials (Waksman 1950). Other properties which make them an ideal candidate for developing inoculants are as follows: (1) their high genetic and metabolic versatility, (2) they can easily be genetically engineered (Pogell et al. 1991), (3) high growth rate and relatively faster colonization efficiency (Hsu and Lockwood 1975), and (4) ability to tolerate high salt concentration (Vassilev et al. 2012). Despite possessing such qualities, actinomycetes in general have been less explored organisms in agricultural technology, among variously distributed soil microflora (Qin et al. 2011).

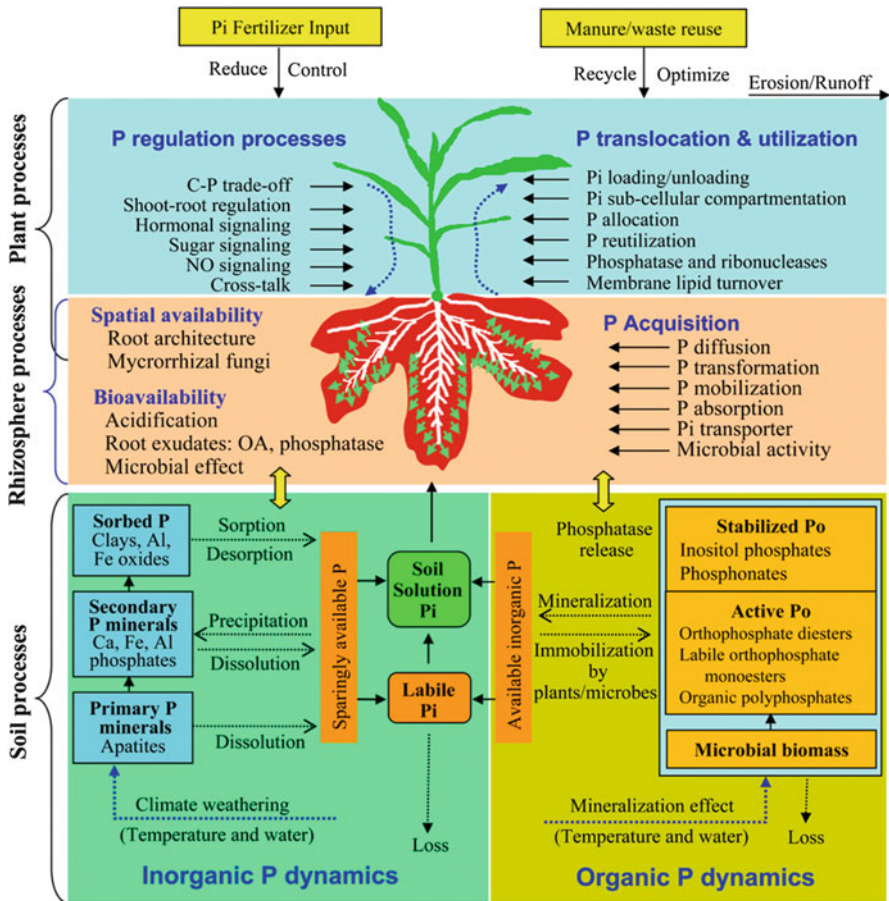


Fig. 6.2 Phosphorus dynamics in soil [Adapted from Shen et al. (2011)]

### 6.3.1 Isolation and Identification of Actinomycetes

Phosphate-solubilizing actinomycetes have been isolated from diverse environment (Matsumoto et al. 1998; Rai et al. 2007; Lee et al. 2008) such as soil (Xu et al. 1996; Debananda et al. 2009; Salcedo et al. 2014), rhizospheres (Norovsuren et al. 2007), phyllosphere (Gupta et al. 2010), and salt and alkaline environments (Jiang et al. 2005) (Table 6.1). The bioprospecting of actinomycetes from the usual or routine habitat is likely to result in rediscovery or the recovery of the same strain with the similar mode of actions (Jensen et al. 2005).

Actinomycetes represent one of the largest domains of bacteria involving 145 genera and more than 4,000 species (Berdys 2005). Their population has been reported highest at the soil surface which, however, decreases with increasing soil depth (Takahashi and Omura 2003). Prior to isolation, soil is pretreated in order

**Table 6.1** Different habitat and varying isolation methods for actinomycetes

Habitat	Actinomycete genus isolated
Cultivated field	<i>Streptomyces</i>
Cultivated paddy field	<i>Micromonospora</i>
Plant matter	<i>Microbispora</i>
Pasture	<i>Micromonospora</i>
Lake sediment	<i>Micromonospora</i>
Mangrove rhizosphere soil	<i>Actinobacteria</i>
Tea field soil	Acidophilic and acid tolerant actinomycetes
Desert soil, marine sediment, seawater, and activated sludge	
Pretreatment	
Yeast extract (6 %, 20 min)	Enrichment of actinomycetes
Heating (100 °C, 1 h)	<i>Streptosporangium</i> , <i>Microbispora</i> , <i>Microtetraspora</i>
Phenol (1.0–1.5 %, 30 min)	<i>Dactylosporangium</i> , <i>Microbispora</i> , <i>Microtetraspora</i>
Pre-culture with CaCO <sub>3</sub>	Enrichment of actinomycetes
Chemotactic method (KCl, $\gamma$ -collidin, xylose)	Motile actinomycetes, actinomycetes, <i>Dactylosporangium</i>
Medium for isolation	
Addition of antibiotics	
Novobiocin	<i>Actinoplanes</i> , <i>Kitasatospora</i>
Tunicamycin	<i>Micromonospora</i>
Rifampicin	<i>Actinomadura</i>
Chlortetracycline	<i>Nocardia</i>
Macrolide or aminoglycoside	Macrolide or aminoglycoside producer
Addition of humic acid	Rare actinomycetes
Addition of proline	Enrichment of actinomycetes
Gellan gum (substitute for agar)	<i>Actinobispora</i>
Conditions for isolation	
High temperature	Thermophilic actinomycetes

Adapted from Takahashi and Omura (2003)

to avoid the emergence of bacterial and fungal contaminants. For this, soil samples are collected bulked, mixed, and allowed to dry heating (at 45 °C for 2 h or 50 °C for 10 min or 60 °C for 30 min) (Goodfellow 1971). The isolation medium is also suspended with antibacterial (penicillin 25 mg/ml) or antifungal (nystatin 0.1 % or cycloheximide 50 mg/ml) agents (Balagurunathan and Radhakrishnan 2007). A 0.1 ml of serially diluted (Nonomura and Ohara 1969) soil sample is spread plated onto different actinomycete isolation media, such as casein starch agar, the Czapek agar, and the oatmeal agar, and incubated at 28 °C for 15–30 days. The resulting colonies are then picked and identified using cultural, morphological (Pridham and Tresner 1974; Nonomura 1989; Sabaou et al. 1998), and physiological (Nonomura and Ohara 1969; Goodfellow 1971) characteristics. The actinomycetes are then identified to species level using fatty acid analysis, mol (%) G + C contents, DNA–DNA hybridization, and 16S rRNA sequencing.

### 6.3.2 *In Vitro* Screening of Phosphate-Solubilizing Actinomycetes

The phosphate-solubilizing activity of the actinomycetal strains is assessed generally on the Pikovskaya (PVK) medium (Pikovskaya 1948) which contains (g/l): glucose 10;  $\text{Ca}_3(\text{PO}_4)_2$ , 5;  $(\text{NH}_4)_2\text{SO}_4$ , 0.5; NaCl, 0.2;  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , 0.1; KCl, 0.2; yeast extract, 0.5;  $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ , 0.002; and  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ , 0.002, agar 15. The streaked/spot inoculated plates are incubated at 22 °C for 14 days and observed for halo formation. The development of a clear zone around the colony on the culture plates is taken as an index of P solubilization. Halo size is calculated by subtracting colony diameter from the total diameter (Valverde et al. 2006). Thereafter, the halo-forming actinobacteria is grown on SRSM-1 medium which has the same composition as that of the PVK medium but is supplemented with bromocresol purple as a pH indicator for determining the involvement of organic acid production in PS activity.

### 6.3.3 Role of Actinobacteria in Rock Phosphate Solubilization

Nearly 20 % of the actinomycetes including *Streptomyces* and *Micromonospora* possess profound phosphate-solubilizing potential (Barreto et al. 2008; El-Tarabily et al. 2008; Hamdali et al. 2008b). Actinomycetes as P solubilizer have received greater attention for two reasons: (1) ability to produce agro-active metabolites, for example, phytohormones, siderophores, and antibiotics, etc. (Hoster et al. 2005; Errakhi et al. 2007; Errakhi et al. 2009), and (2) ability to tolerate different stressor molecules (Fabre et al. 1988; Keiser et al. 2000; Hamdali et al. 2008d). Also, the inoculation with actinomycetal strains has been found to increase the plant growth (Hamdali et al. 2008c). Plants take up the orthophosphorus form of P as nutrient, the availability of which depends on soil characteristics (Nath and Borah 1983). However, Fe and Al at high pH and Ca at low pH fix the soluble form into insoluble form rendering it unavailable to the plants (Rengel and Marschner 2005; Johnson and Loepper 2006). The PS actinomycetes, however, through the release of organic acid (acidification) (Hoberg et al. 2005; Abdulla 2009) and by other mechanisms such as chelation, exchange reactions, and polymeric substances formation (Delvasto et al. 2006) convert the insoluble forms of P into soluble forms. The organic anions assist P solubilization mainly in two ways: (a) lowering pH and (b) ligand exchange reaction (Beunemann et al. 2011; Balemi and Negisho 2012). However, the organic anions in some cases have been found not to acidify the medium, probably because once they are released in soil, they already exist in the dissociated form due to their low acid dissociation constants (pKa). In fact, it is assisted by the proton extrusion accompanying respiration and  $\text{NH}_4^{4+}$  assimilation (Illmer and Schinner 1992), which compensates for the losses of negative charge

and hence lowers the pH values. Organic anions are also involved in ligand exchange or ligand-enhanced desorption and/or chelation of Fe and Al oxides and Ca phosphates, thereby decreasing the positive surface potential on the metal oxide (Filius et al. 1991) and releasing the inaccessible P from the soil matrix (Raghothama and Karthikeyan 2005). The extent of solubilization by actinomycetes however depends on (1) the source of inorganic P (Pi), (2) the intrinsic PS ability of actinomycetal species, and (3) the types and composition of photosynthates available in the rhizospheres (Banik and Dey 1982). Interestingly, both solubilization (acidification of inorganic P) and mineralization (enzymatic dissolution of organic P) may coexist in the same PS actinomycetal strains (Tao et al. 2008).

Recently, numerous rhizoactinomycetes capable of solubilizing insoluble P have been identified (Franco-Correa et al. 2010; Pragma et al. 2012). For example, apart from soil actinomycetes, many marine actinomycetes have also shown the production of phosphatase which consequently enhanced the P availability (Sahu et al. 2007). In a similar study, Franco-Correa et al. (2010) reported that 20 % of the actinomycetes including *Streptomyces* and *Thermobifida*, isolated from the rhizosphere of *Trifolium repens*, grown in the fields of Sabana de Bogotá, Colombia, had quite active P-solubilizing activity. Even though all isolates produced acid phosphatase wherein 43 % isolates demonstrated alkaline phosphatase, which indicated that all the test actinomycete strains could mineralize the organic P sources (Richardson et al. 2009). Among phosphatases, acid phosphatases, a group of enzymes produced by plants/microbes in response to P stress, catalyze hydrolysis of phosphoric esters in a range of organic P complexes, thereby enhancing plant P uptake (Tarafdar and Claassen 1988; Tarafdar and Claassen 2001; Richardson et al. 2011) from unavailable P resources. There are also some other enzymes secreted by actinomycetes that take part in the dissolution process. As an example, Reza-Ghorbani-Nasrabadi et al. (2012) assessed 97 soil samples collected from different soil ecosystems and showed for the first time that actinomycetes had extracellular phytate-degrading activity. Phytases are a group of enzyme responsible for stepwise dephosphorylation of phytate, the most abundant inositol phosphate in nature. Of the total actinomycetal cultures, 46.3 % showed extracellular phytate-degrading activity in liquid culture medium supplemented with 4 g/l Na-phytate as sole P source. The two more closely studied phytase producers were identified according to 16SrRNA sequencing as *Streptomyces* (sp. isolate No. 43 showed 98 % similarity to *Streptomyces alboniger* and *S. venezuelae*, while isolate No. 63 exhibited 98 % sequence relatedness with *S. ambofaciens* and *S. lienomycini*).



### 6.3.4 *Actinomycetes as a Potential Candidate for Increased Plant Growth and Yield*

The agronomic use of PGPR at field scale in general has been hampered by poor understanding of mechanisms that facilitate plant growth, inability of bacterial strains to establish in various soils, rhizosphere incompetence, and changing environmental conditions. On the contrary, the actinobacteria with their ability to (1) sporulate, (2) transform various complex soil nutrients into simple and accessible forms, (3) extensively and efficiently colonize plant roots, (4) manage phytopathogens, and (5) secrete other plant-growth-promoting substances make these organisms as preferred choices for developing potential field bio-inoculants. Actinomycetes are metabolically flexible soil/rhizosphere-colonizing microorganisms (Miller et al. 1990; Euanorasetr et al. 2010; Lei et al. 2013) capable of producing a range of compounds of interest, including (1) antifungal compounds which have been found useful in controlling fungal root diseases (Rothrock and Gottlieb 1984; Zucchi et al. 2010; Bungonsiri et al. 2011; Sreevidya and Gopalakrishnan 2012; Francisco et al. 2013) (2) siderophores (Lee et al. 2012; Nakouti et al. 2012; Najwa et al. 2013), ACC deaminase (El-Tarabily 2008), and (3) plant-growth-promoting hormones (Hamdali et al. 2008a; Khamna et al. 2010). Generally, plant root exudates stimulate growth, proliferation, and rhizosphere colonization of actinomycetes that may act as a strong antagonist to fungal pathogens. The root exudates are utilized as a source of carbon and energy by the actinomycetes and, concomitantly, enhance the synthesis of antimicrobial substances (Crawford et al. 1993; Yuan and Crawford 1995). In addition, actinomycetes synthesize an array of biodegradative enzymes which includes chitinases (Blaak et al. 1993; Gupta et al. 1995; Pattanapitpaisal and Kamlandharn 2012; Sowmya et al. 2012), glucanases (Hopwood 1990; Damude et al. 1993; Mahadevan and Crawford 1996; Harchand and Singh 1997; Thomas and Crawford 1998; Trejo-Estrada et al. 1998; Fayad et al. 2001; Huiling et al. 2014), peroxidases (Ramachandra et al. 1988; Djamila et al. 2011), and other enzymes possibly involved in mycoparasitic activity. Considering the potential role of actinomycetes in the management of plant diseases and plant growth promotion by certain other mechanisms, actinomycetes in recent times are considered as one of the important aspects in sustainable plant production (Palaniyandi et al. 2013) as presented in Table 6.2.

The root-colonizing soil actinomycetes *S. lydicus* WYEC108, for instance, have been reported to influence pea root nodulation and increase the nodulation frequency possibly at the level of infection by *Rhizobium* spp. Following colonization, *S. lydicus* sporulate inside the surface cell layers of the nodules which in turn led to a massive increase in the nodules size. Subsequently, the forms and vigor of bacteroids were greatly improved due to enhanced assimilation of iron and possibly other soil nutrients within nodules. Moreover, bacteroid accumulation of the C storage polymer, poly- $\beta$ -hydroxybutyrate (PHB), was reduced in colonized nodules (Solans 2007). The co-inoculation of rhizoactinomycetes *Streptomyces* MM40,

**Table 6.2** Plant-growth-promoting traits exhibited by phosphate-solubilizing actinobacteria

Actinomycetes	Source of isolation	Test plant	Test condition	Plant-growth-promoting traits	References
<i>Micrococcus</i> sp. NH-0909	Western ghat forest soil in India	Cow pea	In vitro	Auxin production, 1-aminocyclopropane-1-carboxylate deaminase activity, and siderophore production	Dastager et al. (2010)
<i>Microbacterium azadirachtae</i> sp. nov. AI-S262 <sup>1</sup>	Rhizoplane of neem seedlings	–	Plate assay	IAA production, P solubilization, ACC deaminase activity, and sulfur oxidation	Madhaiyan et al. (2010)
<i>Streptomyces rochei</i> IDWR19, <i>Streptomyces carpinensis</i> IDWR53, <i>Streptomyces thermolilacinus</i> IDWR81	Wheat rhizosphere	–	Solid-state fermentation	Soil enzyme production (invertase, cellulase alkaline protease, phytase chitinase)	Jog et al. (2012)
<i>Streptomyces rochei</i> IDWR19, <i>Streptomyces thermolilacinus</i> IDWR81	Wheat rhizosphere	Wheat	Plant growth experiment	Increase in biomass of 1 × 8- and 2 × 3-fold; increase of shoot length of plants	Sheng et al. (2009)
<i>Microbacterium</i> sp. F10a	Oil-polluted soil	Wheat	Pot experiment	Significantly increased growth of wheat indoleacetic acid, siderophore, and 1-aminocyclopropane-1-carboxylate deaminase activity and solubilizing inorganic phosphate polycyclic aromatic hydrocarbon degrading (phenanthrene and pyrene removal)	Qin et al. (2014)
<i>Streptomyces</i> , <i>Microbacterium</i>	Inner tissues of a traditional Chinese folk medicine	–	In vitro		

<i>Streptomyces griseus</i> related strain BH7	<i>Limonium sinense</i> (Girard) Kuntze	Benguerir phosphate mine, Morocco	Wheat ( <i>Triticum durum</i> L.)	Test tube and rock phosphate soil experiment	Indole-3-acetic acid (IAA), N <sub>2</sub> -fixation, ACC deaminase	Hamdali et al. (2008c)
<i>Streptomyces tsusimaensis</i> , <i>Streptomyces caviscabies</i> , <i>Streptomyces setoni</i> , <i>Streptomyces africanus</i> , and an identified species of <i>Streptomyces</i>	Herbal vermicomposts		Sorghum	Greenhouse conditions	Enhanced aerial growth in more than 70 % of test tube and more than 30 % of RP soil as compared to non-inoculated control treatment	Gopalakrishnan et al. (2013)
			Rice	Field conditions	Enhanced plant height, leaf area, stem weight, leaf weight, root length, root surface area, root volume, and root dry weight over the control	
					Enhanced plant height, tillers, primary and secondary panicle number, panicle length, stover and grain yield, total dry matter, and test seed weight over the control. Root length, root volume, and root dry weight significantly enhanced in inoculated plots over the control	Gopalakrishnan et al. (2011)
Actinomycetes strains	Rhizosphere of <i>Araucaria angustifolia</i>		Chickpea	Plate assay	Biocontrol traits against Fusarium wilt	Vasconcellos et al. (2010)
					Indoleacetic acid and chitinases	(continued)

Table 6.2 (continued)

Actinomycetes	Source of isolation	Test plant	Test condition	Plant-growth-promoting traits	References
<i>Streptomyces</i> MCR10, <i>Thermobifida</i> MCR24, <i>Nocardia</i> MCR32, and other unidentified actino- mycete strains	Rhizosphere of <i>Trifolium repens</i> L.	Clover plants ( <i>T. repens</i> L.)	Pot experiment	Siderophore production but few unidentified strains also showed growth in N-free media suggesting that they could be nitrogen- fixing bacteria	Franco-Correa et al. (2010)
<i>Streptomyces</i> MCR9, <i>Thermobifida</i> MCR24, and <i>Streptomyces</i> MCR 26	Rhizosphere of <i>Trifolium repens</i> L.	Clover plants ( <i>T. repens</i> L.)	Co-inoculation with AM fungi <i>Glomus mosseae</i> without host; in vitro and in soil	Stimulated mycelial develop- ment from <i>G. mosseae</i> spores; MCR9 and MCR26 also showed stimulated germination of AM spores	Franco-Correa et al. (2010)
			Pot experiment with host; co-inoculated with AM fungi <i>Glomus mosseae</i>	Significant plant growth (par- ticularly shoot biomass at the end of the assay) Increased N and P acquisition by plants due to synergic effect	Franco-Correa et al. (2010)
<i>Streptomyces</i> spp., <i>Saccharo- polyspora</i> spp., <i>Actinopolyspora</i> spp., <i>Nocardia</i> spp.	Tissue pieces of leaves, stems, and root of rice ( <i>Oryza sativa</i> )	–	Plate assays	Increased the total mycorrhizal root length of <i>Glomus</i> inoculated plants IAA and siderophore produc- tion, antifungal activity against <i>Aspergillus niger</i> , <i>Alternaria brassicicola</i> , <i>Chaetomium globosum</i> , <i>Fusarium oxysporum</i> , <i>Phytophthora dreselea</i> , <i>Rhizoctonia solani</i> , <i>Botry- tis cinerea</i>	Gangwar et al. (2012)

*Actinoplanes* ME3, and *Micromonospora* MM18 has been found to promote the growth of *Discaria trinervis* in symbiosis with *Frankia*; however, no plant-growth-promoting effect was observed when rhizoactinomycetes were applied alone to the plant (Solans 2007). In a similar study, Hamdali et al. (2010) isolated a population of PS actinomycetes spp. from Moroccan phosphate mines and tested their growth-promoting efficacy using wheat as a test plant. The most active RP-solubilizing strains had the highest stimulatory effect on the production of plant biomass. Of the various isolated actinomycetes strains, strain BH7 of *Streptomyces griseus* stimulated aerial growth of the plant by 70 % in test tubes and more than 30 % in RP soil compared to the non-inoculated control plants. In another study, the actinomycetes showed P solubilization activity ( $1,916 \text{ mg l}^{-1}$ ) and produced phytase ( $0.68 \text{ U ml}^{-1}$ ), chitinase ( $6.2 \text{ U ml}^{-1}$ ), IAA ( $136.5 \text{ mg l}^{-1}$ ), and siderophore ( $47.4 \text{ mg l}^{-1}$ ). Furthermore, inoculation of *Streptomyces* mhcr0816 and mhce0811 with *Triticum aestivum* (wheat) significantly improved plant growth, biomass (33 %), and mineral (Fe, Mn, P) content in non-axenic conditions (Jog et al. 2014).

## 6.4 Conclusion

In order to reduce the environmental and economic stress due to massive use of synthetic fertilizers and to achieve food security goals, the use of actinomycete as biofertilizers in intensive agriculture practices appears to be a sound, inexpensive, and eco-friendly option. Even though the physiological functions and symbiotic roles of actinomycetes have been revealed under in vitro condition, the role of actinomycetes in sustainable crop production is not adequately explored. Considering the importance of actinomycetes in plant growth promotion via disease suppression and some other mechanisms, there is urgent need to popularize and maximize the use of actinomycetes in crop production in order to reduce dependence on chemical fertilizers and hence to preserve soil fertility without damaging the soil dwellers.

## References

- Abdulla H (2009) Bioweathering and biotransformation of granitic rock minerals by actinomycetes. *Microb Ecol* 58:753–761
- Ahmad E, Khan MS, Zaidi A (2013) ACC deaminase producing *Pseudomonas putida* strain PSE3 and *Rhizobium leguminosarum* strain RP2 in synergism improves growth, nodulation and yield of pea grown in alluvial soils. *Symbiosis* 61:93–104
- Amoroso MJ, Benimeli CS, Cuozzo SA (2013) Actinobacteria: application in bioremediation and production of industrial enzymes. CRC, Boca Raton, FL, p 296
- Araújo JM, Silva AC, Azevedo JL (2000) Isolation of endophytic actinomycetes from roots and leaves of maize (*Zea mays* L.). *Braz Arch Biol Technol* 43:447–451

- Balagurunathan R, Radhakrishnan M (2007) Actinomycetes: diversity and their importance. In: Trivedi PC (ed) Microbiology—applications and current trends. Pointer Publishers, Rajasthan, India, pp 297–329
- Balemi T, Negisho K (2012) Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. *J Soil Sci Plant Nutr* 12:547–561
- Banik S, Dey BK (1982) Available phosphate content of an alluvial soil as influenced by inoculation of some isolated phosphate solubilizing bacteria. *Plant Soil* 69:353–364
- Barreto TR, da Silva ACM, Soares ACF, de Souza JT (2008) Population densities and genetic diversity of actinomycete associated to the rhizosphere of *Theobroma cacao*. *Braz J Microbiol* 39:464–470
- Berdy J (2005) Bioactive microbial metabolites. *J Antibiot* 58:1–26
- Beunemann EK, Prusisz B, Ehlers K (2011) Characterization of phosphorus forms in soil microorganisms. In: Bunemann E et al (eds) Phosphorus in action, soil biology, vol 26. Springer, Heidelberg, pp 37–57
- Blaak H, Schnellmann J, Walter S, Henrissat B, Schrempf H (1993) Characteristics of an exo-chitinase from *Streptomyces olivaceoviridis*, its corresponding gene, putative protein domains and relationship to other chitinases. *Eur J Biochem* 214:659–669
- Bungonsiri I, Isada M, Takuya N, Yasuhiro I, Watanalai P (2011) Identification of actinomycetes from plant rhizospheric soils with inhibitory activity against *Colletotrichum* spp., the causative agent of anthracnose disease. *BMC Res Notes* 4:98
- Busti E, Monciardini P, Cavaletti L, Bamonte R, Lazzarini A, Sosio M, Donadio S (2006) Antibiotic-producing ability by representatives of a newly discovered lineage of actinomycetes. *Microbiology* 152:675–683
- Crawford DL, Lynch JM, Whipps JM, Ousley MA (1993) Isolation and characterization of actinomycete antagonists of a fungal root pathogen. *Appl Environ Microbiol* 59:3899–3905
- Damude HG, Gilkes NR, Kilburn DG, Miller RC Jr, Warren RA (1993) Endoglucanase CasA from alkalophilic *Streptomyces* strain KSM-9 is a typical member of family B of beta-1,4-glucanases. *Gene* 123:105–107
- Dastager SG, Deepa CK, Pandey A (2010) Isolation and characterization of novel plant growth promoting *Micrococcus* sp NII-0909 and its interaction with cowpea. *Plant Physiol Biochem* 48:987–992
- de Boer W, Folman LB, Summerbell RC, Boddy L (2005) Living in a fungal world: impact of fungi on soil bacterial niche development. *FEMS Microbiol Rev* 29:795–811
- de Vasconcellos RLF, da Silva MCP, Ribeiro CM, Cardoso EJBN (2010) Isolation and screening for plant growth-promoting (PGP) actinobacteria from *Araucaria angustifolia* rhizosphere soil. *Sci Agric* 67(6):743–746
- Debananda SN, Suchitra S, Tamreihao K, Salam N (2009) Antagonistic activities of local actinomycete isolates against rice fungal pathogens. *Afr J Microb Res* 3:737–742
- Delvasto P, Valverde A, Ballester A, Igual JM, Muñoz JA, González F, Blázquez ML, García C (2006) Characterization of brushite as a re-crystallization product formed during bacterial solubilization of hydroxyl-apatite in batch cultures. *Soil Biol Biochem* 38:2645–2654
- Djamila F, Abdelmalek B, Bassem J, Nedja Z, Fatma ZF, Houcine B (2011) Purification and characterization of two extracellular peroxidases from *Streptomyces* sp. strain AM2, a decolorizing actinomycetes responsible for the biodegradation of natural humic acids. *Int Biodeterior Biodegradation* 65:470–478
- Donahue RL, Miller RW, Shickluna JC (1990) Soils: an Introduction to Soils and Plant Growth. Prentice Hall, New Delhi, India, pp 222–234
- Elliot LF, Lynch JM (1995) The international workshop on establishment of microbial inocula in soils: cooperative research project on biological resource management of the organization for economic cooperation and development (OECD). *Am J Alt Agric* 10:50–73
- Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE (2007) Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol Lett* 10:1135–1142

- El-Tarabily KA (2008) Promotion of tomato (*Lycopersicon esculentum* Mill.) plant growth by rhizosphere competent 1-aminocyclopropane-1-carboxylic acid deaminase-producing streptomycete actinomycetes. *Plant Soil* 308:161–174
- El-Tarabily KA, Nassar AH, Sivasithamparam K (2008) Promotion of growth of bean (*Phaseolus vulgaris* L.) in a calcareous soil by a phosphate solubilizing rhizosphere-competent isolate of *Micromonospora endolithica*. *Appl Soil Ecol* 39:161–171
- Errakhi R, Bouteau F, Lebrihi A, Barakate M (2007) Evidences of biological control capacities of *Streptomyces* spp. Against *Sclerotium rolfsii* responsible for damping-off disease in sugar beet (*Beta vulgaris* L.). *World J Microbiol Biotechnol* 23:1503–1509
- Errakhi R, Lebrihi A, Barakate M (2009) *In vitro* and *in vivo* antagonism of actinomycetes isolated from Moroccan rhizospheric soils against *Sclerotium rolfsii*; a causal agent of root rot on sugar beet (*Beta vulgaris* L.). *J Appl Microbiol* 107:672–681
- Euanorasetr J, Nilvongse A, Tantimavanich S, Nihira T, Igarashi Y, Panbangred W (2010) Identification and characterization of soil-isolated *Streptomyces* SJE177 producing actinomycin. *Southeast Asian J Trop Med Public Health* 41:1177–1187
- Fabre B, Armau E, Etienne G, Legendre F, Tiraby G (1988) A simple screening method for insecticidal substances from actinomycetes. *J Antibiot* 41:212–219
- FAOSTAT (2012) <http://faostat.fao.org/site/575/default.aspx#ancor>. Last access date 02/05/2012
- Fayad K, Simao-Beauanoir AM, Gauthier A, Leclerc C, Mamady H, Beaulieu C, Brzezinski R (2001) Purification and properties of a  $\beta$ -1,6-glucanase from *Streptomyces* sp. EF-14, an actinomycete antagonistic to *Phytophthora* spp. *Appl Microbiol Biotechnol* 57:117–123
- Fernández LA, Zalba P, Gómez 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
- Figueiredo MVB, Seldin L, Araujo FF, Mariano RLR (2010) Plant growth promoting rhizobacteria: fundamentals and applications. In: Maheshwari DK (ed) *Plant growth and health promoting bacteria*. Springer, Berlin, pp 21–43
- Filius JD, Hiemstra T, van Riemsdijk WH (1991) Adsorption of small weak organic acids on goethite: modeling of mechanisms. *J Colloid Interface Sci* 195:368–380
- Francisco GC, Tiago DZ, Itamar SDM (2013) Biological control of phytopathogenic fungi by endophytic actinomycetes isolated from maize (*Zea mays* L.). *Braz Arch Biol Technol* 56:948–955
- Franco-Correa M, Quintana A, Duque C, Suarez C, Rodríguez MX, Barea J (2010) Evaluation of actinomycete strains for key traits related with plant growth promotion and mycorrhiza helping activities. *Appl Soil Ecol* 45:209–217
- Froni L (2006) *Microbiología: básica, ambiental y agrícola*. Universidad de la República, Facultad de Agronomía, Uruguay, Montevideo, Uruguay
- Gangwar M, Rani S, Sharma N (2012) Investigating endophytic actinomycetes diversity from rice for plant growth promoting and antifungal activity. *Int J Adv Life Sci* 1:10–21
- Genilloud O, González I, Salazar O, Martín J, Tormo JR, Vicente F (2011) Current approaches to exploit actinomycetes as a source of novel natural products. *J Ind Microbiol Biotechnol* 38:375–389
- Ghai R, McMahan KD, Rodríguez-Valera F (2012) Breaking a paradigm: cosmopolitan and abundant freshwater actinobacteria are low GC. *Environ Microbiol Rep* 4:29–35
- Goodfellow M (1971) Numerical taxonomy of some nocardioform bacteria. *J Gen Microbiol* 69:33–90
- Gopalakrishnan S, Pande S, Sharma M, Humayun P, Kiran BK, Sandeep D, Vidya MS, Deepthi K, Rupela O (2011) Evaluation of actinomycete isolates obtained from herbal vermicompost for biological control of *Fusarium* wilt of chickpea. *Crop Prot* 30:1070–1078
- Gopalakrishnan S, Srinivas V, Vidya SM, Rathore A (2013) Plant growth-promoting activities of *Streptomyces* spp. in sorghum and rice. *Springer Plus* 2:574. doi:10.1186/2193-1801-2-574

- Gupta R, Saxena RK, Chaturvedi P, Viridi JS (1995) Chitinase production by *Streptomyces viridificans* *Streptomyces viridificans*: its potential in fungal cell wall lysis. *J Appl Bacteriol* 78:378–383
- Gupta N, Sahoo D, Basak U (2010) Evaluation of *in vitro* solubilization potential of phosphate solubilising *Streptomyces* isolated from phyllosphere of *Heritiera fomes* (mangrove). *Afr J Microbiol Res* 4:136–142
- Hamdali H, Hafidi M, Virolle MJ, Ouhdouch Y (2008a) Rock phosphate-solubilizing Actinomycetes: screening for plant growth-promoting activities. *World J Microbiol Biotechnol* 24:2565–2575
- Hamdali H, Bouizgarne B, Hafidi M, Lebrihi A, Virolle MJ, Ouhdouch Y (2008b) Screening for rock phosphate solubilizing Actinomycetes from Moroccan phosphate mines. *Appl Soil Ecol* 38:12–19
- Hamdali H, Hafidi M, Virolle MJ, Ouhdouch Y (2008c) Growth promotion and protection against damping-off of wheat by two rock phosphate solubilizing Actinomycetes in a P-deficient soil under greenhouse conditions. *Appl Soil Ecol* 40:510–517
- Hamdali H, Hafidi M, Virolle MJ, Ouhdouch Y (2008d) Actinomycetes with multiple PGPR activities. *World J Microbiol Biotechnol* 24:2565–2575
- Hamdali H, Smirnov A, Esnault C, Ouhdouch Y, Virolle MJ (2010) Physiological studies and comparative analysis of rock phosphate solubilization abilities of actinomycetales originating from Moroccan Phosphate mines and of *Streptomyces lividans*. *Appl Soil Ecol* 44:24–31
- Hamdali H, Moursalou K, Tchangbedji G, Ouhdouch Y, Hafidi M (2012) Isolation and characterization of rock phosphate solubilizing actinobacteria from a Togolese phosphate mine. *Afr J Biotechnol* 11:312–320
- Harchand RK, Singh S (1997) Characterization of cellulase complex of *Streptomyces albaduncus*. *J Basic Microbiol* 37:93–103
- Hinsinger P (2001) Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil* 237:173–195
- Hoberg E, Marschner P, Lieberei R (2005) Organic acid exudation and pH changes by *Gordonia* sp. and *Pseudomonas fluorescence* grown with P adsorbed to goethite. *Microbiol Res* 160:177–187
- Hopwood D (1990) Antibiotic biosynthesis in *Streptomyces*. In: Hopwood DA, Chater K (eds) Genetics of bacterial diversity. Academic, London, pp 129–148
- Hooster F, Schmitz JE, Daniel R (2005) Enrichment of chitinolytic microorganisms: isolation and characterization of a chitinase exhibiting antifungal activity against phytopathogenic fungi from a novel *Streptomyces* strain. *Appl Microbiol Biotechnol* 66:434–442
- Hsu SC, Lockwood JL (1975) Powdered chitin agar as a selective medium for enumeration of actinomycetes in water and soil. *Appl Microbiol* 29:422–426
- Huiling W, Dan D, Jinjin L, Weicheng L, Ting L, Taotao Z, Zhaofeng T (2014) Efficient transformation and expression of the glucanase gene from *Bacillus megaterium* in the biocontrol strain *Streptomyces lydicus* A02. *Biocontrol Sci Technol* 24:90–102
- Illmer P, Schinner F (1992) Solubilization of inorganic phosphates by microorganisms isolated from forest soils. *Soil Biol Biochem* 24:389–395
- Jensen PR, Mincer TJ, Williams PG, Fenical W (2005) Marine actinomycete diversity and natural product discovery. *Anton Leeuw* 87:43–48
- Jiang Y, Li WJ, Xu P, Tang SK, Xu LH (2005) Study on diversity of Actinomycetes salt and alkaline environments. *Wei Sheng Wu Xue Bae* 46(2):191–195
- Jog R, Nareshkumar G, Rajkumar S (2012) Plant growth promoting potential and soil enzyme production of the most abundant *Streptomyces* spp. from wheat rhizosphere. *J Appl Microbiol* 113:1154–1164
- Jog R, Pandya M, Nareshkumar G, Rajkumar S (2014) Mechanism of phosphate solubilization and antifungal activity of *Streptomyces* spp. isolated from wheat roots and rhizosphere and their application in improving plant growth. *Microbiology* 160:778–88. doi:10.1099/mic.0.074146-0



- Johansson JF, Paul LR, Finlay RD (2004) Microbial interactions in the mycorrhizosphere and their significance for sustainable agriculture. *FEMS Microbiol Ecol* 48:1–13
- Johnson SE, Loepper RH (2006) Role of organic acids in phosphate mobilization from iron oxide. *Soil Sci Soc Am J* 70:222–234
- Keiser T, Bibb MJ, Buttner MJ, Chater KF, Hopwood DA (eds) (2000) General introduction to actinomycete biology. In: *Practical Streptomyces genetics*. The John Innes Foundation, Crowes, Norwich, pp 1–21. ISBN: 0-7084-0623-8
- Khamna S, Akira Y, Peberdy JF, Saisamorn L (2010) Indole-3-acetic acid production by *Streptomyces* sp. isolated from some Thai medicinal plant rhizosphere soils. *EurAsia J BioSci* 4:23–32
- 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
- Kunoh H (2002) Endophytic actinomycetes: attractive biocontrol agents. *J Gen Plant Pathol* 68:249–252
- Lee SO, Choi GJ, Choi YH, Jang KS, Park DJ, Kim CJ et al (2008) Isolation and characterization of endophytic actinomycetes from Chinese cabbage roots as antagonists to *Plasmodiophora brassicae*. *J Microbiol Biotechnol* 18:1741–1746
- Lee J, Postmaster A, Soon HP, Keast D, Carson KC (2012) Siderophore production by actinomycetes isolates from two soil sites in Western Australia. *Biometals* 5:285–926
- Lei X, Quanhong X, Qin C, Chaofeng L, Guanghui S, Juan Z (2013) Isolation and evaluation of rhizosphere actinomycetes with potential application for biocontrol of Verticillium wilt of cotton. *Crop Prot* 43:231–240
- Lievien V, Peiffer I, Hudault S, Rochat F, Brassart D, Neeser JR, Servin AL (2000) *Bifidobacterium* strains from resident infant human gastrointestinal microflora exert antimicrobial activity. *Gut* 47:646–652
- Madhaiyan M, Poonguzhali S, Lee JS, Lee KC, Saravanan SK, Santhanakrishnan P (2010) *Microbacterium azadirachtae* sp. nov., a plant-growth-promoting actinobacterium isolated from the rhizoplane of neem seedling. *Int J Syst Evol Microbiol* 60:1687–1692
- Mahadevan B, Crawford DL (1996) Purification of chitinase from the biocontrol agent *Streptomyces lydicus* WYEC108. *Enzyme Microb Technol* 20:489–493
- Matsumoto A, Takahashi Y, Mochizuki M, Seino A, Iwai Y, Omura S (1998) Characterization of actinomycetes isolated from fallen leaves. *Actinomycetologica* 12:46–48
- Miller JJ, Liljeroth E, Williamsen-De Klein MJEIM, Veen JAV (1990) The dynamics of actinomycetes and fluorescent pseudomonads in wheat rhizoplane and rhizosphere. *Symbiosis* 9:389–391
- Najwa E, Cho ZS, Jiesi G, Rachel C (2013) The variable hydroxamic acid siderophore metabolome of the marine actinomycete *Salinispora tropica* CNB-440. *Metallomics* 5:1519–1528
- Nakouti I, Sihanonth P, Hobbs G (2012) A new approach to isolating siderophore-producing actinobacteria. *Lett Appl Microbiol* 55:68–72
- Nath AK, Borah DK (1983) A study on the release on native and applied fixed phosphate as affected by pH and moisture regime. *Indian J Agric Chem* 16:247–251
- Nonomura H (1989) Genus *Streptosporangium* Couch 1955, 148AL. In: Williams ST (ed) *Bergey's manual of systematic bacteriology*, vol 4. The Williams & Wilkins Co., Baltimore, pp 2545–2551
- Nonomura H, Ohara Y (1969) Distribution of actinomycetes in soil. (VI). A culture method effective for both preferential isolation and enumeration of *Microbispora* and *Streptosporangium* strains in soil (part 1). *J Ferment Technol* 47:463–469
- Norovsuren Z, Zenova G, Mosina L (2007) Actinomycetes in the rhizosphere of semi-desert soils of Mongolia. *Eurasian Soil Sci* 40:415–418
- Palaniyandi SA, Yang SH, Zhang L, Suh WJ (2013) Effects of actinobacteria on plant disease suppression and growth promotion. *Appl Microbiol Biotechnol* 97:9621–9636

- Pan J, Plant JA, Voulvoulis N, Oates CJ, Ihlenfeld C (2010) Cadmium levels in Europe: implications for human health. *Environ Geochem Health* 32:1–12
- Pathom-Aree W, Stach JE, Ward AC, Horikoshi K, Bull AT, Goodfellow M (2006) Diversity of actinomycetes isolated from Challenger Deep sediment (10,898 m) from the Mariana Trench. *Extremophiles* 10:181–189
- Pattanapitpaisal P, Kamlandham R (2012) Screening of chitinolytic actinomycetes for biological control of *Sclerotium rolsii* stem rot disease of chilli. *Songklanakarin J Sci Technol* 34:387–393
- Pikovskaya RI (1948) Mobilization of phosphorus in soil in connection with vital activity of some microbial species. *Microbiology* 17:362–370
- Pogell BM, Zhang HL, Feng YM (1991) Expression of veratryl alcohol oxidase activity and cloned fungal lignin peroxidase in *Streptomyces lividans*. International symposium on biology of actinomycetes. Madison, WI
- Pragya R, Yasmin A, Anshula J (2012) An insight into agricultural properties of actinomycetes. *Int J Res BioSci* 1:7–12
- Prapagdee B, Kuekulvong C, Mongkolsuk S (2008) Antifungal potential of extracellular metabolite produced by *Streptomyces hygroscopicus* against phytopathogenic fungi. *Int J Biol Sci* 4:330–337
- Pridham TG, Tresner HD (1974) Streptomycetaceae. In: Buchanan RE, Gibbons NE (eds) Bergey's manual of determinative bacteriology, 8th edn. Williams & Wilkins, Baltimore, p 747
- Qin S, Wang HB, Chen HH, Zhang YQ, Jiang CL, Xu LH, Li WJ (2008) *Glycomyces endophyticus* sp. nov., an endophytic actinomycete isolated from the root of *Carex baccans* Nees. *Int J Syst Evol Microbiol* 58:2525–2528
- Qin S, Xing K, Jiang JH, Lu IH (2011) Biodiversity, bioactive natural products and biotechnological potential of plant-associated endophytic actinobacteria. *Appl Microbiol Biotechnol* 89:457–473
- Qin S, Zhang YJ, Yuan B, Xu PY, Xing K, Wang J, Jiang JH (2014) Isolation of ACC deaminase-producing habitat-adapted symbiotic bacteria associated with halophyte *Limonium sinense* (Girard) Kuntze and evaluating their plant growth-promoting activity under salt stress. *Plant Soil* 374:753–766
- Raghothama KG (1999) Phosphate acquisition. *Annu Rev Plant Physiol Plant Mol Biol* 50:665–693
- Raghothama KG, Karthikeyan AS (2005) Phosphate acquisition. *Plant Soil* 274:37–49
- Rai R, Dash PK, Prasanna BM, Singh A (2007) Endophytic bacterial flora in the stem tissue of a tropical maize (*Zea mays* L.) genotype: isolation, identification and enumeration. *World J Microbiol Biotechnol* 23:853–858
- Ramachandra M, Crawford DL, Hertel G (1988) Characterization of an extracellular lignin peroxidase of the lignocellulolytic actinomycete *Streptomyces viridosporus*. *Appl Environ Microbiol* 54:3057–3063
- Rengel Z, Marschner P (2005) Nutrient availability and management in the rhizosphere: exploiting genotypic differences. *New Phytol* 168:305–312
- Reza-Ghorbani-Nasrabadi GR, Alikhani HA, Hamed J (2012) Identification and determination of extracellular phytate-degrading activity in actinomycetes. *World J Microbiol Biotechnol* 28:2601–2608
- Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant Soil* 321:305–339
- Richardson AE, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Ryan MH, Veneklaas EJ, Lambers H, Oberson A, Culvenor RA, Simpson RJ (2011) Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant Soil* 349:121–156
- Rothrock CS, Gottlieb D (1984) Role of antibiosis in antagonism of *Streptomyces hygroscopicus* var. *geldanus* to *Rhizoctonia solani* in soil. *Can J Microbiol* 30:1440–1447

- Sabaou N, Boudjella H, Bennadji A, Mostefaoui A, Zitouni A, Lamari L, Bennadji H (1998) Les sols des oasis du Sahara algérien, source d'actinomycètes rares producteurs d'antibiotiques. *Sécheresse* 9:147–153
- Sahu MK, Sivakumar K, Kannan L (2007) Phosphate solubilizing actinomycetes in the estuarine environment: an inventory. *J Environ Biol* 28:795–798
- Salcedo LDP, Prieto C, Correa MF (2014) Screening phosphate solubilizing actinobacteria isolated from the rhizosphere of wild plants from the Eastern Cordillera of the Colombian Andes. *Afr J Microbiol Res* 8:734–742
- Shen J, Yuan L, Zhang J, Li H, Bai Z, Chen X, Zhang W, Zhang F (2011) Phosphorus dynamics: from soil to plant. *Plant Physiol* 156:997–1005
- Sheng XF, He LY, Zhou L, Shen YY (2009) Characterization of *Microbacterium* sp. F10a and its role in polycyclic aromatic hydrocarbon removal in low-temperature soil. *Can J Microbiol* 55:529–535
- Smil V (2000) Phosphorus in the environment: natural flows and human interferences. *Annu Rev Energy Environ* 25:53–88
- Solans M (2007) *Discaria trinervis*-*Frankia* symbiosis promotion by saprophytic actinomycetes. *J Basic Microbiol* 47:243–250
- Solans M, Vobis G (2003) Actinomycetes saprofíticos asociados a la rizósfera y rizoplaneo de *Discaria trinervis*. *Ecol Aust* 13:97–107
- Sowmya B, Gomathi D, Kalaiselvi M, Ravikumar G, Arulraj C, Uma C (2012) Production and purification of chitinase by *Streptomyces* sp. from soil. *J Adv Sci Res* 3:25–29
- Sreevidya M, Gopalakrishnan S (2012) Bacteria and actinomycetes as biocontrol agents for the control of fungal pathogens of chickpea and sorghum. In: International conference on plant health management for food security, 28–30 November 2012, Hyderabad, India
- Strap JL (2011) Actinobacteria-plant interactions: a boon to agriculture. In: Maheshwari DK (ed) *Bacteria in agrobiolgy: plant growth responses*. Springer, Berlin, pp 285–307. doi:10.1007/978-3-642-20332-9\_13
- Syers JK, Johnston AE, Curtin D (2008) Efficiency of soil and fertiliser phosphorus use: reconciling changing concepts of soil phosphorus behaviour with agronomic information. *FAO Fertiliser and Plant Bulletin* 18. Food and Agricultural Organization of the United Nations. Rome, ISBN 978-92-5-105929-6
- Takahashi S, Anwar MR (2007) Wheat grain yield, phosphorus uptake and soil phosphorus fraction after 23 years of annual fertilizer application to an Andosol. *Field Crops Res* 101:160–171
- Takahashi Y, Omura S (2003) Isolation of new actinomycete strains for the screening of new bioactive compounds. *J Gen Appl Microbiol* 49:141–154
- Takisawa M, Colwell RR, Hill RT (1993) Isolation and diversity of actinomycetes in the Chesapeake Bay. *Appl Environ Microbiol* 59:997–1002
- Tao G, Tian S, Cai M, Xie G (2008) Phosphate solubilizing and mineralizing abilities of bacteria isolated from soils. *Pedosphere* 18:515–523
- Tarafdar JC, Claassen N (1988) Organic phosphorus compounds as a phosphorus source for higher plants through the activity of phosphatases produced by plant roots and microorganisms. *Biol Fertil Soils* 5:308–312
- Tarafdar JC, Claassen N (2001) Comparative efficiency of acid phosphatase originated from plant and fungal sources. *J Plant Nutr Soil Sci* 164:279–282
- Thangapandian V, Ponnuragan P, Ponnuragan K (2007) Actinomycetes diversity in the rhizosphere soil of different medicinal plants in Kolly Hills Tamil Nadu, India, for secondary metabolite production. *Asian J Plant Sci* 6:66–70
- Thomas L, Crawford DL (1998) Cloning of clustered *S. viridosporus* T7A lignocellulose catabolism genes encoding peroxidase and endoglucanase and their extracellular expression in *Pichia pastoris*. *Can J Microbiol* 44:364–372
- Tirado R, Allsopp M (2012) Phosphorus in agriculture problems and solutions; Greenpeace Research Laboratories Technical Report

- Trejo-Estrada SR, Paszczynski A, Crawford DL (1998) Antibiotics and enzymes produced by the biological control agent *Streptomyces violaceusniger* YCED-9. *J Ind Microbiol Technol* 21:81–90
- Valverde A, Igual JM, Peix A, Cervantes E, Velázquez E (2006) *Rhizobium lusitanum* sp. nov. a bacterium that nodulates *Phaseolus vulgaris*. *Int J Syst Evol Microbiol* 56:2631–2637
- Vance CP, Uhde-Stone C, Allan D (2003) Phosphorus acquisition and use: critical adaptation by plants for securing non-renewable resources. *New Phytol* 15:423–447
- Vassilev N, Eichler-Löbermann B, Vassileva M (2012) Stress-tolerant P-solubilizing microorganisms. *Appl Microbiol Biotechnol* 95:851–859
- Waksman SA (1950) The actinomycete their nature occurrence activities and importance. Chronica Botanica Company, Waltham, MA
- Xu LH, Li QR, Jiang CL (1996) Diversity of soil actinomycetes in Yunnan, China. *Appl Environ Microbiol* 62:244–248
- Yuan WM, Crawford DL (1995) Characterization of *Streptomyces lydicus* WYEC108 as a potential biocontrol agent against fungal root and seed rots. *Appl Environ Microbiol* 61:3119–3128
- Zaidi A, Khan MS, Ahemad M, Oves M (2009) Plant growth promotion by phosphate solubilizing bacteria. *Acta Microbiol Immunol Hung* 56:263–284
- Zhang H, Shan B (2008) Historical records of heavy metal accumulation in sediments and the relationship with agricultural intensification in the Yangtze-Huaihe region, China. *Sci Total Environ* 399:113–120
- Zhang F, Shen J, Zhang J, Zuo Y, Li L, Chen X (2010) Rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China. *Adv Agron* 107:1–32
- Zou X, Binkley D, Doxtader KG (1992) A new method for estimating gross phosphorus mineralization and immobilization rates in soils. *Plant Soil* 147:243–250
- Zucchi TD, Almeida LG, Dossi FCA, Cônsoli FL (2010) Secondary metabolites produced by *Propionicimonas* sp. (ENT-18) induce histological abnormalities in the sclerotia of *Sclerotinia sclerotiorum*. *BioControl* 55:811–819