Chapter

Managing Soil and Plant Nutrients: Role of Microbial Phosphate Solubilisation

A.A. Asanka Udaya Aberathna,
Dilan Amila Satharasinghe, Anura Prasantha Jayasooriya,
H. Rasika Niranjana Jinadasa, Sivabalan Manopriya,
B.P. Ajith Jayaweera, C. Annesly Nandana Fernando,
W.A. Dammika Vijitha Weerathilake, G.A. Prathapasinghe,
Janitha Abeywickrema Liyanage and
J.M. Krishanthi Jayarukshi Kumari Premarathne

Abstract

Phosphorus (P) is one of the macronutrients required for the optimum growth and development of plants. The deficiency of P can be compensated by adding chemical fertilisers, which are expensive and have a negative impact on the ecosystem. Solubilisation of phosphate by microorganisms is an emerging application for eco-friendly and sustainable agriculture practices. This chapter discuss the importance of P for plants, the main problems related to the over-exploitation of natural reserves of P and chemical fertilisers, the diversity of phosphate-solubilising microorganisms (PSM), the ability of microorganisms to solubilise phosphates and key mechanisms of microbial P solubilisation, the capability of microorganisms to formulate phosphate-related nanoparticles, the potential of PSM to develop as commercial level biofertiliser and contribution of PSM for achieving Sustainable Development Goals (SDGs). This chapter will highlight the input of PSM in sustainable agriculture.

Keywords: phosphate, Solubilisation, microorganisms, plant, soil

1. Introduction

Phosphorous (P) is an essential macronutrient in plants [1, 2] which represents 0.12% of earth's crust [3, 4]. The sources of P are available in both organic and inorganic forms [2, 5], which are non-renewable and cannot be substituted [4, 6]. Rock phosphate (apatite) is the best P source compared to the other P resources such as soil, clay, plant and animal matter [4], which is commonly used for phosphate fertiliser production also [7]. Phosphorous is reaching to be a plant nutrient that will limit crop production in the next millennium. P is a major growth-limiting mineral, and unlike nitrogen, there is no large atmospheric source that can provide biologically available P. Furthermore, the low bioavailability of phosphate limits the efficacy of P fertiliser. As the option to manage the bioavailability of phosphate for plants, phosphate-solubilising microorganisms (PSM) can be an effective, eco-friendly and sustainable tool. PSM contributes to improving plant growth and yield while reducing the need for chemical fertilisers that can have negative impacts on the environment. Additionally, PSM phosphate solubilisation can help to improve the overall health and fertility of the soil, promoting sustainable agriculture practices [8].

2. Importance of P for plants

P is engaged in biological processes that are shared by all living species [1, 2, 9]. P, in particular, is the second most limiting macronutrient for plant growth, accounting for 0.2% of plant dry weight [10, 11] and serving as a critical element in animal bodies [12–14]. As a result, P has become a fundamental and necessary component for human well-being [15].

Functions of P in all living organisms included energy metabolism and transmission [1, 9], cell division [2], protein and nucleic acids (DNA and RNA) synthesis [9, 16, 17], being a key component of enzymes, coenzymes, and phospholipids [18] and cell division [2]. In addition, P is essential for plants for photosynthesis [2], nitrogen fixation [14], improving crop quality [14, 16], development of disease resistance [18], root development [3], development of the stems and stalks [15], flower and seed formation [10], conversion of sugar to starch [10], laying down the primordia of propagative parts during the early stages of plant development [16], and proper stress reduction and maturation of plant [10]. A lack of phosphorus can lead to stunted growth, delayed maturity, and lower yield. Therefore, it is essential to ensure that plants receive adequate phosphorus to maintain their health and productivity.

The world population is expected to exceed 9000 million in 2050 [19] and food production requires to be increased globally by 50% as compared to the demand in 2012 [20]. Usability of phosphate has been severely limited due to its low bioavailability. Furthermore, the wastage of phosphate that is unable to be utilised by plants and animals causes additional issues such as eutrophication [10, 21]. The low bioavailability of phosphate is driving its increasing usage, with peak extraction occurring in 2030 [22]. Therefore, the sustainable utilisation of phosphate is needed to increase its bioavailability to avoid the wastage of phosphate [4]. Using microorganisms to increase the bioavailability of phosphate is the emerging eco-friendly technique for sustainable utilisation of phosphate [10, 23].

3. Main problems related to the over-exploitation of natural reserves of P and chemical fertilisers

Global food production needs to be increased due to the rapidly increasing world population [20]. The low bioavailability of phosphate directly affects to not being able to fulfil the required amount of crop production. Due to the low bioavailability, an extra amount of phosphate has to be utilised as fertilisers to provide the optimum requirement of P of plants. Therefore, it is directed to high utilisation, and the peak extraction of phosphate will take place in 2030 [22]. Besides the depletion of natural P resources, over-exploitation of natural reserves of P and excessive use of chemical P fertilisers lead to several environmental and agricultural problems such as soil degradation, groundwater contamination, eutrophication and climate change [10, 21]. Hence, it is highly required for sustainable utilisation of phosphate to minimise wastage [4]. State-of-the-art technique to use microorganisms to solubilise the insoluble forms of phosphates and increase their bioavailability is an effective option [10, 23].

4. Diversity of phosphate-solubilising microorganisms (PSM)

PSM are diverse and can be found in various environments such as water, and plant tissues while the soil is the key habitat [10, 12]. The population of PSMs in soil ranges between 10^4 and 10^6 g^{-1} of soil, and they are accumulated at the rhizosphere of plants, and those organisms are highly metabolically active [10, 24]. In the microbial profile of soil, phosphate-solubilising bacteria (PSB) were responsible for 1–50%, whereas phosphate-solubilising fungi (PSF) represent 0.1–0.5%. The population density of PSB ranged between 8×10^5 and 5.33×10^9 in the different rhizospheres of vegetable fields, with PSB accounting for 3.98% of the total population of bacteria [25]. Most of PSBs are coccus, bacillus or spirillum in shape while the bacillus is the most abundant and spirillum are rare. However, there is a high diversity of PSM in the soil. Among these microbial species, *Bacillus* and *Pseudomonas* are the foremost bacterial genera [4, 12, 24].

The number of PSM is not sufficiently high to compete with other microbial species in the rhizosphere. The profile and population of these PSM vary between ecosystems due to the influence of complex biological factors [25]. Physical-chemical factors of soil such as the soil nutrient status, moisture content, organic matter, soil pH, and soil enzyme activities affect these variations [4, 12, 24]. The diversity of PSM (**Table 1**)

Microorganisms	Country	References
Achromobacter xylosoxidans	China	[26]
Acinetobacter calcoaceticus	Iran	[27]
Advenella mimigardefordensis	Spain	[28]
Arthrobacter luteolus	Iran	[27]
Aspergillus awamori	Indonesia	[29]
Aspergillus niger	India, China	[30, 31]
Aspergillus terreus	Indonesia	[29]
Bacillus amyloliquefaciens	Italy	[32]
Bacillus aryabhattai IA20	Pakistan	[33]
Bacillus cereus	Spain, Iran	[27, 28]
Bacillus cereus MZUTZ01	India	[34]
Bacillus firmus	Pakistan	[35]
Bacillus licheniformis	Pakistan	[35]
Bacillus megaterium	China, Brazil, Spain, Thailand	[28, 36–39]
Bacillus mojavensis	Thailand	[36]
Bacillus pumilus	Mexico	[37]
Bacillus safensis	Pakistan	[35]
Bacillus safensis IALR1035	USA	[38]

Microorganisms	**Country**	**References**
Bacillus siamensis	Mexico	[37]
Bacillus subtilis	India, Indonesia, Brazil	[29, 34, 39]
Bacillus subtilis IA6	Pakistan	[33]
Bacillus subtilis IALR1033	USA	[38]
Bacillus thuringensis MZUTZ13	India	[34]
Burkholderia cenocepacia	Indonesia	[29]
Burkholderia cepacia	Indonesia	[29]
Burkholderia cepacia ISOP5	China	[40]
Burkholderia fungorum	Spain	[28]
Burkholderia gladioli	India	[34]
Burkholderia seminalis	Indonesia	[29]
Burkholderia vietnamiensis	Iran	[27]
Cellulosimicrobium cellulans	China	[26]
Enterobacter bugandensis	Morocco	[41]
Enterobacter cloacae C8	China	[42]
Enterobacter hormaechei (LMG 27195)	China	[43]
Funneliformis mosseae	China	[44]
Funneliformis mosseae BEG234	Italy	[32]
Geobacillus stearothermophillus MZUTZ08	India	[34]
Klebsiella variicola	Brazil	[45]
Nocardiopsis alba	Morocco	[46, 47]
Novosphingobium barchaimii (LL02)	China	[43]
Novosphingobium resinovorum	China	[42]
Ochrobactrum haematophilum	China	[26]
Ochrobactrum pseudogrignonense	Brazil	[45]
Ochrobactrum pseudogrignonense (CCUG30717)	China	[43]
Paenibacillus polymyxa IA7	Pakistan	[33]
Pantoea agglomerans	Tunisia, Morocco	[41, 48]
Pantoea agglomerans IALR1325	USA	[38]
Pantoea agglomerans pv. P5	Iran	[49]
Pantoea ananatis	Brazil	[45]
Pantoea roadsii (LMG26273)	China	[43]
Pantoea stewartii subsp. *Indologenes*	Morocco	[41]
Pantoea vagans IALR611	USA	[38]
Paraburkholderia caffeinilytica (CF1)	China	[43]
Penicillium oxalicum	Pakistan	[35]
Pseudomonas agglomerans	Tunisia	[50]
Pseudomonas azotoformans	India	[51]

Microorganisms	Country	References
Pseudomonas brassicacearum supsp. *Neoaurantiaca*	Morocco	[41]
Pseudomonas cepaceae	Egypt	[52]
Pseudomonas donghuensis (HYS)	China	[43]
Pseudomonas fluorescens	Tunisia	[50]
Pseudomonas grimontii (CFML97 514)	China	[43]
Pseudomonas lactis	Morocco	[41]
Pseudomonas libanensis	Mexico	[37]
Pseudomonas mallei	Egypt	[52]
Pseudomonas palleroniana	India	[51]
Pseudomonas plecoglossicida C10	China	[42]
Pseudomonas proteolytica	India	[51]
Pseudomonas psychrotolerans IALR632	USA	[38]
Pseudomonas putida pv. P13	Iran	[49]
Ralstonia pickettii C9	China	[42]
Rhizophagus irregularis BEG72	Italy	[32]
Rhodopseudomonas palustris ISP-1	China	[40]
Serratia rubidaea	Morocco	[41]
Staphylococcus pastueri MZUTZ02	India	[34]
Stenotrophomonas maltophilia	Tunisia, China	[26, 50]
Streptomyces alboviridis	Morocco	[47]
Streptomyces fulvissimus	Morocco	[46]
Streptomyces griseorubens	Morocco	[46, 47]
Streptomyces microflavus	Morocco	[46]
Streptomyces pratensis	Morocco	[46]
Streptomyces youssoufiensis	Morocco	[46]
Talaromyces minioluteus	Iran	[27]
Talaromyces pinophilus	Iran, Indonesia	[27, 29]
Talaromyces stipitatus	Iran	[27]
Trichoderma asperellum LZ1	China	[53]

Table 1.
Major phosphate solubilizing microorganisms.

is important for maintaining healthy ecosystems, as they play a critical role in the phosphorus cycle by making this important nutrient more available to plants [25].

5. Ability of microorganisms to solubilise phosphates and key mechanisms of microbial P Solubilisation

Phosphorous is available in the soil as a number of organic and inorganic compounds due to its high reactivity, and those are unavailable for plants [54]. PSMs solubilise these insoluble forms of phosphates into soluble by secreting complex compounds such as organic acid anions, protons, exopolysaccharides, siderophores, hydroxyl ions and extracellular enzymes [55]. The phosphate-solubilising mechanism of PSM has two major aspects as inorganic phosphate solubilisation and organic phosphate solubilisation based on the substrate of P [3].

5.1 Inorganic phosphate solubilisation by PSM

Microbial mobilisation of inorganic phosphates is involved with the production and secretion of organic acids, inorganic acids, siderophore and exopolysaccharide and proton extrusion by the PSM [3].

5.1.1 Organic acid production

The key mechanism of phosphate solubilisation is the secretion of the organic acids that result from the carbon metabolism of PSM, which is closely related to the concentration of soluble phosphate [3, 4, 24]. Low-molecular-weight organic acids are synthetised during glucose oxidation through direct periplasmic oxidation and intracellular phosphorylation. The synthesis of organic acids from glucose by the cells of PSMs in phosphate deficient conditions is higher than in phosphate sufficient conditions, which correlates with the effect of soluble phosphate on organic acid production [56].

The release of these organic acids into the environment is accompanied by a decrease in pH and chelate of the cations (such as Al^{3+}, Fe^{3+}, and Ca^{2+}) bound to phosphate ions to release the phosphate [3, 8]. These organic acids compete with the phosphate binding sites of the medium and allow phosphates to be available in free [15] as HPO_4^{-2} and HPO_4^{-3} [10]. However, there is no correlation between pH and the amount of solubilised phosphates [56]. Gluconic acid is the frequent secretion among all organic acids released by PSM (**Table 2**) [3, 10, 54]. PSF may be even more important than PSB since they typically produce and excrete more acids [56].

5.1.2 Inorganic acid production

Inorganic acid-producing bacteria also involve with phosphate solubilisation through acidification. Bacteria, engaged in nitrification and sulphur-oxidation, which have the ability to produce inorganic acids, are involved with phosphate solubilisation by secreting nitric, carbonic, sulphuric [3] and hydrochloric acids [4, 24]. Nitrifying bacteria such as *Nitrosovibrio*, *Nitrosomonas*, *Nitrobacter*, *Nitrosospira* frequently secrete nitric acid [61] and sulphur oxidising bacteria such as *Thiobacillus thiooxidans* [62] produce sulphuric acid directly involve to solubilisation of phosphate which is required to be further studied. Acidification of the media by secreting inorganic acids and H^+ substitution reactions release the phosphates by converting insoluble phosphate to its soluble form [4, 24]. However, the efficacy of phosphate solubilisation by inorganic acids is lower than the efficiency of organic acids [3, 8].

5.1.3 Proton extrusion

Another alternative mechanism to solubilise phosphate is extrusion of proton, which minimise the requirement to synthesis acids [3]. Excretion of H^+ through H_2CO_3 production, NH_4^+ assimilation and liberation of organic acid anions facilitate the solubilisation of phosphates by acidifying the media [3, 8, 10]. The release of H^+ to the extracellular surface of PSM through the exchange of cation or the ATPase activity

Organic acid	PSM		References
Acetic acid	*Bacillus amyloliquefaciens* *Bacillus atrophaeus* *Bacillus licheniformis* *Chryseomonas Luteola* *Enterobacter aerogenes* *Enterobacter asburiae*	*Enterobacter taylorae* *Kluyvera cryocrescens* *Penibacillus macerans* *Pseudomonas aerogenes* *Vibrio proteolyticus* *Xanthobacter agilis*	[57]
Caproic acid	*Actinomadura oligospora* *Bacillus subtilis var.2*	*Citrobacter* sp.	[57]
Citric acid	*Arrhrobacter* *Aspergillus flavus* *Aspergillus niger FS 1* *Enterobacter* *Eupenicillium ludwigii FS 27*	*Penicillium canescens* *Penicillium canescens FS 23* *Penicillium islandicum FS 30* *Penicillium rugulosum* *Penicillium trivialis*	[12]
	Arthrobacter sp. *Aspergillus flavus* *Aspergillus foetidus* *Aspergillus japonicas* *Aspergillus niger* *Bacillus firmus B-7650*	*Bascillus* sp. *Chaetomium nigricolor* *Enterobacter agglomerans* *Penicillium fluorescens* *Penicillium canescens* *Penicillium rugulosum*	[57]
	Aspergillus *Azospirillum* sp. *Bacillus* sp.	*Penicillium* sp. *Proteus* sp. *Pseudomonas*	[10, 58–60]
Formic Acid	*Pseudomonas trivialis*		[12]
	Actinomadura oligospora *Bacillus pumilus var.2* *Bacillus subtilis var.2*	*Citrobacter* sp. *Pseudomonas trivialis*	[57]
Fumaric acid	*Azospirillum* sp. *Bacillus* sp.	*Proteus* sp. *Pseudomonas*	[10, 59, 60]
Gluconic acid	*Arrhrobacter* *Aspergillus flavus* *Aspergillus niger FS 1* *Enterobacter* *Enterobacter intermedium* *Enterobacter sps Fs 11*	*Eupenicillium ludwigii FS 27* *Penicillium canescens FS23* *Penicillium islandicum* *Penicillium rugulosum* *Pseudomonas fluorescens*	[12]
	Actinomadura oligospora *Aspergillus flavus* *Aspergillus foetidus* *Aspergillus japonicas* *Aspergillus niger* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp. *Penicillium canescen* *Penicillium radicum* *Penicillium rugulosum* *Pseudomonas fluorescens*	[57]
	Aspergillus *Azospirillum* sp. *Bacillus* sp. *Erwinia herbicola*	*Penicillium* sp. *Proteus* sp. *Pseudomonas*	[10, 58–60]
Glycolic acid	*Aspergillus niger*	*Penicillium* sp.	[12]
	Aspergillus sp.	*Penicillium* sp.	[10, 58]

Organic acid	**PSM**		**References**
Heptonic acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]
Indole acetic acid	*Psedomonas nitroreducens*		[12]
Isobutyric acid	*Bacillus amyloliquefaciens* *Bacillus atrophaeus* *Bacillus licheniformis* *Chryseomonas luteola* *Enterobacter aerogenes* *Enterobacter asburiae*	*Enterobacter taylorae* *Kluyvera cryocrescens* *Penibacillus macerans* *Pseudomonas aerogenes* *Vibrio proteolyticus* *Xanthobacter agilis*	[57]
Isocaproic acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]
Isovaleric acid	*Actinomadura oligospora* *Bacillus atrophaeus* *Bacillus licheniformis* *Bacillus pumilus var.2* *Bacillus subtilis var.2* *Bacillus amyloliquefaciens* *Chryseomonas luteola* *Citrobacter* sp.	*Enterobacter asburiae* *Enterobacter taylorae* *Enterobacter aerogenes* *Kluyvera cryocrescens* *Penibacillus macerans* *Pseudomonas aerogenes* *Vibrio proteolyticus* *Xanthobacter agilis*	[57]
Itaconic acid	*Bacillus atrophaeus* *Bacillus licheniformis* *Bacillus amyloliquefaciens* *Chryseomonas luteola* *Enterobacter asburiae* *Enterobacter taylorae*	*Enterobacter aerogenes* *Kluyvera cryocrescens* *Penibacillus macerans* *Pseudomonas aerogenes* *Vibrio proteolyticus* *Xanthobacter agilis*	[57]
Lactic acid	*Aspergillus niger* *Penicillium* sp.	*Pseudomonas trivialis*	[12]
	Arthrobacter sp. *Aspergillus niger* *Bacillus atrophaeus* *Bacillus licheniformis* *Bacillus amyloliquefaciens* *Bacillus firmus B-7650* *Bacillus megaterium* *Chryseomonas luteola* *Enterobacter asburiae* *Enterobacter taylorae*	*Enterobacter aerogenes* *Escherichia freundii* *Kluyvera cryocrescens* *Pseudomonas trivialis* *Penibacillus macerans* *Penicillium* sp. *Pseudomonas aerogenes* *Bacillus subtilus* *Vibrio proteolyticus* *Xanthobacter agilis*	[57]
Malic acid	*Arrhrobacter* *Enterobacter sps Fs 11*	*Pseudomonas fluorescens*	[12]
	Bacillus megaterium *Bacillus subtilus*	*Pseudomonas fluorescens*	[57]
	Aspergillus *Bacillus* sp. *Penicillium* sp.		[10, 58, 59]
Malonic acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]
Oxalacetic acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]

Organic acid	**PSM**		**References**
Oxalic acid	*A. niger FS 1* *Aspergillus flavus* *Eupenicillium ludwigii FS 27*	*Penicillium canescens FS23* *Penicillium canescens,* *Penicillium islandicum*	[12]
	Actinomadura oligospora *Aspergillus flavus* *Aspergillus foetidus* *Aspergillus japonicas* *Aspergillus niger* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Chaetomium nigricolor* *Citrobacter* sp. *Enterobacter agglomerans* *Penicillium canescens*	[57]
	Aspergillus sp.	*Penicillium* sp.	[10, 58]
Propionic acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]
Succinic acid	*Aspergillus flavus* *Aspergillus niger*	*Penicillium canescens*	[12]
	Actinomadura oligospora *Aspergillus flavus* *Aspergillus foetidus* *Aspergillus japonicas* *Aspergillus niger*	*Bacillus pumilus var.2* *Bacillus subtilis var.2* *Chaetomium nigricolor* *Citrobacter* sp. *Penicillium canescens*	[57]
	Aspergillus *Azospirillum* sp. *Bacillus* sp.	*Penicillium* sp. *Proteus* sp. *Pseudomonas*	[10, 58–60]
Tartaric acid	*Arrhrobacter* *Enterobacter*	*Pseudomonas trivialis*	[12]
	Aspergillus japonicas *Aspergillus foetidus*	*Pseudomonas fluorescens*	[57]
	Bacillus sp.		[10, 59]
Valeric acid	*Actinomadura oligospora* *Bacillus pumilus var.2*	*Bacillus subtilis var.2* *Citrobacter* sp.	[57]
2-Keto gluconic acid	*Enterobacter intermedium*		[12]
	Aspergillus sp. *Chaetomiumnigricolor*	*Enterobacter intermedium* *Penicillium* sp.	[57]
	Erwinia herbicola	*Pseudomonas*	[10, 59, 60]

Table 2.
Major examples of the production of organic acids by PSM.

with H+ translocation, lead to the solubilisation of P [56]. *Pseudomonas fluorescens* [63], *Bacillus* sp., *Azospirillum* sp. [64] significantly exhibit this mechanism of H^+ extrusion in the process of phosphate solubilisation.

5.1.4 Exopolysaccharide production

Exopolysaccharides are high molecular weight compounds that indirectly affect the solubilisation of P in soil [65]. Microorganisms secrete exopolysaccharides under stress conditions; exhibit the potential to promote phosphate solubilisation [3, 66]. Exopolysaccharides have a strong affinity with the metal ions in the soil, which have formed complexes with phosphates and release those phosphates. There is a positive correlation between the rate of phosphate solubilisation and the concentration of exopolysaccharides [3]. Different exopolysaccharides have different binding affinities with various metals, and there are also different binding strengths between the metals themselves. *Arthrobacter* sp. ArHy-505, *Azotobacter* sp. AzHy-510 and Enterobactersp. EnHy-401 exhibits higher tricalcium phosphate solubilisation capacity by producing exopolysaccharides [65].

5.1.5 Siderophore production

Siderophore production is a usual ability of microorganisms, while it is used by PSM as another alternative method to solubilise the phosphate [3, 10, 15]. Siderophores are low-molecular-weight secondary metabolites synthesised by PSM that have a strong affinity for inorganic iron and act as metal chelators. Siderophores contain three functional groups hydroxamates, catecholates, and carboxylates, which catalyse the reduction of Fe^{3+} to Fe^{2+}. PSM use siderophores to obtain the Fe as the requirement of cellular functions, and during the dissociation of its bond, P is released and available for plants. *Streptomyces* sp. successfully increase the bioavailability of P through the production of sideraphores [65].

5.2 Organic phosphate solubilisation mechanisms

5.2.1 Enzyme production

The content of organic phosphorus in the soil can reach 30–50% of the total amount, which is represented by compounds such as phosphonates, phytic acid, polyphosphonates, sugar phosphates [3, 56], phosphomonoesters, phosphodiesters, phosphotriesters [8], phospholipids and nucleic acids [3, 8]. Generally, these high molecular weight organic compounds are resistant to chemical hydrolysis and need to be converted into soluble ionic phosphate or low-molecular-weight organic phosphates for plant uptake [56].

PSM produce and secrete the enzymes to solubilise the organic phosphates [8]. There are several groups of enzymes are secreted by PSM as [3, 8, 54–56],

1. Non-Specific Acid Phosphatases (NSAPs)

2. Phytases

3. Phosphonatases

4. Carbon–Phosphorus Lyases

NSAPs are a class of enzymes secreted extracellularly or bound to the lipoprotein membranes of PSM. NSAP are generally known as phosphomonoesterases, which dephosphorylate a wide variety of phosphoesters, solubilising around 90% of organic phosphate in soils. The proportion of phosphatases and abundance of P in the soil has a direct relationship, which influences the availability of phosphates to plants.

According to the authors, the activity of NSAPs is more concentrated in the rhizosphere than in other parts of soil and phosphatase activity, P uptake by plants and nodule weight has a positive correlation [56].

Phytase enzymes are phosphatases produced by PSM, which have the capability to hydrolyse phytic acid by acting on the phosphomonoester bonds present in the compound, originating two subgroups, myo-inositol hexaphosphate or phytate. In addition to P, this process makes biologically available other nutrients such as zinc and iron [65].

Phosphatases (phosphonate hydrolases) are enzymes, which promote the breaking of C-P bonds of phosphonates by catalysing this reaction from a group carbonyl electron scavenger that allows heterologous cleavage between nutrients. Phosphonatases act on several substrates, including phosphoenolpyruvate, phosphonoacetate, and phosphoenol-acetaldehyde and make biologically available P for plants [56, 65].

Carbon–phosphorus lyases are a complex of membrane enzymes released by PSM that also allow the making available of P, cleaving the C–P bonds of phosphonates, producing hydrocarbons and inorganic Phosphate. This complex is the leading mechanism for the utilisation of phosphonates by PSM. The enzymes and proteins of C–P lyases are complex and specific to their substrates. *Escherichia* coli and *Enterobacter cloacae* K7 are commonly involved with solubilisation of phosphates by using C–P lyases [65].

6. Capability of microorganisms to formulate phosphate-related nanoparticles

Nanotechnology is a state-of-the-art technique of using particles between 1 to 100 nm, which originated as both organic and inorganic forms [67–69]. Nano minerals are currently used as plant fertilisers due to their Nano size, high surface area, and higher solubility in different solvents and penetrative capacity than conventional mineral fertilisers. Reduction of the particle size is directed to an increment of the surface area of particle and the number of particles per unit in fertiliser, which facilitate higher nutrient utilising efficacy. Nanoparticles enter into plants through nano and microscale openings, which are most commonly available in roots and leaves [70, 71]. Generally, root tips, rhizodermis, lateral root junctions and wounding of roots are the entering pathways to nanoparticles. Enhanced bioavailability of nano fertilisers than conventional fertilisers cause to prevent loss of nutrients from leaching, denitrification, volatilisation, and fixation in the soil to confirm the sustainable utilisation of minerals [70].

Microorganisms including bacteria, fungi, actinobacteria and viruses have the ability to synthesise phosphorus-related nanoparticles with well-defined chemical composition, morphology and size either intra-or extracellularly [71–73]. But no in-depth study or work has been done so far [74]. Enzymes [75, 76] such as phytase, phosphatases [75], extracellular polymeric substances (EPS) [76] and proteins [75] are the key potential materials to synthesise phosphorus-related nanoparticles which are produced by microorganisms. In addition, proteins act as capping agents to stabilise the produced nanoparticles [75]. This is a new arising area in nano formulations [74]. Therefore, limited research has been conducted on synthesising phosphorus-related nanoparticles by using microorganisms, as mentioned in **Table 3**.

Microbe	Type of Nano P	Size/Shape	Application	References
Aspergillus flavus TFR-1	Phosphorous	17–64 nm	Plant fertiliser	[77]
Aspergillus fumigatus TFR-8	Phosphorous	37-81 nm	Plant fertiliser	[77]
Aspergillus oryzae TFR-9	Phosphorous	23–88 nm	Plant fertiliser	[77]
Aspergillus terreus CZR-1	Phosphorous	11–74 nm	Plant fertiliser	[77]
Aspergillus tubingensis TFR-3	Phosphorous	5–49 nm	Plant fertiliser	[77]
Bacillus megaterium JCT13	Phosphorous	20–91 nm	To maintenance of soil fertility	[73, 75]
Emericella nidulans TFR-14	Phosphorous	55–92 nm	Plant fertiliser	[77]
Rhizoctonia bataticola TFR-6	Phosphorous	12–36 nm	Plant fertiliser	[77]
Yeast	Zinc Phosphate	10–80 nm in width and 80–200 nm in length, Butterfly like shape	Antirust pigment and electronic luminophore	[78]

Table 3.
Microbial synthesis of phosphorus-related nanoparticles.

7. Potential of PSM to develop as a commercial level biofertiliser

The distinctive and unique ability of PSMs to solubilise organic and inorganic phosphates, leads to their developed as commercial level bio fertilisers [10, 12]. Biofertilisers are microbiologically active, eco-friendly, low-cost products applied to soil expecting soil health and growth promotion of plants [10, 15]. Biofertilisers can be replaced by 50% instead of chemical fertilisers without any reduction of the yield [15]. These phosphate bio fertilisers are not crop-specific and able to be used for any type of plant, expecting growth promotion, high yield and crop quality through optimum phosphate absorption [10]. *Azotobacter* inoculation and *Bacillus* inoculants have success stories with yield increments of sugarcane and wheat. Application of the combination of *Bacillus megaterium* and *Azotobacter chroococcum* as biofertiliser remark the yield increment by 10–20%. *Bacillus circulans, Bacillus megaterium, Bacillus subtilis*, and *Pseudomonas striata* reach the commercial level in the phosphate biofertiliser industry [10].

Biofilm inoculants and nano-bio inoculants are ultra-modern techniques in biofertiliser formulation technology. Biofilm inoculants are the combination of two microorganisms, while one microorganism colonises over the other microorganism. The second microorganism act as a biotic surface for the first microorganism to develop a metabolically enhanced biofilm rather than a single culture [3]. Even though these relationships affect the high phosphate solubilisation and growth promotion of plants, the abundance in the soil is very low [3, 79]. Therefore, applying these biofilms as biofertilisers through artificial formulation is advantageous in agriculture [3]. *Pleurotus ostreatus*, *Xanthoparmelia mexicana* and *Penicillium* spp. are the most prominent PSMs, which have the potential to be used in biofilms for substantial impact [80].

8. Contribution of PSM to achieving sustainable development goals (SDGs)

Collection of 17 interlinked objectives focusing on prosperity for people and the planet called United Nations Sustainable Development Goals (SDGs) able to be enforced with PSMs. Microbial phosphate solubilisation makes way for sustainable development by promoting plant growth, food security, industrial growth, environmental sustainability and water security [81, 82].

Continuous fertilisation to supply the optimum requirement of phosphate for crops due to the low bioavailability is not the appropriate way, and it is a waste of the resource [83]. Responsible consumption of the resource (SDG 12) able to be confirmed by the involvement of PSMs in increasing the bioavailability of phosphate. It reduces the accumulation of excess phosphate with associated other chemicals as fertilisers to soil and contributes to building up sustainable terrestrial ecosystems with reverse land degradation to halt biodiversity loss (SDG 15) [84]. Moreover, the sequestration of phosphate in the soil leads to eutrophication, which causes disruptions of valuable aquatic resources and pollution the water [85]. Therefore, reducing the excess utilisation of phosphate fertilisers by developing PSM as biofertilisers will ensure the sustainable conservation of aquatic resources (SDG 14) and sustainable management of available clean water (SDG 06) [82, 86].

The contribution of PSM to sustainable agriculture through plant growth promotion ensures sufficient food production empowering food security, which promotes public nutrition and ends hunger (SDG 02) [87, 88]. Development of the sustainable agricultural industry (SDG 09) confirm sustainable economic growth (SDG 08) with moving forward to the reduction of poverty (SDG 01) [89]. Society, which reaches economic development by overcoming poverty and hunger, ensures a better living environment promoting a sustainable peaceful society by accessing justice (SDG 16) [90]. The direct and indirect contributions of PSMs to achieve the SDGs affect significantly strengthen the framework of the 2030 agenda of the United Nations [82].

9. Conclusion

The application of PSMs as a tool in managing soil and plant nutrients through Solubilising phosphate is an efficient and eco-friendly method. Bacterial and fungal species are majorly involved in the phosphate solubilisation in soil, remarking *Bacillus*, *Pseudomonas*, *Penicillium* and *Aspergillus* species as the most frequent organisms. Even the PSMs are using a number of mechanisms to solubilise the phosphate, organic acid production is the leading mechanism, and gluconic acid is the foremost organic acid involved in the Phosphate immobilisation process. As a cutting-edge technology, PSMs can be used for the formulation of phosphate-related nanoparticles to increase bioavailability. Current arising biofertiliser technology using this potential of PSMs at the commercial level. Biotechnological applications are able to be used to develop the ability of PSMs to obtain maximum output. Furthermore, PSMs are directly and indirectly affecting to achievement SDGs to serve as a "shared blueprint for peace and prosperity for people and the planet, now and into the future".

Acknowledgements

The paper was supported by the research grant of "Accelerating Higher Education and Development" (AHEAD) under development-oriented research (DOR) of STEM grant number AHEAD/RA3/DOR/WUSL/LAS No.57 funded by the World Bank.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

A.A. Asanka Udaya Aberathna[1], Dilan Amila Satharasinghe[2], Anura Prasantha Jayasooriya[2], H. Rasika Niranjana Jinadasa[3], Sivabalan Manopriya[1], B.P. Ajith Jayaweera[1], C. Annesly Nandana Fernando[4], W.A. Dammika Vijitha Weerathilake[1], G.A. Prathapasinghe[1], Janitha Abeywickrema Liyanage[5] and J.M. Krishanthi Jayarukshi Kumari Premarathne[1]*

1 Department of Livestock and Avian Sciences, Faculty of Livestock, Fisheries and Nutrition, Wayamba University of Sri Lanka, Makandura, Sri Lanka

2 Department of Basic Veterinary Sciences, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, Peradeniya, Sri Lanka

3 Department of Veterinary Pathobiology, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, Sri Lanka

4 Department of Nano Science Technology, Faculty of Technology, Wayamba University of Sri Lanka, Kuliyapitiya, Sri Lanka

5 Department of Chemistry, Faculty of Science, University of Kelaniya, Dalugama, Sri Lanka

*Address all correspondence to: krissjayaruk@wyb.ac.lk

References

[1] Aliyat FZ, Maldani M, El GM, Nassiri L, Ibijbijen J. Isolation and characterization of phosphate Solubilising bacteria from phosphate solid sludge of the Moroccan phosphate mines. Open Agric J. 2020;**14**(17):16-24

[2] Chawngthu L, Hnamte R, Lalfakzuala R. Isolation and characterization of Rhizospheric phosphate Solubilising bacteria from wetland isolation and characterization of Rhizospheric phosphate Solubilising bacteria. Geomicrobiology Journal. 2020;**37**:1-10. DOI: 10.1080/01490451.2019.1709108

[3] Prabhu N, Borkar S, Garg S. Phosphate Solubilisation by microorganisms: Overview, mechanisms, applications and advances. In: Advances in Biological Science Research. USA: Elsevier Inc.; 2019. pp. 161-176. DOI: 10.1016/B978-0-12-817497-5.00011-2

[4] Samreen S, Kausar S. Phosphorus fertilizer: The original and commercial sources. In: Phosphorus - Recovery and Recycling. Aligarh, India: London, UKIntechOpen; 2019. pp. 81-92

[5] Sharon JA, Hathwaik LT, Glenn GM, Imam SH, Lee CC. Isolation of efficient phosphate Solubilising bacteria capable of enhancing tomato plant growth. Journal of Soil Science and Plant Nutrition. 2016;**16**(2):525-536

[6] Sarikhani MR, Khoshru B, Greiner R. Isolation and identification of temperature tolerant phosphate Solubilising bacteria as a potential microbial fertilizer. World Journal of Microbiology and Biotechnology. 2019;**1**:1-10. DOI: 10.1007/s11274-019-2702-1

[7] Ameen F, Alyahya SA, Alnadhari S, Alasmari H, Wainwright M. Phosphate Solubilising bacteria and fungi in desert soils: Species, limitations and mechanisms. Archives of Agronomy and Soil Science. 2019;**65**(10):1476-3567. DOI: 10.1080/03650340.2019.1566713

[8] Alori ET, Glick BR, Babalola OO. Microbial phosphorus Solubilisation and its potential for use in sustainable agriculture. Frontiers in Microbiology. 2017;**8**(Jun):10-13

[9] Chen Q, Liu S. Identification and characterization of the phosphate-Solubilising bacterium Pantoea sp. S32 in reclamation soil in Shanxi, China. Frontiers in Microbiology. 2019;**10**:1-12

[10] Kalayu G. Phosphate Solubilising microorganisms: Promising approach as Biofertilisers. Intenational J Agron. 2019;**2019**:1-6

[11] Li Y, Zhang J, Zhang J, Xu W, Mou Z. Characteristics of inorganic phosphate-Solubilising bacteria from the sediments of a eutrophic lake. International Journal of Environmental Research and Public Health. 2019;**16**(12):2141

[12] Anand K, Kumari B, Mallick MA. Phosphate Solubilising microbes: An effective and alternative approach as biofertilisers. International Journal of Pharmacy and Pharmaceutical Sciences. 2016;**8**(2):37-40

[13] Pande A, Pandey P, Mehra S, Singh M. Phenotypic and genotypic characterization of phosphate Solubilising bacteria and their efficiency on the growth of maize. Journal, Genetic Engineering & Biotechnology. 2017;**15**(2):379-391. DOI: 10.1016/j.jgeb.2017.06.005

[14] El-hamshary OI, El-hamshary OIM, Bohkari FM, Al-aklouk LA, Noor SO, Najjar AA. Molecular characterization of some phosphate Solubilising microorganisms. Pharmacophore. 2019;**10**(1):37-51

[15] Satyaprakash M, Nikitha T, Reddi EUB, Reddi EUB, Sadhana B. Phosphorous and phosphate Solubilising bacteria and their role in plant nutrition. Int J Curr Microbiol Appl Sci. 2017;**5**(4):2133-2144

[16] Fenta L. Isolation and characterization of phosphate Solubilising bacteria from tomato (Solanum l.) rhizosphere and their effect on growth and phosphorus uptake of the host plant under green house experiment. Lamenew Fenta Under The Guidance of. International Journal of Advanced Research. 2017;**5**(Jan):1-49

[17] Suleman M, Id SY, Rasul M, Yahya M, Atta M, Mirza MS. Phosphate Solubilising bacteria with glucose dehydrogenase gene for phosphorus uptake and beneficial effects on wheat. PLOSONE. 2018;**13**(9):1-28

[18] Yuliantia E, Rakhmawati A. Screening and characterization of phosphate Solubilising bacteria from isolate of thermophilic bacteria screening and characterization of phosphate Solubilising bacteria from isolate of thermophilic bacteria. In: 4th Int Conf Res Implementation, Educ Math Sci (4th ICRIEMS): New York: AIP. 2018. 2017. p. 090015

[19] Azaroual SE, Hazzoumi Z, El N, Abderrahim M, Issam A, Kadmiri M. Role of inorganic phosphate Solubilising bacilli isolated from Moroccan phosphate rock mine and rhizosphere soils in wheat (Triticum aestivum L) phosphorus uptake. Current Microbiology. 2020;**77**:2391-2404. DOI: 10.1007/s00284-020-02046-8

[20] Hii YS, San CY, Lau SW, DMK. Isolation and characterisation of phosphate Solubilising microorganisms from peat. In: Biocatalysis and Agricultural Biotechnology. Vol. 26. Netherlands: Elsevier; 2020. p. 101643. DOI: 10.1016/j. bcab.2020.101643

[21] Paul D, Sinha SN. Biological removal of phosphate using phosphate Solubilising bacterial consortium from synthetic wastewater: A laboratory sale. Environ. Asia. 2015;**8**(1):1-8

[22] Rosemarin A, de Bruijne G, Caldwell I. Peak phosphorus: The next inconvenient truth. Brok. 2009;**200**(15):6-9

[23] Dipak P, Sinha SN. Bacteria showing phosphate Solubilising efficiency in river sediment. Electron J Biosci. 2013;**1**(1):1-5

[24] Khan MS, Zaidi A, Musarrat J, Technology M. In: Khan MS, Musarrat J, editors. Phosphate Solubilising Microorganisms. New York: Springer; 2014. pp. 1-287

[25] Djuuna IAF, Prabawardani S, Massora M. Population distribution of phosphate-Solubilising microorganisms in agricultural soil. Microbes and Environments. 2022;**37**(1):1-8

[26] Ding Y, Yi Z, Fang Y, He S, Li Y, He K, et al. Multi-omics reveal the efficient phosphate-Solubilising mechanism of bacteria on rocky soil. Frontiers in Microbiology. 2021;**12**(December):761972

[27] Beheshti M, Ali H, Ali A, Etesami H, Asadi H, Norouzi M. Rhizosphere Periphytic biofilm and rice rhizosphere phosphate-Solubilising bacteria and fungi: A possible use for activating occluded P in periphytic

biofilms in paddy fields. Rhizosphere. 2021;**19**(June):100395. DOI: 10.1016/j.rhisph.2021.100395

[28] Ibáñez A, Alba Diez-Galán RC, Calvo-Peña C, Barreiro C, Jesús Medina-Turienzo MS-G, JJRC. Using rhizosphere phosphate Solubilising bacteria to improve barley (Hordeum vulgare) plant productivity. Microorganisms. 2021;**9**(8):1619

[29] Sembiring M, Sabrina T. Diversity of phosphate Solubilising bacteria and fungi from andisol soil affected by the eruption of mount Sinabung, North Sumatra. Indonesia. Biodiversitas. 2022;**23**(2):714-720

[30] Alam K, Barman M, Kumar S, Ray P. Release pattern of soil phosphorus as affected by phosphate Solubilising microorganisms in an Ultisol. Pharma Innov J. 2021;**10**(10):823-827

[31] Shao X, Hao W, Konhauser KO, Gao Y, Tang L, Su M, et al. The dissolution of fluorapatite by phosphate-Solubilising fungi: A balance between enhanced phosphorous supply and fluorine toxicity. Environmental Science and Pollution Research. 2021;**28**:69393-69400

[32] Cozzolino V, Monda H, Savy D, Di MV, Vinci G. Cooperation among phosphate-Solubilising bacteria, humic acids and arbuscular mycorrhizal fungi induces soil microbiome shifts and enhances plant nutrient uptake. Chem Biol Technol Agric. 2021;**8**:1-18. DOI: 10.1186/s40538-021-00230-x

[33] Ahmad I, Ahmad M, Hussain A, Jamil M. Integrated use of phosphate-Solubilising Bacillus subtilis strain IA6 and zinc-Solubilising bacillus sp. strain IA16: A promising approach for improving cotton growth. Folia Microbiologia (Praha). 2020;**66**(1):115-125

[34] Khiangte L, Lalfakzuala R. Effects of heavy metals on phosphatase enzyme activity and Indole-3-acetic acid (IAA) production of phosphate Solubilising bacteria effects of heavy metals on phosphatase enzyme activity and Indole-3-acetic. Geomicrobiology Journal. 2021;**38**:494-503. DOI: 10.1080/01490451.2021.1894271

[35] Qarni A, Billah M, Hussain K, Shah SH, Ahmed W, Alam S, et al. Isolation and characterization of phosphate Solubilising microbes from rock phosphate mines and their potential effect for sustainable agriculture. Sustainability. 2021;**13**:2151

[36] Chungopast S, Thongjoo C, Islam AKMM, Yeasmin S. Efficiency of phosphate-Solubilising bacteria to address phosphorus fixation in Takhli soil series : A case of sugarcane cultivation, Thailand efficiency of phosphate-Solubilising bacteria to address phosphorus fixation in Takhli soil series: A case of sugarcane cultivation, Thailand. Plant and Soil. 2021;**18**(March):347-357

[37] Sanchez-gonzalez ME, Mora-herrera ME, Wong-villarreal A, De LN, Sanchez-paz L, Lugo J, et al. Effect of pH and carbon source on phosphate Solubilisation by bacterial strains in Pikovskaya medium. Microorganisms. 2023;**11**:1-11

[38] Mei C, Chretien RL, Amaradasa BS, He Y, Turner A, Lowman S. CharacterizationofphosphateSolubilising bacterial endophytes and plant growth promotion In vitro and in greenhouse. Microorganisms. 2021;**9**(9):1935

[39] Erica A, De SS, Rodrigues M, Barbosa J, Rafael B, Moreira DA, et al. UAV multispectral data: A reliable approach for managing phosphate-Solubilising bacteria in common bean. Agronomy. 2022;**12**(10):2284

[40] Wang Y, Peng S, Hua Q, Qiu C, Wu P. The long-term effects of using phosphate-Solubilising bacteria and photosynthetic bacteria as Biofertilisers on Peanut yield and soil bacteria community. Frontiers in Microbiology. 2021;**12**(July):1-14

[41] Aliyat FZ, Maldani M, El GM, Nassiri L, Ibijbijen J. Phosphate-Solubilising bacteria isolated from phosphate solid sludge and their ability to solubilise three inorganic phosphate forms: Calcium, iron, and aluminum phosphates. Microorganisms. 2022;**10**:1-13

[42] Song C, Wang W, Gan Y, Wang L. Growth promotion ability of phosphate-Solubilising bacteria from the soybean rhizosphere under maize – Soybean intercropping systems. Journal of the Science of Food and Agriculture. 2021;**102**:1430-1442

[43] Chen J, Zhao G, Wei Y, Dong Y, Hou L. Isolation and screening of multifunctional phosphate Solubilising bacteria and its growth - promoting effect on Chinese fir seedlings. Scientific Reports. 2021;**11**:1-13. DOI: 10.1038/s41598-021-88635-4

[44] An X. Optimizing phosphorus application rate and the mixed inoculation of Arbuscular Mycorrhizal fungi and phosphate-Solubilising bacteria can improve the phosphatase activity and organic acid content in alfalfa soil. Sustainability. 2022;**14**(18):11342

[45] Silva UC, Cuadros-orellana S, Silva DRC, Freitas-júnior LF, Fernandes AC, Leite LR, et al. Genomic and phenotypic insights into the potential of rock phosphate Solubilising bacteria to promote millet growth in vivo. Frontiers in Microbiology. 2021;**11**(January):1-17

[46] Soumare A, Boubekri K, Lyamlouli K, Hafidi M, Ouhdouch Y, Kouisni L. From isolation of phosphate Solubilising microbes to their formulation and use as Biofertilisers: Status and needs. Frontiers in Bioengineering and Biotechnology. 2020;**7**:1-14

[47] Boubekri K, Soumare A, Mardad I, Lyamlouli K, Hafidi M, Ouhdouch Y, et al. The screening of potassium-and phosphate-Solubilising actinobacteria and the assessment of their ability to promote wheat growth parameters. Microorganisms. 2021;**9**(3):1-16

[48] Saadouli I, Mosbah A, Ferjani R, Stathopoulou P, Galiatsatos I. The impact of the inoculation of phosphate-Solubilising bacteria Pantoea agglomerans on phosphorus availability and bacterial community dynamics of a semi-arid soil. Microorganisms. 2021;**9**(8):1661

[49] Aboksari HA, Hashemabadi D, Kaviani B. Effects of an organic substrate on Pelargonium peltatum and improvement of its morphological, biochemical, and flowering parameters by root-inoculated phosphate Solubilising microorganisms. Communications in Soil Science and Plant Analysis. 2021;**52**(15):1772-1789. DOI: 10.1080/00103624.2021.1892735

[50] Amri M, Mateus D, Gatrouni M, Rjeibi MR, Asses N. Co-inoculation with phosphate-Solubilising microorganisms of rock phosphate and Phosphogypsum and their effect on growth promotion and nutrient uptake by ryegrass. Appl Biosci. 2022;**1**:179-197

[51] Adhikari P, Jain R, Sharma A, Pandey A. Plant growth promotion at low temperature by phosphate-Solubilising pseudomonas Spp. isolated from high-altitude Himalayan soil. Microbial Ecology. 2021;**82**(3):677-687

[52] Bamagoos AA, Alharby HF, Belal EE, Khalaf AEA, Abdelfattah MA, Rady MM, et al. Phosphate-Solubilising bacteria as a panacea to alleviate stress effects of high soil $CaCO_3$ content in Phaseolus vulgaris with special reference to P-releasing enzymes. Sustainability. 2021;**13**:1-22

[53] Guo S, Feng B, Xiao C, Wang Q, Chi R. Phosphate-Solubilising microorganisms to enhance phytoremediation of excess phosphorus pollution in phosphate mining wasteland soil. Bioremediation Journal. 2021;**25**:1-15. DOI: 10.1080/10889868.2021.1884528

[54] Liang JL, Liu J, Jia P, Yang T, Zeng Q, Zhang S, et al. Novel phosphate-Solubilising bacteria enhance soil phosphorus cycling following ecological restoration of land degraded by mining. The ISME Journal. 2020;**14**:1600-1613. DOI: 10.1038/s41396-020-0632-4

[55] Ingle KP. Phosphate Solubilising microbes: An overview. Int J Curr Microbiol Appl Sci. 2017;**6**(1):844-852

[56] Timofeeva A, Galyamova M, Sedykh S. Prospects for using phosphate-Solubilising microorganisms as natural fertilizers in agriculture. Plants. 2022;**11**:1-23

[57] Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate Solubilising microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. Springer Plus. 2013;**2**(1):1-14

[58] Sane SA, Mehta SK. Isolation and evaluation of rock phosphate Solubilising fungi as potential bio- fertilizer. J Fertil Pestic. 2015;**6**(2):1-6

[59] Selvi KBPJJA, JJA P, Vijaya V, Saraswathi K. Analyzing the efficacy of phosphate Solubilising microorganisms by iMedPub journals analyzing the efficacy of phosphate Solubilising microorganisms by enrichment culture techniques abstract. Biochemistry & Molecular Biology Journal. 2017;**3**(1):1-7

[60] Kumar A, Kumar A, Patel H. Role of microbes in phosphorus availability and acquisition by plants. Int J Curr Microbiol Appl Sci. 2018;**7**(5):1344-1347

[61] Sand W, Ahlers B, Bock E. The impact of microorganisms - especially nitric acid producing bacteria - on the deterioration of natural stones. In: Science, Technology, and European Cultural Heritage: Proceedings of the European Symposium, Bologna, Italy, 13-16 June. UK: Butterworth-Heinemann Publishers; 1991. pp. 481-484. DOI: 10.1016/B978-0-7506-0237-2.50072-1

[62] Liu HL, Lan YW, Cheng YC. Optimal production of sulphuric acid by Thiobacillus thiooxidans using response surface methodology. Process Biochemistry. 2004;**39**(12):1953-1961

[63] Park KH, Lee CY, Son HJ. Mechanism of insoluble phosphate Solubilisation by Pseudomonas fluorescens RAF15 isolated from ginseng rhizosphere and its plant growth-promoting activities. Letters in Applied Microbiology. 2009;**49**(2):222-228

[64] Öğüt M, Er F, Neumann G. Increased proton extrusion of wheat roots by inoculation with phosphorus solubilising microorganims. Plant and Soil. 2011;**339**:285-297

[65] da Silva LI, Pereira MC, de Carvalho AMX, Buttrós VH, PasqualM,DóriaJ.Phosphorus-Solubilising microorganisms: A key to sustainable agriculture. Agriculture. 2023;**13**(2):462

[66] Ionescu M, Belkin S. Overproduction of exopolysaccharides by an

Escherichia coli K-12 rpoS mutant in response to osmotic stress. Applied and Environmental Microbiology. 2009;**75**(2):483-492

[67] Gangadoo S, Stanley D, Hughes RJ, Moore RJ, Chapman J. Nanoparticles in feed: Progress and prospects in poultry research. Trends Food Sci Technol [Internet]. 2016;**58**:115-126. DOI: 10.1016/j.tifs.2016.10.013

[68] Adamo G, Campora S, Ghersi G. Chapter 3 – functionalization of nanoparticles in specific targeting and mechanism release. In: Nanostructures for Novel Therapy. Netherlands: Elsevier Inc.; 2017. pp. 57-80. DOI: 10.1016/B978-0-323-46142-9/00003-7

[69] Adegbeye MJ, Elghandour MMMY, Barbabosa-Pliego A, Monroy JC, Mellado M, Ravi Kanth Reddy P, et al. Nanoparticles in equine nutrition: Mechanism of action and application as feed additives. J Equine Vet Sci. 2019;**78**:29-37. DOI: 10.1016/j.jevs.2019.04.001

[70] Qureshi A, Singh DK, Dwived S. Nano-fertilizers: A novel way for enhancing nutrient use efficiency and crop productivity. Int J Curr Microbiol Appl Sci. 2018;**7**(2):3325-3335

[71] OPK SB, Souto EB. Biosynthesis of Nanonutrients for agricultural applications. In: NanoAgroceuticals & NanoPhytoChemicals. Boca Raton: CRC Press; 2019. pp. 15-30

[72] Swain PS, Rajendran D, Rao SBN, Dominic G. Preparation and effects of nano mineral particle feeding in livestock: A review. Vet World. 2015;**8**(7):888-891

[73] Tarafdar JC, Rathore I. Microbial synthesis of nanoparticles for use in agriculture ecosystem. Microbes Plant Stress Manag. 2016;**2016**(June):105-118

[74] Tarafdar JC, Raliya R, Rathore I. Microbial synthesis of phosphorous nanoparticle from tri-calcium phosphate using aspergillus tubingensis TFR-5. Journal of Bionanoscience. 2012;**6**(2):84-89

[75] Rathore I, Sen M, Gharu AD, Tarafdar JC. An efficient Bm strain JCT13 producing nano- phosphorus particles from phytin and Solubilising phosphates. Int J Curr Eng Technol. 2016;**5**(February):3872-3878

[76] Pirzadah TB, Malik B, Maqbool T, Rehman RU. Development of Nano-bioformulations of nutrients for sustainable agriculture. In: Nanotechnol. Life Sci. Cham: Springer; 2019. pp. 381-394

[77] Tarafdar J, Rathore I, Kaur R, Jain A. Biosynthesis of Nanonutrients for agricultural applications. In: NanoAgroceuticals & NanoPhytoChemicals. New York: CRC Press; 2019. pp. 15-30

[78] Yan S, He W, Sun C, Zhang X, Zhao H, Li Z, et al. The biomimetic synthesis of zinc phosphate nanoparticles. Dyes and Pigments. 2009;**80**(2):254-258. DOI: 10.1016/j.dyepig.2008.06.010

[79] Taktek S, St-arnaud M, Piché Y, Fortin JA, Antoun H. Igneous phosphate rock Solubilisation by biofilm-forming mycorrhizobacteria and hyphobacteria associated with Rhizoglomus irregulare DAOM 197198. Mycorrhiza. 2017;**27**:13-22. DOI: 10.1007/s00572-016-0726-z

[80] Babu SV, Triveni S, Reddy RS, Sathyanarayana J. Persistence of PSB-fungi biofilmed Biofertiliser in the soils and its effect on growth and yield of maize. Int J Curr Microbiol Appl Sci. 2017;**6**(12):1812-1821

[81] Timmis K, de Vos WM, Ramos JL, Vlaeminck SE, Prieto A, Danchin A, et al. The contribution of microbial biotechnology to sustainable development goals. Microbial Biotechnology. 2017;**10**(5):984-987

[82] Aberathna AAAU, Satharasinghe DA, Jayasooriya AP, Jinadasa RN, Manopriya S, Jayaweera BPA, et al. Increasing the bioavailability of phosphate by using microorganisms. Int. J Agron. 2022;**2022**:4305501

[83] Chen X, Yan X, Wang M, Cai Y, Weng X, Su D, et al. Long-term excessive phosphorus fertilization alters soil phosphorus fractions in the acidic soil of pomelo orchards. Soil and Tillage Research. 2022;**215**:105214

[84] Thuy PTP, Hoa NM, Dick WA. Reducing phosphorus fertilizer input in high phosphorus soils for sustainable agriculture in the mekong delta, Vietnam. Agriculture. 2020;**10**(3):87

[85] Oliveira M, Machado AV. The role of phosphorus on eutrophication: A historical review and future perspectives. Environ Technol Rev. 2013;**2**(1):117-127

[86] Wimalawansa SA, Wimalawansa SJ. Protection of watersheds, and control and responsible use of Fertiliser to prevent phosphate eutrophication of reservoirs. Int J Res Environ Sci. 2015;**1**(2):1-18

[87] El Bilali H, Callenius C, Strassner C, Probst L. Food and nutrition security and sustainability transitions in food systems. Food and Energy Security. 2019;**8**(2):1-20

[88] Wu JL, Chen Y, Zhang L, Zhang Y, Wang S, Xin Shi LL, et al. Effects of phosphate Solubilising bacteria on the growth, photosynthesis, and nutrient uptake of Camellia oleifera Abel. Forests. 2019;**10**(348):1-10

[89] Musvoto C, Nortje K, De Wet B, Mahumani BK, Nahman A. Imperatives for an agricultural green economy in South Africa. South African Journal of Science. 2015;**111**(1-2):1-8

[90] Santhirasegaram S. Peace and economic growth in developing countries: Pooled data cross – country empirical study. Peace and economic growth in developing countries: Pooled data cross - country. In: International Conference on Applied Economics – ICOAE. Kastoria, Greece: TEI of Western Macedonia Press; 2008;**2008**. pp. 807-814