International Journal of Life Science and Agriculture Research

ISSN (Print): 2833-2091, ISSN (Online): 2833-2105

Volume 02 Issue 09 September 2023

DOI: https://doi.org/10.55677/ijlsar/V02I09Y2023-02

Page No : 281-287

The Role of Phosphate-Solubilizing Microorganisms in Soil Health and Phosphorus Cycle: A Review

Nisrina Salsabila[1], Betty Natalie Fitriatin[2], Reginawanti Hindersah[3]
[1,2,3] Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran
Jalan Ir. Soekarno Km. 21, Jatinangor, Sumedang 45363, Indonesia

ABSTRACT: The role of phosphate-solubilizing microorganisms (PSM) in soil health and Phosphorus (P) cycle is a crucial aspect of agricultural productivity. Recent research has emphasized the importance of microorganisms in maintaining soil health. Phosphorus is an essential macronutrient for plant growth and development and significantly affects crop productivity. The PSM solubilize phosphate by producing metabolites such as organic acids, inorganic acids, hydrogen sulphide,-exopolysaccharide, and siderophore. Studies have shown that the combination of PSM with phosphate fertilizers increase the efficiency of the fertilizers in soils. The efforts have been made to integrate exogenous soil microorganisms into P cycling models. This review highlights the critical role of microorganisms in maintaining soil health and promoting P cycle, emphasizing the importance of incorporating them into soil management practices

Published Online:
08 September 2023

KEYWORDS: phosphate-solubilizing microorganisms, metabolites, P-cycle, solubilization mechanism.

Corresponding Author:
Nisrina Salsabila

INTRODUCTION

Agriculture is fundamental to human beings and the constitution of society (Kavanagh et al., 2018). Soil health is essential for sustainable agricultural productivity including food production. Microorganisms play a critical role in maintaining soil health and promoting plant growth. Among these microorganisms, phosphate-solubilizing microorganism (PSM) are gaining attention due to their ability to solubilize phosphorus in the soil, making it more available to plants. As a result, PSM are natural alternatives for chemical fertilizers to improve soil health and P cycle in agricultural systems.

Phosphorus is an essential macronutrient for plant growth and development, and its availability in the soil significantly affects crop productivity. The use of high-concentration phosphate fertilizers continuously has become a common practice that threatens natural resources (Silva et al., 2023). Besides, most of the fertilizers applied to the soil become unavailable for assimilation by plants and can even lead to biological imbalances in soil and water (Blanco-Vargas et al., 2020; Silva et al., 2019). However, the majority of phosphorus in the soil is present in insoluble forms, making it unavailable to plants. The PSM can solubilize this insoluble phosphorus by secreting organic acids, phosphatases, and other metabolites, thereby making it available to plants.

The use of PSM in agriculture has several advantages, including improving plant growth, increasing nutrient uptake efficiency, and reducing the dependence on chemical fertilizers. Moreover, the use of PSM can reduce environmental contamination caused by excessive use of chemical fertilizers, which can lead to water bodies eutrophication; soil acidification, and hence soil degradation. These microorganisms also enable to solubilization of phosphate in acidic and alkaline soils and degrade xenobiotic compounds (Silva et al., 2023). PSM plays an important role in improving soil quality that associated with its ability to increase nutrient availability (Rafique et al., 2017) and reduce excessive use of inorganic fertilizers (Sharma et al., 2013). This study addresses the importance of phosphate solubilizing microorganism and its role in soil health and P cycle. In this way, this study presents bibliographic review about phosphate solubilization, metabolites produced by MPF, inorganic fertilizer efficiency, P cycle, and soil health.

Soil Phosphorus Cycle

In most soils, the concentration of total P is higher than that of other essential nutrients like nitrogen (N) and potassium (K). However, over 80% of P is immobile and not readily available to plants (Xu et al., 2020). Phosphorus is present in different forms in the soil, primarily as inorganic P and organic P, and the distribution between these two forms varies as the soil matures (Figure 1). The significance role of the soil microorganism to influence soil P dynamics is recognized in agriculture. Therefore, exogenous microbial incorporation will maintain P cycling.

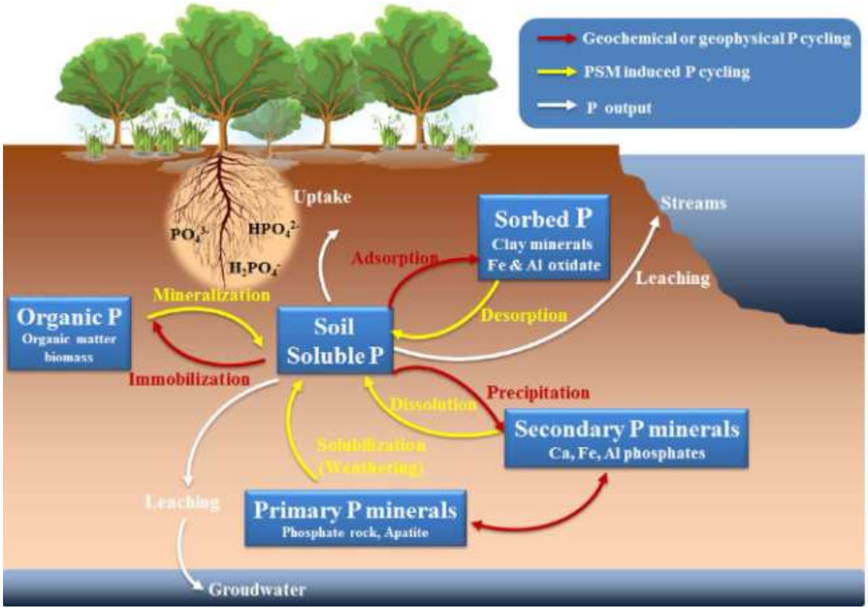


Figure 1. Soil phosphorus (P) cycle (Tian et al., 2021)

The atmosphere has limited involvement in P movement since P and its compounds are primarily in solid form at the standard temperature and pressure ranges found on Earth (Kumar et al., 2018). A significant portion of total soil P is contributed by organic P, which primarily originates from biological tissues where P is a constituent element of organic compounds such as nucleotides, phosphoproteins, phospholipids, and coenzymes. Compared to organic P, inorganic P in soil is present in a relatively insoluble and stable form. The P ions in unoccupied are attracted to the surfaces of Fe and Al oxides, and they can be easily leached. In contrast, occluded P is incorporated into layers and concretions of developing Fe and Al oxides during diffusive penetration and soil evolution, making it less easily leached (Tian et al., 2021).

Inorganic P is present in soil in a variety of forms and proportions (Mathew et al., 2020). It may leach into rivers to store P in marine sediments, or absorbed by plants or soil microbes to participate in the secondary organic phosphorus cycle. Long-term geochemical processes, such as weathering, adsorption/desorption, precipitation/dissolution, and solid-phase transformation, influence the form and distribution of P in soil in the majority of natural ecosystems (Hou et al., 2018).

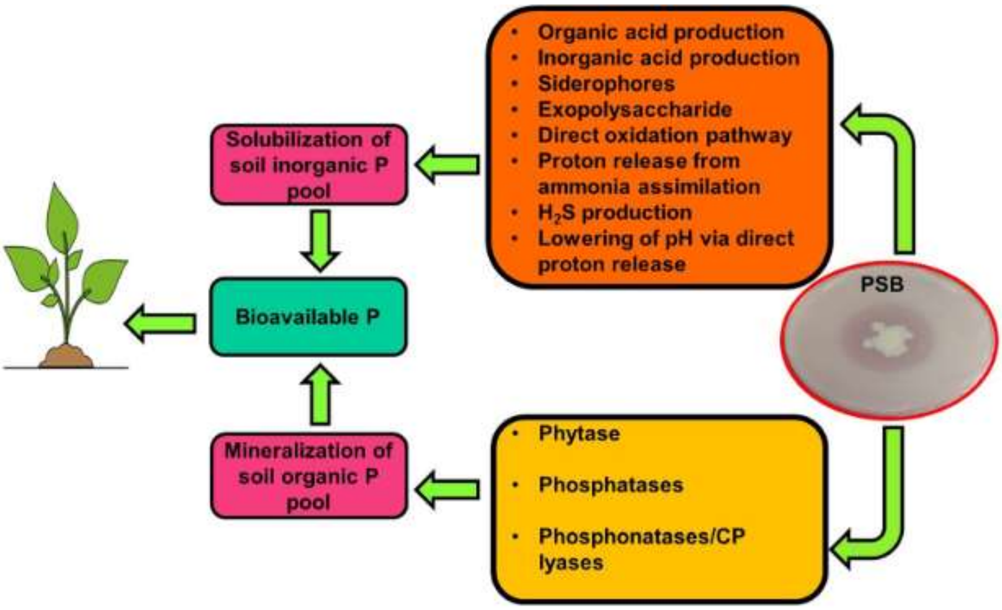
Soil organic originates from various biomolecules such as nucleotides, phosphides, co-enzymes, phosphoproteins, sugar phosphates, and phosphonates (Tamburini et al., 2012). These organic P compounds have relatively short lifespans and can make up to 65% of the total P content in typical soils (Dodd & Sharpley, 2015; Fabianska et al., 2019). Soil soluble orthophosphate ions can be immobilized in microbial cells to improve biomass growth (Tian et al., 2021). It is found that most of the P mineralized from organic P by PSM is incorporated into the bacterial cells as cellular P (Tao et al., 2008).

Controlling the release of orthophosphate from organic P sources in the soil is a significant aspect of the soil P cycle. Soil microbes, especially PSM, can enhance soil organic P cycle through organic P mineralization and decomposition (Tian et al., 2021). These biogeochemical processes are mainly moderated by the activities of phosphatase enzymes in PSM and soils (Sun et al., 2020).

The organic P hydrolysis activities of extracellular phosphatase enzymes are affected by soil properties, microbial interactions, plant cover, and environmental inhibitors and activators (Nannipieri et al., 2011). While soil PSM plays a role in organic P mineralization and the P cycle across different levels, the predominant enzymes and functional genes involved tend to be consistent (Tian et al., 2021). The relationship between microbial genes and the expression of phosphatase enzymes is recognized as the fundamental mechanism governing the conversion of organic P into bioavailable orthophosphates by PSMs (Bi et al., 2018).

Mechanism of Phosphate Solubilization by PSM and Metabolites Produced

The P availability in soil solution controlled by chemical processes (precipitation and dissolution of primary and secondary minerals), physico-chemical processes (adsorption and desorption of P from clays, oxides, and minerals) and biological processes (Frossard et al., 2000; Shen et al., 2011; Sims et al., 2002). The Biological mechanisms to control inorganic P availability in soil mineralization, solubilization, and immobilization are the predominant ways of dissemination of phosphorus in soil by PSMs, which are influenced by available inorganic minerals in the soil (Rawat et al., 2020).



Phosphate solubilization by PSM (Rawat et al., 2020)

PSM solubilize phosphate by producing some metabolites, including organic acids, inorganic acids, Hydrogen sulphide (H_2S), exopolysaccharide (EPS), and siderophore. Organic acids released by PSM are citric acid, gluconic acid, oxalic acid, and tartaric acid (Table 1). These acids dissolve inorganic phosphates through several mechanisms (Kishore et al., 2015): (a) chelation of cations bound to phosphate, (b) reducing pH, (c) complexation with metal ions bound to phosphates, and (d) challenging P for adsorption site.

Table 1. Organic acids produced by Phosphate Solubilizing Microbes

Microbes	**Organic Acids**	**References**
Pseudomonas spp.	Gluconic, formic, and citric acid	Pande et al., 2017
Pseudomonas prosekii	Gluconic, caprylic, fumaric, carboxylic, and benzoic acid	Yu et al., 2019
Pseudomonas poae	Gluconic and malic acid	Vyas & Gulati, 2009
Pseudomonas fluorescens	Gluconic, lactic, dan succinic acid	Vyas & Gulati, 2009
Pseudomonas trivialis	Gluconic, lactic, succinic, formic, dan malic acid	Vyas & Gulati, 2009
Bacillus sp.	Citric, malic, succinic, fumaric, tartaric, and gluconic acid	Selvi et al., 2017
Proteus sp.	Citric, succinic, fumaric, and gluconic acid	Selvi et al., 2017
Aspergillus sp.	Citric, gluconic, oxalic, succinic, malic, and glycolic acid	Sane & Mehta, 2015
Azospirillum sp.	Citric, succinic, fumaric, and gluconic acid	Selvi et al., 2017
Penicillium sp.	Gluconic, glycolic, succinic, malic, oxalic, and citric acid	Sane & Mehta, 2015
Erwinia herbicola	Gluconic acid	Kumar et al., 2018
Bacillus megaterium	Gluconic, lactic, succinic, and propionic acid	Saeid et al., 2018
Bacillus subtilis	Lactic, succinic, and propionic acid	Saeid et al., 2018
Enterobacter sp.	Acetic and malic acid	Suleman et al., 2018

In addition to organic acids, PSM also produces inorganic acids. According to reports, PSMs generate nitric acid, carbonic acid, sulfuric acid, and hydrochloric acid that dissolve phosphate, but these acids are not as efficient as organic acids (Rawat et al., 2020). Nitrobacter and Thiobacillus produce inorganic acids such as nitric acids and sulfuric acid, respectively, to solubilize phosphates (Shrivastava et al., 2018). Another mechanism to dissolve inorganic P involves the production of H_2S, which reacts with ferric phosphate to generate ferrous sulfate and release phosphate (Florentino et al., 2016).

Microorganisms produce EPS in harsh condition that lead to biofilm formation. The EPS constitute a substantial portion of bacterial mass within the extracellular matrix, typically accounting for anywhere between 40% and 95% (Flemming & Wingender, 2001). The presence of EPS contributes to an enhanced solubilization of phosphorus (P) by disrupting the P-solubilization homeostasis, leading to a greater release of phosphorus from insoluble phosphate compounds (Yi et al., 2008). Complex of EPS and metals is present in soil indicating their involvement in the solubilization of phosphorus in the soil (Ochoa-Loza et al., 2001).

Microorganisms also produce siderophores which are low molecular weight high-affinity iron chelating compounds that are excreted in response to iron stress in the environment (Rawat et al., 2020). The production of siderophores by PSB indirectly enhances the availability of phosphorus, as these ligands also have the capability to extract iron from ferric citrate and ferric phosphate (Zaidi et al., 2009). According to a report, in alkaline conditions, several phosphate solubilizers including *Rhizobium radiobacter*, *Pantoea allii*, *Bacillus subtilis*, and *Bacillus megaterium* produced siderophores ranging from 80 to 140 µmol/L which facilitate the survival of organisms in stressful environments and enhanced the solubilization of phosphorus (Ferreira et al., 2019).

Soil Health Improvement by PSM

Microorganisms have the ability to solubilize the insoluble phosphates and maintain the soil health and quality (Richardson, 2001). Rhizospheric microorganisms mediate soil process such as decomposition, nutrient mobilization and mineralization, and storage release of nutrients and water (Khan et al., 2007). Inoculation of *Bacillus cereus* and *Pseudomonas moraviensis*, exhibited 35% higher soil organic matter in rhizosphere of pots grown wheat plants, and a further 25% increase was observed both in pot and field grown plants, when tryptophan was added (Hassan & Bano, 2015). Inoculation of *Bacillus cereus* and *P. moraviensis* also increase P contents 25%, K contents 35%, Ca and Mg 20% in rhizosphere soil (Hassan & Bano, 2015).

Soil properties including total bacteria, organic matter and total N showed positive and significant correlation with phosphate solubilizing bacteria (PSB) population (Rfaki et al., 2018). The application of the P Solubilizing Purple Non-sulfur Bacteria biofertilizers improved some soil chemical properties, such as pH_{H2O}, EC, NH_4^+, and available P (Huu et al., 2022). The PSB were able to reduce the soil acidity, meaning that biofertilizers play key roles in raising pH as well; in this case, leading to an increase in NH_4^+ and soluble P concentrations in soil and increase in high available nutrients such as N, P, K, Ca, and Mg (Huu et al., 2022). The increase of total N in soil up to 10% and available P up to 28% following PSB inoculation was reported (Fatima et al., 2022).

CONCLUSION

Phosphate-solubilizing microorganisms play a critical role in maintaining soil health, P cycle, and inorganic P fertilizer efficiency by solubilizing phosphorus in the soil, making it more available to plants. PSM solubilize phosphate by producing metabolites such as organic acids, inorganic acids, H_2S, exopolysaccharide, and siderophore. The use of PSM can help reduce environmental contamination caused by excessive use of chemical fertilizers. PSM can enhance soil organic P cycle through organic P mineralization and decomposition. PSM also improve soil health by maintaining soil properties. It is suggested that PSM shall be utilized in sustainable food crop production.

REFERENCES

1. Adnan, M., Fahad, S., Zamin, M., Shah, S., Mian, I., Danish, S., . . . Saeed, B. (2020). Coupling Phosphate-Solubilizing Bacteria with Phosphorus Supplements Improve Maize Phosphorus Acquisition and Growth under Lime Induced Salinity Stress. *Plants, 9, 900*.
2. Ahmad, I., Pichtel, J., & Hayat, S. (2008). Plant-bacteria Interactions: Strategies and Techniques to Promote Plant Growth. *John Wiley & Sons*.
3. Alansari, A. S., Yassin, M. M., & Seheib, M. W. (2018). Role of Organic Acids on Phosphorus Fractions in Silty Clay Loam Soil. *Al-Qadisiyah Journal For Agriculture Sciences*, *8(2)*, 12-21.
4. Alori, E. T., Glick, B. R., & Babalola, O. O. (2017). Microbial Phosphorus Solubilization and Its Potential for Use in Sustainable Agriculture. *Front. Microbiol. 8:971*.
5. Arif, M. S., Shahzad, S. M., Yasmeen, T., Riaz, M., Ashraf, M., Ashraf, M., . . . Kausar, R. (2017). Improving plant phosphorus (P) acquisition by phosphate-solubilizing bacteria. *Essential Plant Nutrients: Uptake, Use Efficiency, and Management*, 513-556.
6. Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y., & Dhiba, D. (2018). Soil Microbial Resources for Improving Fertilizers Efficiency in an Integrated Plant Nutrient Management System. *Front. Microbiol., 9*.

7. Bi, Q. F., Zheng, B. X., Lin, X. Y., Li, K. J., Liu, X. P., Hao, X. L., Zhang, H., Zhang, J. B., Jaisi, D. P., & Zhu, Y. G. (2018). The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. Chemical Geology, 483, 56–64. https://doi.org/10.1016/J.CHEMGEO.2018.02.013
8. Blanco-Vargas, A., Rodríguez-Gacha, L. M., Sánchez-Castro, N., Garzón-Jaramillo, R., Pedroza-Camacho, L. D., Poutou-Piñales, R. A., Rivera-Hoyos, C. M., Díaz-Ariza, L. A., & Pedroza-Rodríguez, A. M. (2020). Phosphate-solubilizing Pseudomonas sp., and Serratia sp., co-culture for Allium cepa L. growth promotion. Heliyon, 6(10), e05218. https://doi.org/10.1016/j.heliyon.2020.e05218
9. Dodd, R. J., & Sharpley, A. N. (2015). Recognizing the role of soil organic phosphorus in soil fertility and water quality. Resources, Conservation and Recycling, 105, 282–293.
10. Fabianska, M. J., Kozielska, B., Konieczynski, J., & Bielaczyc, P. (2019). Occurrence of organic phosphates in particulate matter of the vehicle exhausts and outdoor environment – A case study. Environmental Pollution, 244, 251–360.
11. Fatima, F., Ahmad, M. M., Verma, S. R., & Pathak, N. (2022). Relevance of phosphate solubilizing microbes in sustainable crop production: a review. In *International Journal of Environmental Science and Technology* (Vol. 19, Issue 9, pp. 9283–9296). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s13762-021-03425-9
12. Ferreira, C., Vilas-Boas, A., Sousa, C., Soares, H., & Soares, E. (2019). Comparison of five bacterial strains producing siderophores with ability to chelate iron under alkaline conditions. *AMB Express 9*, 1-12.
13. Flemming, H. C., & Wingender, J. (2001). Relevance of microbial extracellular polymeric substances (EPSs)-Part I: structural and ecological aspects. *Water Sci Technol 43*, 1-8.
14. Florentino, A. P., Weijma, J., Stams, A. J. M., & Sánchez-Andrea, I. (2016). Ecophysiology and Application of Acidophilic Sulfur-Reducing Microorganisms. In P. H. Rampelotto (Ed.), Biotechnology of Extremophiles: Advances and Challenges (pp. 141–175). Springer International Publishing. https://doi.org/10.1007/978-3-319-13521-2_5
15. Frossard, E., Condron, L. M., Oberson, A., Sinaj, S., & Fardeau, J. C. (2000). Processes Governing Phosphorus Availability in Temperate Soils. *Journal of Environmental Quality*, *29*(1), 15–23. https://doi.org/10.2134/jeq2000.00472425002900010003x
16. Hassan, T. U., & Bano, A. (2015). The stimulatory effects of L-tryptophan and plant growth promoting rhizobacteria (PGPR) on soil health and physiology of wheat. *Journal of Soil Science and Plant Nutrition*, *15*(1), 190–201.
17. Hou, E., Chen, C., Luo, Y., Zhou, G., Kuang, Y., Zhang, Y., Heenan, M., Lu, X., & Wen, D. (2018). Effects of climate on soil phosphorus cycle and availability in natural terrestrial ecosystems. Global Change Biology, 24(8), 3344–3356. https://doi.org/10.1111/GCB.14093
18. Huu, T. N., Giau, T. T. N., Ngan, P. N., Van, T. T. B., & Khuong, N. Q. (2022). Potential of Phosphorus Solubilizing Purple Nonsulfur Bacteria Isolated from Acid Sulfate Soil in Improving Soil Property, Nutrient Uptake, and Yield of Pineapple (Ananas comosus L. Merrill) under Acidic Stress. *Applied and Environmental Soil Science*, *2022*. https://doi.org/10.1155/2022/8693479
19. Kavanagh, P. H., Vilela, B., Haynie, H. J., Tuff, T., Lima-Ribeiro, M., Gray, R. D., Botero, C. A., & Gavin, M. C. (2018). Hindcasting global population densities reveals forces enabling the origin of agriculture. *Nature Human Behaviour*, *2*(7), 478–484. https://doi.org/10.1038/s41562-018-0358-8
20. Kishore, N., Pindi, P. K., & Reddy, S. R. (2015). Phosphate-Solubilizing Microorganisms: A Critical Review. *Plant Biology and Biotechnology: Volume I: Plant Diversity, Organization, Function and Improvement*, 307-333.
21. Kumar, A., Kumar, A., & Patel, H. (2018). Role of microbes in phosphorus availability and acquisition by plants. *Int.J.Curr.Microbiol.App.Sci*, *7*(5), 1344–1347. https://doi.org/10.20546/ijcmas.2018.705.161
22. Lopes, C., Silva, A., Estrada-Bonilla, G., Ferraz-Almeida, R., Vieira, J., Otto, R., . . . Cardoso, E. (2021). Improving the fertilizer value of sugarcane wastes through phosphate rock amendment and phosphate-solubilizing bacteria inoculation. *Journal of Cleaner Production 298*.
23. Manzoor, M., Abbasi, M., & Sultan, T. (2017). Isolation of Phosphate Solubilizing Bacteria from Maize Rhizosphere and Their Potential for Rock Phosphate Solubilization–Mineralization and Plant Growth Promotion. *Geomicrobiol. J., 34*, 81-95.
24. Mathew, D., T.R., G., K.K., B., P.B., U., K., S., P.M., D., M., N., N.V., M., & K.R., M. (2020). Influence of hypoxia on phosphorus cycling in Alappuzha mud banks, southwest coast of India. Regional Studies in Marine Science, 34, 101083. https://doi.org/https://doi.org/10.1016/j.rsma.2020.101083
25. Nannipieri, P., Giagnoni, L., Landi, L., & Renella, G. (2011). Role of Phosphatase Enzymes in Soil. In *Book cover Book cover Phosphorus in Action* (pp. 215–243). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-15271-9_9
26. Ochoa-Loza, F. J., Artiola, J. F., & Maier, R. M. (2001). Stability constants for the complexation of various metals with a rhamnolipid biosurfactant. *Journal of Environmental Quality*, *30*, 479-485.

27. Pande, A., Pandey, P., Mehra, S., Singh, M., & Kaushik, S. (2017). Phenotypic and genotypic characterization of phosphate solubilizing bacteria and their efficiency on the growth of maize. *Journal of Genetic Engineering and Biotechnology*, *15*(2), 379–391. https://doi.org/10.1016/J.JGEB.2017.06.005
28. Rawat, P., Das, S., Shankhdhar, D., & Shankhdhar, S. C. (2020). Phosphate-Solubilizing Microorganisms: Mechanism and Their Role in Phosphate Solubilization and Uptake. *Journal of Soil Science and Plant Nutrition 2020 21:1*, *21*(1), 49–68. https://doi.org/10.1007/S42729-020-00342-7
29. Rfaki, A., Zennouhi, O., Nassiri, L., & Ibijbijen, J. (2018). Soil Properties Related to the Occurrence of Rock Phosphate-Solubilizing Bacteria in the Rhizosphere Soil of Faba Bean (Vicia faba L.) in Morocco. *Soil Systems*, *2*(2), 31. https://doi.org/10.3390/soilsystems2020031
30. Richardson, A. E. (2001). Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. *Australian Journal of Plant Physiology*, *28*(9), 897–906. https://doi.org/10.1071/PP01093
31. Saeid, A., Prochownik, E., & Dobrowolska-Iwanek, J. (2018). Phosphorus Solubilization by Bacillus Species. *Molecules 2018, Vol. 23, Page 2897*, *23*(11), 2897. https://doi.org/10.3390/MOLECULES23112897
32. Saghir Khan, M., Zaidi, A., Wani, P. A., & Saghir KHAN, M. (2007). Role of phosphate-solubilizing microorganisms in sustainable agriculture-A review Role of phosphate-solubilizing microor-ganisms in sustainable agriculture-A review. Agronomy for Sustainable Development Role of phosphate-solubilizing microorganisms in sustainable agriculture-A review. *Agron. Sustain. Dev*, *27*(1), 29–43. https://doi.org/10.1051/agro:2006011
33. Sane, S. A., & Mehta, S. K. (2015). Isolation and evaluation of rock phosphate solubilizing fungi as potential biofertilizer. *Journal of Fertilizers and Pesticides*, *6*(2).
34. Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., & Zhang, F. (2011). Phosphorus Dynamics: From Soil to Plant. *Plant Physiology*, *156*(3), 997–1005. https://doi.org/10.1104/pp.111.175232
35. Shrivastava, M., Srivastava, P. C., & D'Souza, S. F. (2018). Phosphate-solubilizing microbes: diversity and phosphates solubilization mechanism. *Role of Rhizospheric Microbes in Soil: Volume 2: Nutrient Management and Crop Improvement*, 137-165.
36. Silva, L. I. da, Pereira, M. C., Carvalho, A. M. X. de, Buttrós, V. H., Pasqual, M., & Dória, J. (2023a). Phosphorus-Solubilizing Microorganisms: A Key to Sustainable Agriculture. *Agriculture*, *13*(2), 462. https://doi.org/10.3390/agriculture13020462
37. Silva, L. I. da, Pereira, M. C., Carvalho, A. M. X. de, Buttrós, V. H., Pasqual, M., & Dória, J. (2023b). Phosphorus-Solubilizing Microorganisms: A Key to Sustainable Agriculture. *Agriculture (Switzerland)*, *13*(2). https://doi.org/10.3390/AGRICULTURE13020462
38. Silva, F. B. V., Nascimento, C. W. A., Alvarez, A. M., & Araújo, P. R. M. (2019). Inputs of rare earth elements in Brazilian agricultural soils via P-containing fertilizers and soil correctives. *Journal of Environmental Management*, *232*, 90–96. https://doi.org/10.1016/j.jenvman.2018.11.031
39. Sims, J. T., Maguire, R. O., Leytem, A. B., Gartley, K. L., & Pautler, M. C. (2002). Evaluation of Mehlich 3 as an Agri-Environmental Soil Phosphorus Test for the Mid-Atlantic United States of America. *Soil Science Society of America Journal*, *66*(6), 2016–2032. https://doi.org/10.2136/sssaj2002.2016
40. Suleman, M., Yasmin, S., Rasul, M., Yahya, M., Atta, B. M., & Mirza, M. S. (2018). Phosphate solubilizing bacteria with glucose dehydrogenase gene for phosphorus uptake and beneficial effects on wheat. *PLoS ONE*, *13*(9), 1–28.
41. Sun, F., Song, C., Wang, M., Lai, D. Y. F., Tariq, A., Zeng, F., Zhong, Q., Wang, F., Li, Z., & Peng, C. (2020). Long-term increase in rainfall decreases soil organic phosphorus decomposition in tropical forests. *Soil Biology and Biochemistry*, *151*, 108056. https://doi.org/10.1016/J.SOILBIO.2020.108056Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mader, P., & Mathimaran, N. (2018). Improving crop yield and nutrient use efficiency via biofertilization-a global meta-analysis. *Front. Plant Sci. 8, 2204*.
42. Tao, G. C., Tian, S. J., Cai, M. Y., & Xie, G. H. (2008). Phosphate-Solubilizing and -Mineralizing Abilities of Bacteria Isolated from Soils. *Pedosphere*, *18*(4), 515–523.
43. Tamburini, F., Pfahler, V., Bünemann, E. K., Guelland, K., Bernasconi, S. M., & Frossard, E. (2012). Oxygen Isotopes Unravel the Role of Microorganisms in Phosphate Cycling in Soils. Environmental Science & Technology, 46(11), 5956–5962. https://doi.org/10.1021/es300311h
44. Tian, J., Ge, F., Zhang, D., Deng, S., & Liu, X. (2021). Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical p cycle. *Biology*, *10*(2), 1–19. https://doi.org/10.3390/biology10020158
45. Vyas, P., & Gulati, A. (2009). Organic acid production in vitro and plant growth promotion in maize under controlled environment by phosphate-solubilizing fluorescent Pseudomonas. *BMC Microbiology*, *9*(1), 1–15. https://doi.org/10.1186/1471-2180-9-174/TABLES/7

46. Wani, P., Khan, m., & Zaidi, A. (2007). Co-inoculation of nitrogen-fixing and phosphate-solubilizing bacteria to promote growth, yield and nutrient uptake in chickpea. *Acta Agron. Hung, 55*, 315-323.
47. Yi, Y., Huang, W., & Ge, Y. (2008). Exopolysaccharide: a novel important factor in the microbial dissolution of tricalcium phosphate. *World J Microbiol Biotechnol 24*, 1059–1065.
48. Yu, L. Y., Huang, H. B., Wang, X. H., Li, S., Feng, N. X., Zhao, H. M., Huang, X. P., Li, Y. W., Li, H., Cai, Q. Y., & Mo, C. H. (2019). Novel phosphate-solubilising bacteria isolated from sewage sludge and the mechanism of phosphate solubilisation. *Science of The Total Environment*, *658*, 474–484. https://doi.org/10.1016/J.SCITOTENV.2018.12.166
49. Zaidi, A., Khan, M., Ahemad, M., & Oves, M. (2009). Plant growth promotion by phosphate solubilizing bacteria. *Acta Microbiologica et Immunologica Hungarica*, *56*, 263-284.