Ecological and Economical Impact of Phosphate Solubilizing Bacteria

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ABSTRACT-

Phosphorous is one of the most essential macronutrient for plant development and growth. It plays a significant role in crop production. Despite being one of the most prevalent metals found in the Earth's crust, due to its insoluble nature, only trace amounts are available for plant uptake. In the soil 70% of phosphorous is present in the inorganic form that is inaccessible to plants. These forms of inorganic phosphorous are generally complexed with calcium, aluminum, or iron. The problem of phosphate inaccessibility was traditionally tackled by using phosphate fertilizers, with organic fertilizers, manure and composts showing more effectiveness than their chemical counterparts. One of the main objectives of sustainable agriculture is to make phosphates more bioavailable to plants. At this junction, phosphate-solubilizing bacteria have recently been highlighted for their ability to decrease phosphorous deficiency by improving phosphorous bioavailability to plants. When used as inoculants, phosphate-solubilizing bacteria have demonstrated an increased phosphorous uptake by plants. Moreover, because of their numerous benefits including being environmentally safe, cost-effective and great biological effectiveness, these microbes are currently the subject of attention. These bacteria also enable the potential of using phosphatic rocks for agricultural development. In this review, we discuss about these phosphate-solubilizing microorganisms, their mechanism of phosphate solubilization and the various ecological and economical aspects related to their use. We signify that phosphate solubilizing bacteria are highly effective biofertilizers because they boost plant phosphorous uptake, encourage sustainable farming, enhance soil fertility and increase crop yields.

Keywords- Phosphate solubilizing bacteria, PSB, Phosphate solubilizing microorganisms, Biofertilizer

INTRODUCTION-

Phosphorous is one of the essential micronutrients affecting plant growth and development. Soil contains 0.05% phosphorous out of which 0.1% phosphorous is used by plants. In soil, phosphorous is present in both organic and inorganic forms (Aliyat et al., 2022). It is the key nutrient for the productivity of the crop. It is involved in many metabolic activities that occur in plants like photosynthesis, energy transfer, nitrogen fixation, and membrane formation. It is associated with the various key functions including the development of root and stem systems as well as assist the plant to produce growth regulators like auxins, cytokinines, and gibberellins (Satyaprakash et al., 2017).

The soil mainly contains phosphorous in insoluble forms which is unavailable for plant uptake. These insoluble forms of phosphorous compounds are usually complexed with various soil minerals like aluminum (Al), iron (Fe), manganese (Mn), and calcium (Ca). These complexes vary between different soils and are mainly determined by the pH of the soil and concentration of the soil minerals. Phosphorous mainly forms a complex with Aluminum, Iron and Manganese in acidic soil, while in alkaline soil it forms complex with calcium (Walpola & Yoon et al., 2012). The other organic form of phosphorous in soil occurs as sugar phosphates, phosphoproteins, phosphates, and phospholipids in various forms. A deficiency of phosphorous can restrict the growth and development of plants and leads to the formation of short, dark and dull leaves. Unavailability of phosphorous can also inhibit the growth of plants altogether. To fulfill the deficiency of phosphorous in soil, phosphatic fertilizers are used which contain phosphorous that converts the insoluble form of phosphate to soluble phosphate.

Soil contains some naturally occurring organisms that can convert inorganic phosphate into orthophosphates which can be easily taken up by plants. Bacteria that are capable of phosphate solubilization are called Phosphate Solubilizing Bacteria (PSB). Phosphate solubilizing bacteria offer an ecologically acceptable means for converting insoluble phosphate into soluble phosphate through the process of acidification, chelation, and production of organic acids. They are used as biofertilizers as they can induce plant growth.

Phosphate deficiency can be solved by using phosphorous fertilizers. Phosphate biofertilizers are used because it increases the productivity and yield of the crop. Soil organisms play a key role in soil phosphorous dynamics and subsequent phosphate availability to plants. Several studies reported that optimization of phosphate solubilizing microorganisms promotes growth, yield, and quality in crops like apples, maize, rice, mustard, wheat, chickpeas, and legumes (Kalayu et al., 2019). Several studies indicate that the implementation of phosphate solubilizing microorganisms and phosphate fertilizers increase the grain yield by around 22%, phosphorous uptake by 26% and decrease the usage of fertilizers upto 30% (Rawat et al., 2020). It is safe and non toxic to the environment. PSM can solubilize mineral compounds and excrete some growth hormones and also protect the plants from the pathogens present in the soil.

PHOSPHATE SOLUBILIZING MICROORGANISMS-

Microorganisms are an integral component of soil morphology because of their direct and indirect effect on the health of the soil. It has been established from as early as 1903 that microorganisms play an important role in mineral phosphate solubilization process. This was followed by a lot of research on the solubilization of mineral phosphate by naturally occurring microbes (Khan et al., 2009). Phosphate solubilizing microorganisms encompass a group of bacteria, fungus, actinomycetes and algae, with bacteria generally being more efficient phosphate solubilizers than their fungal counterparts. About 1 to 50% of phosphates solubilizing bacteria are present in the microbial population in soil (Satyaprakashet et at., 2017). There are some important genera of phosphate solubilizers which include *Pseudomonas* and *Bacillus* (Khan et al., 2009).

Phosphate solubilizing microorganisms (PSM) have great advantages as they offer higher efficiency and are cost-effective. Many bacterial species can dissolve phosphate. The presence of a variety of species and microorganisms in the soil makes a plant’s root system complex. These bacteria are present near or around the root of the plant. Some rhizobacteria are found inside the tissue of plants which are called endophytes. Plant can access more phosphorous from the soil because of phosphate solubilizing bacteria. They mineralize and dissolve insoluble organic phosphates and insoluble inorganic phosphorous in minerals (Timofeeva et al., 2022).

The species and population of PSB vary from soil to soil. PSB are present in higher amounts in mild and moist soil and generally low in arid and semi-arid conditions. PSB generally induce the solubilization of insoluble phosphorous compound by the release of organic acids, phosphatase, and phytase enzyme which is present in the form of soil microorganism. PSM is mostly rich in the rhizosphere because they are more active than others. Major species of bacteria reported as phosphate solubilizers are *Rhodococcus, Arthrobacter, Serratia, Gordonia,* and *Phyllobaterium* (Walpola & Yoon et al., 2012). Studies report a temperature of 25-30 ^{o}C to be optimum for phosphorous solubilization (Alori et al., 2017). PSB improves the productivity of agricultural lands and also promote promote the cell division, cell differentiation, shoot growth, root development and flowering (Puri et al., 2020).

MECHANISM OF PHOSPHATE SOLUBILIZING BACTERIA-

The soil microbes have an ability to solubilize available phosphorous sources into forms which can be assimilated by plants assimilating forms (Toro et al., 2007). There are many phosphate-solubilization mechanisms present in bacteria. The bacterial species that can dissolve phosphorous are found in the genera of *Bacillus, Burkholderia, Rhizobium, Pseudomonas, Archromobacter, Agrobacterium, Micrococcus, Enterobacter, Flavobacterium, Azotobacter, Paenibacillus* and *Erwinia*. Certain bacterial species can perform both the tasks i.e., solubilization of inorganic phosphate or mineralization of organic phosphate (Khiari et al., 2005).

A large number of saprophytic bacteria and fungi act on sparingly soluble soil phosphate, mainly by a chelating-mediated mechanism for the accomplishment of phosphorous solubilization by converting insoluble forms of phosphate to soluble forms (HPO_4^{-2} and $HP0_4^{-3}$). The bacteria also generate organic and inorganic acids which converts calcium phosphate to di- or monobasic phosphate (Walpola & Yoon et al., 2012). Soil fertility is influenced by the microbial community through the process of decomposition, mineralization, and release of stored nutrients (Khan et al., 2009). A further advantage of phosphate compounds is that they can precipitate heavy metals, including lead, in contaminated environments by immobilizing them through their compounds. However, due to its insolubility in soil, most of the phosphorous compounds are not used for immobilization. In order to prevent eutrophication, there is a limit to the amount of phosphate that can be added to the environment (Park et al., 2011).

Different kinds of minerals, such as iron-containing minerals, are often adsorbed with phosphate. Considering the geochemical interactions between two elements, researchers suggest that some bacteria can dissolve iron chelating minerals in order to access the adsorbed phosphate under phosphate starvation (Chouyia et al., 2020).

INORGANIC PHOSPHATE SOLUBILIZATION-

Multiple studies have revealed that certain bacterial species have the capacity to liquefy insoluble inorganic phosphate complexes like tricalcium phosphate, dicalcium phosphate, hydroxyapatite, and rock phosphate (Ahmed et al., 2009). The main method by which phosphate-solubilizing microorganisms release phosphorous is through the production of organic acids, either by lowering pH or by enhancing chelation of the cations bound to phosphate by competing with phosphorous for adsorption sites on the soil or by forming soluble complexes with metal ions associated with insoluble phosphorous (Ca, Al, Fe). The production of organic acids is symbolized by a decrease in pH (Sharma et al., 2013). By exchanging phosphate ions with acid ions, organic acids can either directly dissolve the mineral phosphate or chelate the Fe, Al, and Ca ions that are linked with phosphate (Sharma et al., 2013). Gluconic acid, oxalic acid, citric acid, lactic acid, tartaric acid and aspartic acid are some of the main acids that are generated by PSM during the solubilization of insoluble phosphorous. A significant soluble form of inorganic phosphate that typically occurs at lower pH is the monovalent anion phosphate H_2PO_4. Yet, the divalent and trivalent forms of inorganic phosphate (HPO_4^{-2} and $HP0_4^{-3}$, respectively) also appear with a rise in the pH of the soil environment (Sharma et al., 2013). When phosphorous is added to soil, it reacts with other metallic elements like Fe, Al and Ca ions rendering it unavailable to plants through the formation of ferrous phosphate, aluminium phosphate, calcium phosphate, etc,.

The release of organic acids by PSM triggers the chelation reaction, which releases the bound phosphorous to other metallic elements and makes it free to be used by plants. When the acidity increases, protons compete with metal ions like Fe^{3+} and Al^{3+} for the binding site, which results in the release of phosphorous from the metal complexes. Similarly, an acidic anion may compete with PO_4^{3-} consequently resulting in the release of phosphate. Bacterial production of inorganic acids such as sulfuric-, nitric-, hydrochloric-, and carbonic acid contribute to a lesser extent to inorganic phosphate solubilization (Zutter et al., 2022). Alkaline phosphatase (PhoA), phospholipase (PhoD), and glycerophosphate-diester are the most common enzymes that are responsible for inducing inorganic phosphate starvation in bacteria, this allows an increased phosphate solubilization. The use of phosphate solubilizing bacteria (PSB) as inoculants for the rhizosphere is a well-known strategy to mitigate phosphorous deficiency in plants (Timofeeva et al., 2022).

ORGANIC PHOSPHATE SOLUBILIZATION-

In the soil 4-90% organic phosphate is present, with 20-80% of organic phosphorous mostly present in the upper layer of soil (Quiquampoix & Mousain et al., 2005, Sharma et al., 2013). The solubilization of organic phosphate, also known as the mineralization of organic phosphorous is done by an enzyme known as phosphatase (Sivasakthivelan et al., 2021). Figure 1 depicts a diagrammatic representation of the solubilization of the various inorganic and organic forms of phoshphorous present in soil by phosphate solubilizing microorganisms. Organic phosphorous mineralization avails the soil of phosphorous by increasing the solubility of phosphorous already present in the soil (Quiquampoix & Mousain et al., 2005). Phosphate solubilizing microorganisms release some enzymes which are involved in the process of phosphate mineralization. In the soil phosphorous is present in the form of phosphomonoesters, phosphodiesters, phospholipids, nucleic acids, and inositol phosphatase. In terms of quantity and as a percentage of the total organic phosphorous the amount of inositol phosphates is high. In the soil 80% of inositol phosphate is present and they are present in different forms like myo-inositol, scylla-inositol, D-chiro inositol, and neo-inositol phosphates. Only 0.5-7% of phospholipid is present in the soil while nucleic acid is present in even less than 3% in the form of organic acids (Quiquampoix & Mousain et al., 2005). The plant seeds and pollen contain phytate (i.e., the primary source of inositol) which is a good component of organic phosphate in soil (Sivasakthivelan et al., 2021). Organic phosphates like alkaline phosphatase and acid phosphatase are used as a substrate for converting them into an inorganic form. The organic phosphate is hydrolyzed by plant roots/microbes or alkaline phosphate by releasing organic anions and the production of siderophores (Yadav and Tarafdar et al., 2001). The mineralization of soil organic phosphorous plays an important role in phosphorous cycling. The phosphate produced by PSM has a good affinity for organic phosphatase compounds than the phosphate produced by plants root. The organic phosphate solubilization is done by nonspecific acid phosphatase (NSAP), phytases, phosphonates, and C-P lyases enzymes. Xenobiotic phosphonates are used in large amounts in the form of pesticides, detergent additives, antibiotics, and flame retardants from which microbial phosphorous is released (Ahmed et al., 2009). Rainfall, temperature, drainage, soil pH, or cultivation of crop can affect the organic phosphorous present in the soil.

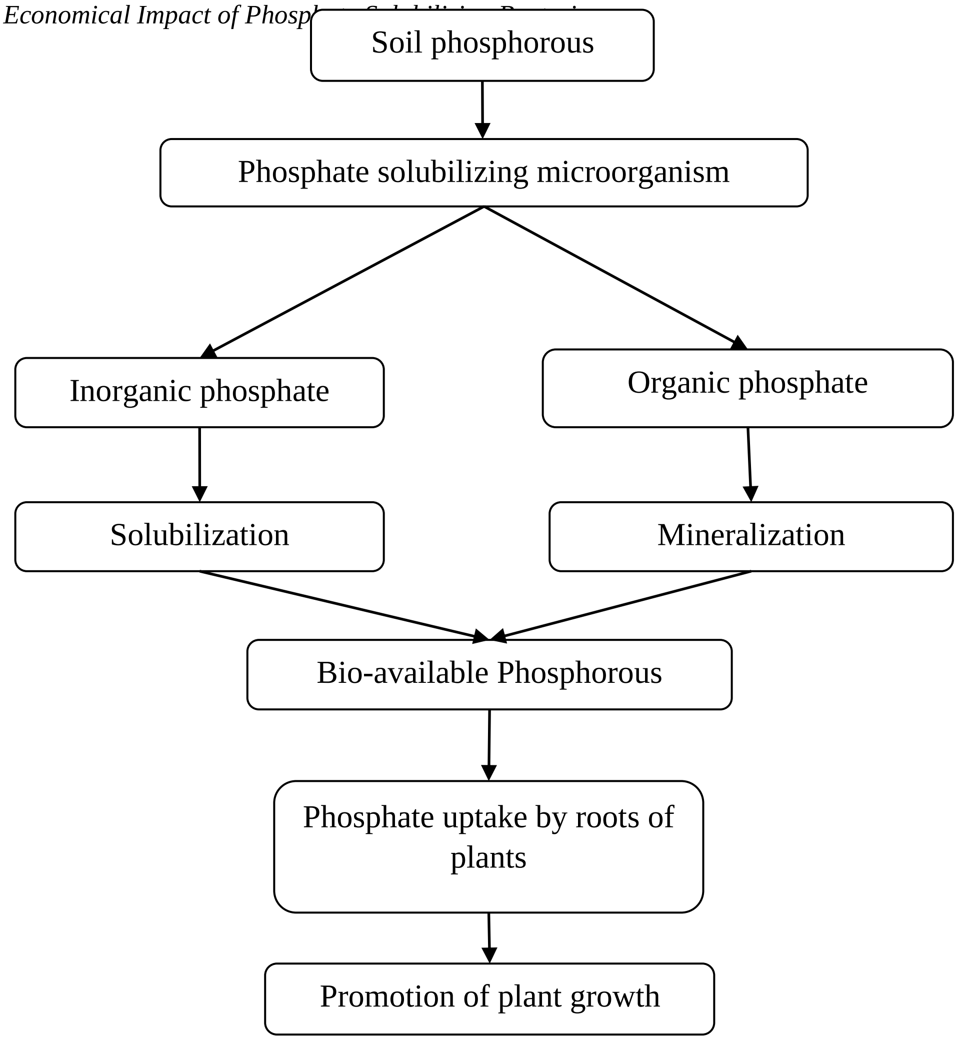

Figure 1: Solubilization of inorganic and organic forms of phosphororus present in the soil by phosphate solubilizing microorganisms.

ECOLOGICAL ASPECT-

The bioavailability of phosphates is one of the primary goals of sustainable agriculture. PSB aids in promoting sustainable agriculture as they raise crop yield and improve soil fertility (Pradhan and Sukla et al., 2006). The use of phosphate soluble microorganisms can increase the crop yields up to 70% (Shahzad et al., 2022). There are two benefits of microorganism with phosphate solubilizing capacity it increase the availability of soluble phosphate and improve biological nitrogen fixation. *Pseudomonas* can increase the amount of nodules, their dry weight, the components of yield, the grain yield and the availability and uptake of the nutrients (Khan et al., 2009). Dual inoculation without phosphate fertilizer increased grain yield up to 20% more compared to single phosphate fertilization, whereas single and dual inoculation with phosphate fertilizers boosted the grain yield by 30-40% (Afzal and Bano et al 2008).

The function of phosphate solubilizing microorganisms as inoculants is diverse and dependent on a number of factors including soil type, physical and chemical properties of soils, plant genotypes, type and qualities of root exudates and inherent phosphate-solubilizing effectiveness of bacteria. By introducing phosphate solubilizing bacteria into soil, the dehydrogenase, phosphatase and accessible phosphate levels of soil are boosted. To increase the production and effectiveness of different crops, various phosphate solubilizing microorganisms can be used in consortium. The growth and yield of crops can be improved upon combining two phosphate solubilizing strains with various amounts of nitrogen, phosphorous and potassium. For instance, using *Pseudomonas* in conjunction with the right amounts of fertilizers shows enhanced plant development (Ahemad et al., 2009).

The efficiency of plants to absorb phosphate from chemical fertilizers is only 5.25%, leading to the loss of soil fertility (Jain et al., 2022). By adding PSB to the plant it improves the productivity of plant by producing other secondary metabolites. Moreover, repeated use of chemical fertilizers can degrade the soil and decrease crop yield. Phosphorous biofertilizers are biodegradable and improves food production by increasing crop yield, they are also low cost and give the plants a sufficient amount of phosphorous, all the while without disturbing the biochemical composition of the soil. Upon application, they supplement plant growth, yield, phosphate uptake and crop quality. When a proper amount of phosphorous is supplied to plants, it aids in early maturation, early ripening, seed formation and encourages younger plants to form deeper and heavy roots. Usage of PSM and plant growth-promoting rhizobacteria jointly can decrease the reliance on phosphatic fertilizer by upto 50%. It is useful for improving the fertility of the soil by producing organic nutrients for the soil. PSB also function in the decontamination of heavy metals and development of salt stress tolerance in plants which is quite beneficial for sustainable agriculture and relatively rare in other methods (Shahzad et al., 2022). Soil bacteria are in cocci, bacilli, or spiral shapes, with bacilli found commonly in the soil while spirilli are rarely found outside in natural environment (Sharma et al., 2013).

Many PSB have been shown to be efficient biocontrolling or biofertilizing agents. Effective PSB biofertilizers are *Bacillus subtilis, Bacillus megaterium, Pseudomonas straita* and *Bacillus circulans.* When these phosphate solubilizing bacteria are employed, they enhance plant growth and development despite the presence various stressors. For instance, *Pseudomonas* sp. increase the plant growth in salt stress and *Pseudomonas putida,* *Pseudomonas corrugate*, *Mycobacterium* sp. are cold tolerant. *Pseudomonas* sp., *Arthrobacter* sp., *Bacillus* sp. enhances the plant growth in drought stress. *Bacillus* sp. and *Hallobacillus* increase plant growth in the salinity stress (Satyaprakash et al., 2017).

Phosphorous is the second most important ingredient for plant growth in terms of agronomy after nitrogen. In legume plants phosphorous boost nitrogen fixation and it is essential for the formation of sugar, energy and photosynthesis in plants. However, the majority of the research on phosphate solubilization is focused on isolating the microorganisms from the rhizosphere of soil and assessing their phosphate solubilizing activity in in-vitro conditions. Many studies have shown that phosphate solubilizing strains of the bacteria *Rhizobium*, *Bradyrhizobium* and *Azotobacter* boost the growth and phosphorous content of both leguminous and non leguminous plants. Co-inoculation with other microorganisms or utilizing mixed cultures are two alternatives for using PSM as microbial inoculants. Crop production has already increased from the use of phosphate solubilizing bacteria as efficient inoculants in agronomic methods (Khan et al., 2009). Various phosphate solubilizing bacteria being used as growth promoters for different crops and plants have been enlisted in Table 1.

Table 1. Various phosphate solubilizing bacteria being used as growth promoters for different crops and plants.

Phosphate solubilizing microorganisms	**Tested crops**	**Results**	**References**
Bacillus megaterium, Arthrobacter chlorophenolicus and Enterobacter sp.	Wheat	Enhance productivity of wheat	Kumar et al., 2014
Aspergillus niger	Chinese cabbage	Increased growth	Wang et al., 2015
Aspergillus niger	Wheat	Incresased growth	Xiao et al., 2013
Bacillus thuringiensis	Rice	Increased shoot length	David et al., 2014
Burkholderia gladioli	Sweetleaf	Increased plant growth	Mamta et al., 2010
Burkholderia cepacia	Maize	Increased plant growth	Zhao et al., 2014
Glomus fasciculatum and *Pseudomonas striata*	Wheat and soybean	Increased grain yield and Better root property	Mahanta et al., 2014
Pseudomonas aeruginosa	Chinese cabbage	Increased total weight and total length	Wang et al., 2010
Pseudomonas sp. and *Basillus sp.*	Sesame	Increased seed yield	Jahan et al., 2013
P. favisporus TG1R2	Soybean	Increased dry biomass	Bidondo et al.,2011
Rhizobium tropici CIAT899	Beans	Enhanced increased; nodule number, nodule mass and root growth	Tajini et al., 2012

ECONOMICAL ASPECT-

Microbial inoculants and biofertilizers nowadays offer a more economic and eco-friendly alternative for traditionally used chemical fertilizers which are expensive as well as have a damaging effect on the environment. PSBs fulfill the assurance of commercial bio-inoculants. Plant growth-promoting rhizobacteria (PGPR) and PSB have been found to work together and reduce the application of phosphatic fertilizers by 50% without any significant reduction in crop yield (Yazdani et al., 2009). Since the 1950's PSB are being used as biofertilizers. There is also some evidence of naturally occurring rhizospheric phosphorous solubilizing micro-organisms since 1903 (Anand et al., 2016).

The primary method for investigating PSM's potential in agriculture is the production of biological inoculants. According to projections, in 2023 the global market for biofertilizers is expected to increase at a compound annual growth rate of approximately 14%. The market for biofertilizers was worth USD 1106.4 million in 2016, and by the end of 2024 it is expected to be increased by USD 3124.5 million at a rate of 14% (Silva et al., 2023).

The cost of phosphatic fertilizers saw an increase due to the quality of phosphatic reserves and depletion of PR resources. Due to increased global agriculture, there was a shortage of fertilizers during the years 2007-2008, which resulted in a significant increase in demand for fertilizers made of phosphate. Comparing 2008 to 2007, there was a price hike of nearrly 800%. This came to be as a result of the demand in rise of phosphatic fertilizers for use in agricultural and other industries (Wendimu et al., 2023).

According to the global bank, the cost of phosphatic fertilizers observed an increase by 292.7% between 2000 and 2022 with an increase of 92.6% between 2017 (89.69 USD mt^{-1}) and 2022 (172.82 USD mt^{-1}) itself (Wendimu et al., 2023). This trend of growing price of phosphatic fertilizers has been shown in figure 2. Due to an increase in production costs, the cost of crop production has also been increased. Therefore, a sharp rise in the price of phosphatic fertilizers observed because of the lack of proper PR reserves, also led to a hike in the price of global food production (Mew el al., 2016).

Chemical fertilizers have also become unaffordable due to the rise in fertilizers prices, which has negative consequences on farmers and consumers. It is a hint that a terrible disruption in the fertilizers markets may occur in the future due to the quick shift and increase in prize (Elseret at., 2014). Several studies have found that, the volatility of fertilizers prizes has moved into a new high price regime (Wendimu et al., 2023). The issue of high prices can be resolved by increased crop nutrient usage efficiency and the use of innovative technology for improved nutrient recycling from various sources. Hence, it is now necessary to consider other alternatives in order to make phosphatic fertilizers more affordable, address demand difficulties and avert environmental disasters. This approach should concentrate on effective phosphorous resource management and strategies for providing crops with useable phosphorous through PSB (Wendimu et al., 2023).

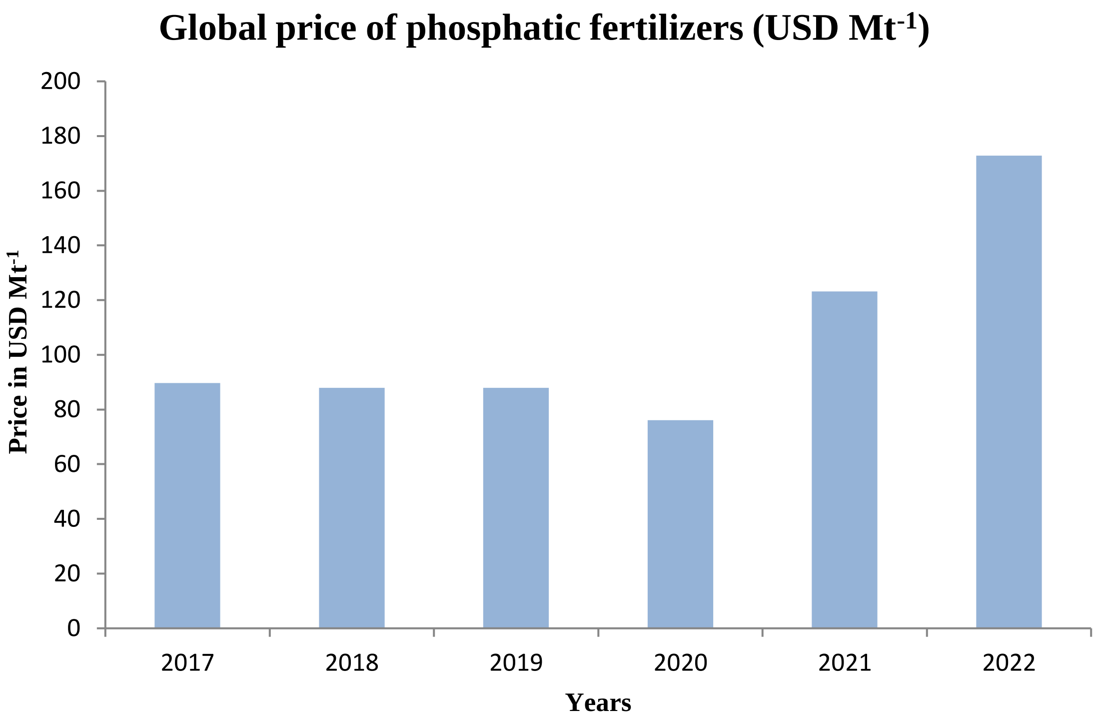

Figure 2. Global price of Phosphatic fertilizer from 2017-2022.

FUTURE PROSPECTS-

Environmental friendly solutions are needed that accomplish the same goals as synthetic fertilizers without the drawbacks (Rawat et al., 2021). Chemicals from many industries are polluting our all the facets of our environment, especially agricultural lands. Chemical phosphatic fertilizers are major pollutants with a very damaging effect on the environment. There are no signs that this situation is improving or slowing down. In order to address the risk to the environment and public health, it is crucial to minimize both the production of chemical fertilizers in industries and the amount used in farmlands. Therefore, it is crucial to consider all available options. Optimization of PSB inoculants as phosphate biofertilizers is also obligatory for contributing to a decrease in the manufacture of industrial phosphate fertilizers, preserving PR reserves and preventing various environmental crises. Studies on this topic should focus on manipulating PSB as much as possible to increase their effectiveness as the main objective. PSB shield the ecosystem not just from the negative effects of chemical fertilizers but also from more risky substances like pesticides. It is paramount to focus our research on the multi-dimensional use of PSB in order to harness its numerous benefits for agricultural and environmental health as well as to replace chemical phosphatic fertilizers.

CONCLUSION-

Phosphorous is an essential component for crop nutrition. Despite being present in large amounts in the soil, phosphorous is not available for plant uptake because of its insoluble nature. To provide phosphorous to the crops, inorganic phosphate fertilizers may be used but these are costly and damaging to the environment as a whole. The alternative for inorganic phosphate fertilizers are certain microbes which naturally occur in the soil and possess the ability of converting insoluble phosphate into the soluble form that plant can easily take. Such microbes are known as phosphate solubilizing microorganisms and their inoculation results in a marked increase in plant growth, crop production and performance. The most significant phosphate solubilizers for boosting phosphate bioavailability in the soil are various bacteria including *Bacillus*, *Pseudomonas*, *Rhizobium* and *Aspergillus*. PSM also work as a disease control measure against pathogenic germs.

Phosphate solubilizing bacteria have become widely accepted because it is safe for the environment and easy to obtain. There are numbers of phosphate solubilizing bacteria have been identified from which some chosen ones are utilized for the plant development. These PSB are common in soil and have some important role in mineralization and solubilization of phosphate, which increases the concentration of orthophosphates and phosphates in the soil.

Phosphatic nutrition is a global constraint on crop yield. Phosphate fertilizers are commonly administered in an unbalanced manner, which harms the soil and the health of crops. For sustainable farming, using PSB as biofertilizers is an effective alternative to chemical phosphorous fertilizers. PSB inoculation considerably improves plant development by influencing shoot length, root length, leaf weight and biomass by increasing phosphate accessibility in the soil and its uptake. Inoculating soil with phosphate solubilizing bacteria could increase the effectiveness of employing phosphates in agriculture by increasing phosphate availability without changing the soil’s biochemical makeup. Hence using phosphate solubilizing microorganisms in the soil is a potential strategy towards sustainable agriculture without adversely impacting the environment or the economy, which is the need of the present as well as the future.

REFERENCES

Afzal, A., & Bano, A. (2008). Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (Triticum aestivum). *Int J Agric Biol, 10*(1), 85-88.

Ahemad, M., Zaidi, A., Khan, M. S., & Oves, M. (2009). Biological importance of phosphorus and phosphate solubilizing microbes–An overview. *Phosphate Solubilising Microbes for Crop Improvement, eds MS Khan and A. Zaidi (New York, NY: Nova Science Publishers, Inc)*, 1-14.

Ahmed, N., & Shahab, S. (2009). Phosphate solubilization: their mechanism genetics and application. *Internet J Microbiol*, *9*(1).

Aliyat, F. Z., Maldani, M., El Guilli, M., Nassiri, L., & Ibijbijen, J. (2022). Phosphate-solubilizing bacteria isolated from phosphate solid sludge and their ability to solubilize three inorganic phosphate forms: Calcium, iron, and aluminum phosphates. *Microorganisms*, *10*(5), 980.

Alori, E. T., Glick, B. R., & Babalola, O. O. (2017). Microbial phosphorus solubilization and its potential for use in sustainable agriculture. *Frontiers in microbiology, 8*, 971.

Anand, K. U. M. A. R., Kumari, B. A. B. Y., & Mallick, M. A. (2016). Phosphate solubilizing microbes: an effective and alternative approach as biofertilizers. *Int. J. Pharm. Pharm. Sci*, *8*(2), 37-40.

Bidondo, L. F., Silvani, V., Colombo, R., Pérgola, M., Bompadre, J., & Godeas, A. (2011). Pre-symbiotic and symbiotic interactions between Glomus intraradices and two Paenibacillus species isolated from AM propagules. In vitro and in vivo assays with soybean (AG043RG) as plant host.*Soil Biology and Biochemistry*, *43*(9), 1866-1872.

Chouyia, F. E., Romano, I., Fechtali, T., Fagnano, M., Fiorentino, N., Visconti, D., ... & Pepe, O. (2020). P-Solubilizing Streptomyces roseocinereus MS1B15 with multiple plant growth-promoting traits enhance barley development and regulate rhizosphere microbial population.*Frontiers in Plant Science*, *11*, 1137.

De Zutter, N., Ameye, M., Vermeir, P., Verwaeren, J., De Gelder, L., & Audenaert, K. (2022). Innovative rhizosphere-based enrichment under P-limitation selects for bacterial isolates with high-performance P-solubilizing traits.*Microbiology Spectrum*, *10*(6), e02052-22.

Elser, J. J., Elser, T. J., Carpenter, S. R., & Brock, W. A. (2014). Regime shift in fertilizer commodities indicates more turbulence ahead for food security. *PLoS One*, *9*(5), e93998.

Glick, B. R., Liu, C., Ghosh, S., & Dumbroff, E. B. (1997). Early development of canola seedlings in the presence of the plant growth-promoting rhizobacterium Pseudomonas putida GR12-2. *Soil Biology and Biochemistry*, *29*(8), 1233-1239.

Sivasakthivelan, P., P., S., Al Tawaha, A. R., .K, A., Imran, & Amanullah, P. (2021). Phosphate solubilizing bacteria and its role in plant growth enhancement: A review. *Advances in Environmental Biology*, *15*, 1–8.

Jahan, M., Mahallati, M. N., Amiri, M. B., & Ehyayi, H. R. (2013). Radiation absorption and use efficiency of sesame as affected by biofertilizers inoculation in a low input cropping system. *Industrial Crops and products*, *43*, 606-611.

Jain, P. (2022). Sustainable Agriculture with Rhizobacteria (PGPR). *International Journal of Current Science Research and Review*, *05*(06). https://doi.org/10.47191/ijcsrr/V5-i6-02

Kalayu, G. (2019). Phosphate solubilizing microorganisms: promising approach as biofertilizers. *International Journal of Agronomy*, *2019*, 1-7.

Khan, A. A., Jilani, G., Akhtar, M. S., Naqvi, S. M. S., & Rasheed, M. (2009). Phosphorus solubilizing bacteria: occurrence, mechanisms and their role in crop production. *J agric biol sci*, *1*(1), 48-58.

Khan, M. S., Zaidi, A., & Wani, P. A. (2009). Role of phosphate solubilizing microorganisms in sustainable agriculture-a review. *Sustainable agriculture*, 551-570.

Khiari, L., & Parent, L. E. (2005). Phosphorus transformations in acid light-textured soils treated with dry swine manure.*Canadian Journal of Soil Science, 85*(1), 75-87.

Kumar, A., Maurya, B. R., & Raghuwanshi, R. (2014). Isolation and characterization of PGPR and their effect on growth, yield and nutrient content in wheat (Triticum aestivum L.). *Biocatalysis and Agricultural Biotechnology*, *3*(4), 121-128.

Mahanta, D., Rai, R. K., Mishra, S. D., Raja, A., Purakayastha, T. J., & Varghese, E. (2014). Influence of phosphorus and biofertilizers on soybean and wheat root growth and properties. *Field Crops Research*, *166*, 1-9.

Mew, M. C. (2016). Phosphate rock costs, prices and resources interaction. *Science of the Total Environment*, *542*, 1008-1012.

Park, J. H., Bolan, N., Megharaj, M., & Naidu, R. (2011). Isolation of phosphate solubilizing bacteria and their potential for lead immobilization in soil. *Journal of hazardous materials*,*185*(2-3), 829-836.

Pradhan, N., & Sukla, L. B. (2006). Solubilization of inorganic phosphates by fungi isolated from agriculture soil. *African Journal of Biotechnology*, *5*(10).

Puri, A., Padda, K. P., & Chanway, C. P. (2020). In vitro and in vivo analyses of plant-growth-promoting potential of bacteria naturally associated with spruce trees growing on nutrient-poor soils. *Applied Soil Ecology*, *149*, 103538.

Quiquampoix, H., & Mousain, D. (2005). Enzymatic hydrolysis of organic phosphorus. In *Organic phosphorus in the environment* (pp. 89-112). Wallingford UK: CABI publishing.

Rahi, P., Pathania, V., Gulati, A., Singh, B., Bhanwra, R. K., & Tewari, R. (2010). Stimulatory effect of phosphate-solubilizing bacteria on plant growth, stevioside and rebaudioside-A contents of Stevia rebaudiana Bertoni. *Applied Soil Ecology*, *46*(2), 222-229.

Raj, D. P. R. S., Linda, R., & Babyson, R. S. (2014). Molecular characterization of phosphate solubilizing bacteria (PSB) and plant growth promoting rhizobacteria (PGPR) from pristine soils. *Int J Innov Sci Eng Technol*, *1*, 317-324.

Rawat, P., Das, S., Shankhdhar, D., & Shankhdhar, S. C. (2021). Phosphate-solubilizing microorganisms: mechanism and their role in phosphate solubilization and uptake. *Journal of Soil Science and Plant Nutrition*, *21*, 49-68.

Rawat, P., Shankhdhar, D., & Shankhdhar, S. C. (2020). Plant growth-promoting rhizobacteria: a booster for ameliorating soil health and agriculture production. *Soil health*, 47-68.

Satyaprakash, M., Nikitha, T., Reddi, E. U. B., Sadhana, B., & Vani, S. S. (2017). Phosphorous and phosphate solubilising bacteria and their role in plant nutrition. *International Journal of Current Microbiology and Applied Sciences*, *6*(4), 2133-2144.

Shahzad, A., Aslam, U., Ferdous, S., Qin, M., Siddique, A., Irfan, M., ... & Kayani, S. (2022). Plant defense promoting potential of novel endophytic Bacillus mycoid in combination with rock phosphate under contaminated soil.

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils.*SpringerPlus*, *2*, 1-14.

Silva, L. I. D., Pereira, M. C., Carvalho, A. M. X. D., Buttrós, V. H., Pasqual, M., & Dória, J. (2023). Phosphorus-Solubilizing Microorganisms: A Key to Sustainable Agriculture. *Agriculture*, *13*(2), 462.

Tajini, F., Trabelsi, M., & Drevon, J. J. (2012). Combined inoculation with Glomus intraradices and Rhizobium tropici CIAT899 increases phosphorus use efficiency for symbiotic nitrogen fixation in common bean (Phaseolus vulgaris L.).*Saudi journal of biological sciences*, *19*(2), 157-163.

Timofeeva, A., Galyamova, M., & Sedykh, S. (2022). Prospects for using phosphate-solubilizing microorganisms as natural fertilizers in agriculture. *Plants*, *11*(16), 2119.

Toro, M. (2007). Phosphate solubilizing microorganisms in the rhizosphere of native plants from tropical savannas: An adaptive strategy to acid soils?. In *First International Meeting on Microbial Phosphate Solubilization* (pp. 249-252). Springer Netherlands.

Walpola, B. C., & Yoon, M. H. (2012). Prospectus of phosphate solubilizing microorganisms and phosphorus availability in agricultural soils: A review. *African Journal of Microbiology Research*, *6*(37), 6600-6605.

Wang, H. Y., Shen, L. I. U., Zhai, L. M., Zhang, J. Z., Ren, T. Z., Fan, B. Q., & LIU, H. B. (2015). Preparation and utilization of phosphate biofertilizers using agricultural waste. *Journal of Integrative Agriculture*, *14*(1), 158-167.

Wang, S. L., Hsu, W. H., & Liang, T. W. (2010). Conversion of squid pen by Pseudomonas aeruginosa K187 fermentation for the production of N-acetyl chitooligosaccharides and biofertilizers. *Carbohydrate Research*, *345*(7), 880-885.

Wendimu, A., Yoseph, T., & Ayalew, T. (2023). Ditching Phosphatic Fertilizers for Phosphate-Solubilizing Biofertilizers: A Step towards Sustainable Agriculture and Environmental Health. *Sustainability*, *15*(2), 1713.

World-Bank. World Bank Phosphate Rock Price Index. Available online: https://www.dataandcharts.com/world-bank-phosphate-rock-price-index/3913 (accessed on 6 April 2022).

Xiao, C., Zhang, H., Fang, Y., & Chi, R. (2013). Evaluation for rock phosphate solubilization in fermentation and soil–plant system using a stress-tolerant phosphate-solubilizing Aspergillus niger WHAK1. *Applied biochemistry and biotechnology*, *169*, 123-133.

Yadav, R., & Tarafdar, J. (2001). Influence of organic and inorganic phosphorus supply on the maximum secretion of acid phosphatase by plants. *Biology and Fertility of Soils*, *34*, 140-143.

Yazdani, M., Bahmanyar, M. A., Pirdashti, H., & Esmaili, M. A. (2009). Effect of phosphate solubilization microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) on yield and yield components of corn (Zea mays L.). *World Academy of Science, Engineering and Technology*, *49*(1), 90-92.

Zhao, K., Penttinen, P., Zhang, X., Ao, X., Liu, M., Yu, X., & Chen, Q. (2014). Maize rhizosphere in Sichuan, China, hosts plant growth promoting Burkholderia cepacia with phosphate solubilizing and antifungal abilities. *Microbiological Research*,*169*(1), 76-82.