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Review Article

Global perspective of phosphate solubilizing microbes and phosphatase for improvement of soil, food and human health

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ABSTRACT

Soil microbial flora has a pivotal role in the phyto-availability of phosphorus and other necessary minerals and nutrients. The primary class of Rhizobacteria involved in the solubilization of phosphate from non-available forms to available forms is Phosphate solubilizing bacteria (PSB). The application of Phosphate solubilizing bacteria increased phosphorus availability, which is one of the major factors responsible for the increase in the yield of crops. The phosphorus content is higher in the seeds than in the other plant parts; it helps plants in disease resistance and stress management such as winter rigors and improves the quality of fruits, vegetables, and cereal crops. Application of PSB as the biofertilizers positively affects the secretion of siderophores, nitrogen fixation, Indole acetic acid (IAA), 1-aminocylopropane-1-carboxylate (ACC) deaminase, chitinase, and protease. PSB can solubilize useful phosphate from rock phosphate and phosphate present in the combined state in lower to higher pH range (4 to 10), lower to a higher temperature (20 to 40 ^{0}C), and even in the higher salt ranges (0 to 7.5 % NaCl). Microbes help in the assimilation of phosphates and hydrocarbons by the secretions of different phosphatases such as monoesterase, diesterases, C-P lyase, and phosphatase and phytases. Using chemical P fertilizer in sustainable agricultural methods needs to be reduced. For this purpose, alternative and inexpensive technology are required so that plants can be provided with a sufficient amount of P. Phosphate solubilizing microbes can be an excellent option to replace chemical P fertilizers for improved agricultural production and soil fertility. The fertility of farm fields can be improved by using PSB as the bio-fertilizer and it will enhance the nutritional quality of plants and plant products which are directly or indirectly taken as food. Applying these microbes to soil/seeds makes good quality fruits and can help to fulfill the nutritional hunger of the world.

1. Introduction

Low phosphate phytoavailability is the primary factor affecting the growth of the crop plant in the Indian soil. Most of the P in the soil is fixed and unavailable to plants[1], and only 0.1% of the total phosphate is available to the plants[2]. The primary issue

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with phosphate availability is that it solubilizes and gets fixed in both acidic and alkaline soil. Microbial flora of the rhizosphere has a significant role in phosphate solubilization, which has now been well documented but very less is known about the magnitude of their activities. Bacterial and fungal species can both solubilize organic and inorganic phosphates respectively. The unavailable soil fixed P can be solubilized by the phosphate solubilizing bacteria (PSB). PSBs release organic acids in soil which solubilizes P, thus making it available to the plants[3].

The activity of this microbial flora depends on environmental conditions such as pH, and temperature. These microbes contribute not only solubilized phosphate but also various plant growth-promoting activities and biocontrol activities by secretion of the hormone Indole acetic acid (IAA). Production of organic acids and secretions of phosphatase by PSBs has a crucial role in the mineralization of phosphorus in the soil and farm field. These microbes are also involved in the synthesis and secretions of phytohormones for plant growth promotions[4]. The application of PSB as the bio-inoculants increases the P uptake and crop yield. Bio-inoculation of sole PSB or their consortium with other microbes (e.g. *Mycorrhiza*) increases the nitrogen efficiency, availability of trace elements, and production of plant growth-promoting substances which leads to enhanced plant growth and crop yield. The most powerful phosphate solubilizing microbes belongs to the genera such as *Pseudomonas*, *Bacillus,* and *Rhizobium* [5, 6]. These increase the prospect and impact of applying phosphate rocks in the farm field along with these PSB [7]. This review aims to give an overview of the most significant role of phosphorus and microbes which can functionally work as solubilizers for sustainable agricultural production.

2. Phosphorus as an essential nutrient value

Phosphorus (P) is among the significant macronutrient necessary for several metabolic activities such as DNA synthesis, cell division (growth and development), photosynthesis, and nutrient transport[8] (Figure 1). Its low availability in soil restricts its use by plants for their growth and development.P is one of the vital components of nucleotides for the formation of phosphate diester linkage necessary for the formation of the phosphate backbone of DNA; hence it is essential for the transfer of genetic information and vital metabolic pathways [9]. Phosphate minerals are present in a soil solution in unavailable forms in combination with various cations such as Ca^{2+}, Al^{3+}, Fe^{2+} or Mn^{2+}. As it is generally found in anionic forms, it can easily combine with metallic cations. The external environmental factors of soil solutions for the formation of combinations with these cations are the type of microbes involved, soil pH, and organic matter contents [10, 11]. The more common form of combination is inorganic phosphate produced by the wear and tear and weathering of rocks derived from dead decaying organic matter of plants, animals, and microbes. Unlike other macronutrients, it is the least mobile element and precipitates in the soil by forming orthophosphates of Fe and Al oxides [12].

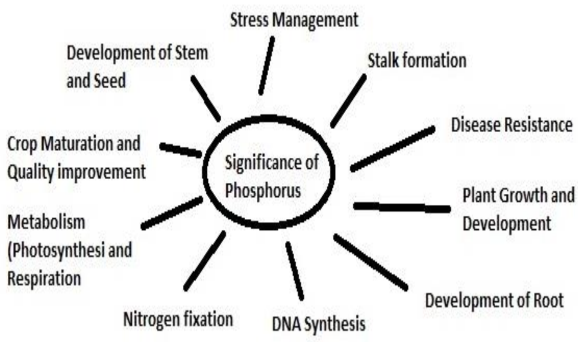

Fig. 1. Significance of Phosphorus in Plant system

3. Screening of ecological sources for suitable application

The main application of PSB is as a Bio-inoculant. Several trials are reported to isolate and find the best-suited PSB for agriculture by using Pikovaskaya's medium (PVK). During isolations, authors reported that PSB floras are densely concentrated in the rhizospheric soil of the plants. Screening and spot selection for the isolation of PSB were chosen based on the most probable occurrence of PSB. With the aid of tricalcium phosphate within the PVK medium, it is being used to isolate the PSB [5, 13].

3.1. Phosphate solubilizing microbes in the rhizosphere of crop plants

Numerous phosphate soluble bacteria can be easily isolated from several crop plants, such as *Arthrobacter* and *Bacillus* from tomato; *Aspergillus*, *Bacillus*, *Streptomyces*, *Nocardia,* and Actinomycetes from Betel vine; *Paenibacillus* sp. B1 strain, *Pseudomonas*, *Sphingobium* sp. SX14 from Maize; *Pseudomonas* from Chinese cabbage [5, 14](Table 1). These microbes are sustainable in varied temperature ranges, and pH and salt stress and are even able to solubilize phosphate salts of Fe and Al. These PSB bacteria produce plant growth-promoting substances such as organic acids, phytohormones, siderophores secretions, and many more[15].

The phosphate-solubilizing microbes are broadly categorized into two groups, viz., phosphate-solubilizing bacteria (PSB) and phosphate-solubilizing fungi (PSF). PSF also has an essential role in improving soil productivity and the plants' health through soil agglomeration. PSB is the primary group of microbes in the rhizosphere of plants, beneficial for plant health, quality improvement, and productivity. Henceforth, the application of PSB as a biofertilizer is the primary focus area of most researchers. The plant growth-promoting rhizobacteria include several genera such as *Azospirillum*, *Bacillus*, *Rhizobium*, *Pseudomonas*, *Burkholderia*, *Erwinia*, *Enterobacter*, *Serratia*, *Alcaligens*, *Acinetobacter*, *Arthrobacter*, *Flavobacterium*, and many more. These genera are directly involved in nitrogen fixations and phosphorus solubilization[16, 17].

3.2. Occurrence of phosphate solubilizing bacteria

The active group of PSB has concentrated in the rhizosphere and rhizoplane soils of the plants are metabolically more active. PSB in the rhizospheric soil flora occurs in several shapes, commonly ascocci and bacilli, whereas spiralPSBs are rarely observed. The presence of active PSB flora also depends on the soil characteristics such as organic matter and P content of the soil matrix's physical and chemical properties. Physical and chemical characteristics of the soil matrix are also essential factors for mobilizing nutrient contents from the soil [5, 24].

Table 1. Phosphate solubilizing Microbes isolated from the rhizosphere

Row	Organism isolated	Reference	Row	Organism isolated	Reference
1	*Aspergillus fumigatus*	[18]	15	*Erwinia*	[19]
2	*A. flavus*	[18]	16	*Psuedomonas sp*	[20]
3	*Yeast*	[18]	17	*Psuedomonas striata*	[21]
4	*A. niger*	[18]	18	*Burkholderia cepacia*	[19]
5	*A.clavatus*	[18]	19	*Rhizobium sp.*	[22]
6	*Pseudomonas*	[19]	20	*Rhizobium meliloti*	[22]
7	*Bacillus*	[19]	21	*Rhizobium legumonosarum*	[22]
8	*Rhizobium*	[19]	22	*Rhizobium loti*	[22]
9	*Burkholderia*	[19]	23	*Bacillus amyloliquefaciens*	[23]
10	*Achromobacter*	[19]	24	*Bacillus polymyxa*	[21]
11	*Agrobacterium*	[19]	25	*Bacillus megaterium*	[21]
12	*Micrococcus*	[19]	26	*Bacillus pulvifaciens*	[21]
13	*Aereobacter*	[19]	27	*Bacillus circulans*	[21]
14	*Flavobacterium*	[19]	28	*Citrobacter freundi*	[21]

4. Phosphate Solubilization

Most of the P contents are present in the unavailable forms in the earth crust and their recovery does not exceed 20 % of the total contents of P. With the application of PSB, phyto-availability of P is increased and plants can quickly assimilate it. Phyto-available P through microbial solubilization is getting more attention [5, 24].

4.1. Mechanism of Phosphate Solubilization

The secretions of enzyme phosphatases responsible for the mineralization and subsequent secretion of organic acids lower the soil pH leading to the solubilization in the soil solutions [6](Figure 2). P is the major growth-limiting factor, and unlike nitrogen, there is no easy source of Phosphorus. Phosphorus nutrition is related to many mechanisms of plant growth and development such as the development of roots, formation of stalk, stem, and seed, maturity of the crop, and fixation of N in leguminous plants. The P is also a significant factor related to disease resistance and crop quality. Fewer reports are available on the applications of bio-inoculants for improving soil productivity, unlike nitrogen fixation [25].

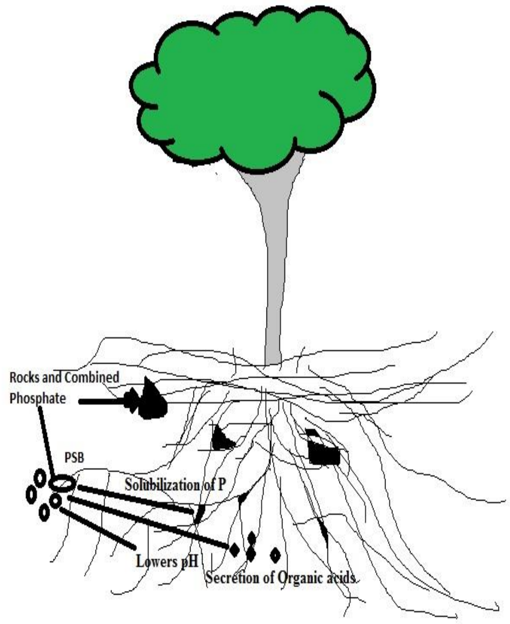

Fig. 2. Phosphate solubilization by Phosphate solubilizing bacteria by the secretion of organic acid.

The presence of phyto-available P is characterized by physicochemical and biological processes such as sorption-desorption immobilization, and mineralization with the soil.. The unavailability of P in the soil because of high affinity with Ca, Fe, and Al. The reactive Al^{3+}, Fe^{3+} in acidic soils, and Ca^{2+} in normal soils react with P allowing it to precipitate in immobilized pools when the P is applied as biofertilizers[26, 27].

The unavailable P which is not taken up by the plants is present in the combined form in inorganic and organic forms such as appetite and its derivatives and inositol phosphotriester respectively. The microbial secretions of organic acids which cause a reduction in the surrounding pH and Fe and Al chelating activity by anion exchange lead to the mineralization of Phosphates. The simple and effective mechanism against phosphate solubilization is the acidification of soil by the production of the organic acid, secretions of acid phosphatases and phytase, and proton extrusion which are involved with the ammonium assimilations. There is a need to isolate PSB from the rhizosphere of several plants to have diverse applications in crop fields to maintain pH and salt balance, and solubilization of insoluble phosphate. Some authors reported that *Pantoea agglomerans*is a well-suited bacterium isolated from the rhizosphere of soybean beans for phosphate solubilization [24, 27].

4.2. Molecular biology of mineralization of phosphorus

There are genes responsible for the phosphatases which are responsible for the mineralization of phosphates and increasing the availability in the soil solutions. The genetic make-up of *Erwiniaherbicola* has genes responsible for mineral phosphate solubilization[28]. Isolation and cloning of this gene in *E. coli* HB101 involves expression of mineral phosphate solubilization and production of gluconic acid, through the synthesis of pyrroloquinoline quinone (PQQ) synthase responsible for the synthesis of PQQ [29]. In a direct oxidation pathway, PQQ acts as an essential co-factor for the formation of holoenzyme glucose dehydrogenase (GDH)-PQQ, necessary for converting glucose into gluconic acid. Similar genetic make-up having a gene (*gabY*) observed in the case of *Pseudomonas cepacia*, involves expression of mineral phosphate solubilization through gluconic acid production in *E. coli* JM109 [30].

5. Role of enzymes in phosphate solubilization

The insoluble complex of phosphate is made available to the plants by the phosphate solubilizers. The PSM brings about solubilization of organic phosphorus or mineralization through the secretion of membrane-bound or extracellular enzymes such as phosphatases, phytase, phosphonatase, and C-P lyase[31]. Sequential processes involved in the dissolution of P in bacteria include; the secretion of siderophores, CO_2, and organic acids which dissolve complex forms of phosphate, extracellular enzyme secretion, and substrate degradation[32].

Efflux of the proton, secretion of organic acid, and synthesis of phosphatases enzymes are the critical steps in phosphate solubilization in biological systems of plants and microbes. These phosphate solubilizing enzymes are abundant in the microbial system which causes increased phosphatases activity in the rhizosphere with pH variations. Enzymes in the cytoplasmic and periplasmic space of Gram-negative bacteria are involved in the production of organic acids that helps in the solubilization of phosphate by reducing rhizospheric soil pH [33].

The simple mechanism present in these bacteria for the production of organic acids involves direct glucose oxidative pathway with the production of gluconic (by pyrroloquinolinequinone-dependent glucose dehydrogenase) and 2-ketogluconic acids (through FAD-linked gluconate dehydrogenase. Other than glucose another substrate present in the soil as an amendmentisalso acted by the bacteria to release inorganic P. Mycorrhiza (e.g. *Piriformospora indica*) known for the plant growth promotional activity also serves as the source of acid phosphatases and is present in hyphal tips[34].

5.1. Phosphatases

Phosphatases, hydrolases, or phosphoric monoester hydrolases are assembled in acidic, neutral, or basic conditions (EC 3.1.3). Based on pH variations, these enzymes are categorized into three types viz. acid, neutral, and alkaline phosphatases. With the substrate specificity, these acid phosphatases are also categorized into specific or non-specific phosphatases. Phosphatases enzymes by the hydrolysis of esterphosphate bonds convert complex forms of combined phosphate (i.e. orthophosphoric acid) except rock phosphate into simpler molecules leading to the release of phosphate ions [35]. Phosphatases are key enzymes that make phosphorus's phytoavailability and its assimilation in bacteria and plants [35]. The major contribution of phosphatases activity is of microbial origin[36].

Coincidental mechanism of phosphatase activity and amount of usable phosphate found in the bacterial system as low phosphate concentrations enhance the phosphatases activity[31]. Along with the deficiency of phosphorus, pH variations also signal secretions of phosphatases in microbes, leading to the consumption of phosphorus-containing compounds. The enzyme activity of phosphatases also depends on temperature, enzyme concentrations, substrate, and products. Phosphatase activity for the release of phyto-available phosphorus was also recorded in several synthetic sources of phosphorus. Several microbes isolated from soil reported phosphatases activity such as *Bacillus subtilis*, *Aspergillus niger*, *Penicillium* sp. *Psuedomonas*, etc[3, 15, 17].

Non-specific acid phosphatases (NSAPs) are inducible ectoenzymes that occur in the aquatic environment, known for dephosphorylation of phosphor-ester or phosphor-hydride bonds of organic content. Phosphatases are often known by phosphor-monoesterase abundant in soil on pH optima grouped into acid and alkaline phosphatases[31]. Both are adaptive enzymes[37] produced by microbes and plants. In the marine environment, alkaline phosphatases are present on the cell surface of bacteria responsible for the liberation of inorganic phosphate from organic phosphorus compounds. Phosphatase activity variations also depend on their form such as particulate or dissolved one. The dissolved form of phosphatases (phytases) was recorded with around 70 % of alkaline phosphatases activity and release of usable phosphorus.[12] Further, these phosphatases are also categorized into phosphomonoesterase, phosphodiesterases, phosphatases, and phytases [38].

5.2. Phytase

The phosphatases involved in the lysis of phytic acid (phytate) or myo-inosito phosphate compounds are supposed to be phytases[39], specifically responsible for the release of P. The stored form of phytate is seeds and pollens an essential source of inositol and a significant contributor of P in the soil around 50%. The application of phytate as a source of phosphorus in plants is very limited unless it is transformed with the phytase gene (phyA) of *Aspergillus niger* [27, 30].

5.3. Phosphatase and C-P lyases

These sorts of phosphatases help in the assimilation of phosphorus and hydrocarbons by the lysis of ester bonds of phosphonates such as phosphoenolpyruvate and phosphonoacetate. Specifically, it is the cleaving of C-P bonds of organophosphates. In soil, actinobacteria can sustain in unfavorable conditions by forming spores that are the primary source of these hydrolytic enzymes [40, 41].

6. Significance of phosphorus in plant growth

Applying chemical fertilizers directly impacts the environment in the form of eutrophication and depletion of soil productivity. In this scenario, phosphate solubilizing microbes are the best candidates to increase P availability and fulfill nutritional requirements. The purpose of P management through PSM instead of chemical fertilizer is to maintain P content in the soil to avoid loss and to increase the crop yield. P is the major growth-limiting factor involved in the development of numerous metabolic pathways, including photosynthesis, and respiration. The major role involved in cell enlargement, cell division, and energy storage in the plants[42].

The development of root and reproductive parts is very effective when optimum concentrations of P are supplied during the early stages of metabolic and growth development and also improves the quality of fruits in later stages and increases disease resistance in some of the plants. Along with the development of reproductive parts, it is also essential for seed formations, single transductions, respirations and biosynthesis of macromolecules, energy transfer, and photosynthesis. A higher amount of P is present in the seeds than in any other part of the plant and it contributes to around 0.2 % dry weight of the plants. P is a significant and vital component of various necessary metabolites such as phytin, nucleic acids, and phospholipids. Also, presence of P is directly related to microbial nitrogen fixations. Fossils and traces under the rocks formed during the geological ages are the sources of inorganic P [32, 33, 40].

Even if the significant amount of P present in the earth's crust are useless as it is not readily soluble, and whatever soluble P is applied to the agriculture field in the form of chemical fertilizer readily reacts with the reactive metals and is immobilized and also it forms precipitation of tricalcium phosphate [$Ca_3(PO_4)_2$], $FePO_4$, $AlPO_4$, and only 25 % of total P content are in available form. The primary focus is given to the PSM to utilize an unavailable form of P. Often the application of P as the chemical fertilizer and its chelations with the reactive metals makes the fertile agriculture soil non-productive and also chemical fertilizers are costly. The scarcity of Phosphate nutrients limits biomass accumulation in the agro-system, and excessive application of P as the bio-fertilizer is eco-friendly[43]. Chemical fertilizers are responsible for forming algal blooms and agro-systems eutrophication and affecting soil productivity. PSB has a significant role in the conversion and biochemical cycling of unavailable phosphate into readily available form[28, 29, 39].

7. Application of Phosphate solubilizing bacteria (PSB)

PSB helps in plant growth enhancement, leading to an increase in crop yield. Several side effects of synthetic fertilizer can be minimized by using PSB as a biofertilizer. Some of the applications of PSB are mentioned below[2, 27, 44]..

7.1. Nitrogen fixation

PSB also can fix environmental nitrogen to make it available for crop plants. PSB belongs to the Rhizobiaceae family and acts as symbiotic a non-symbiotic nitrogen fixers. The ability to fix nitrogen varies from species to species and is done by the complex enzymes of nitrogenase and hydrogenase. PSB like plant growth-promoting rhizobacteria (PGPR) secretes siderophores used to chelate and uptake iron from the environment. Iron uptake is necessary for the enzymes such as Nitrogenase and hydrogenase [45, 46].

7.2. PSB as a potential biofertilizer

PSB can be a potent biofertilizer as it provides phyto-available P which increases the growth of plants in several aspects. With phosphate solubilization, PSB synthesizes siderophores, plant hormones such as auxins, and gibberellic acid. Some PSB can also synthesize antibiotics and help in disease management. PSB can synthesize ACC deaminase (1-aminocyclopropane-1-carboxylate) which converts ACC to ammonia and prevents the inhibitory effect of ethylene as ACC is an immediate precursor of ethylene [47-49].

7.3. Phosphate Solubilizing Microbes And Phosphatase on Human And Food Health

Phosphorus is one of the most vital nutrients required by plants and humans. It comprises the structural part of human and plant genetic material playing a key role in cell division and growth[44].This nutrient deficiency causes poor appetite, anemia, muscle weakness, bone diseases like osteomalacia and rickets, bone pain, and more susceptibility to infections in humans and the same deficiency in plants leads to stunted growth in them. The leaves of the affected plants turn dull, dark blue-green, or sometimes reddish violet in color. Though Phosphorus is present in plenty on earth but mostly unavailable and hence the deficit was fulfilled chemically [50]. But due to the undesirable effects of chemicals on humans and our food (as plant products) PSBs were introduced to restore the dependence on chemical fertilizers. They promote sustainable agriculture, and soil fertility and further increases crop productivity. PSBs also aid plant growth by enhancing biological nitrogen fixation, phytohormones synthesis, and increased availability of trace elements such as zinc and iron [51, 52].

The modernizations and increasing populations expect cultivations of more and more food quantity. While meeting large quantities of food, nutritional quality and vigor of food and products are might be lost. Applications of biopesticides and biofertilizers are having a significant impact on the quality of food in comparison to synthetic pesticides and fertilizers. Synthetic fertilizers remain on farm fields for long periods, and gradually, make the field infertile. The Phosphate solubilizing Bacteria (PSB) act as biofertilizers and secrete phosphatases in rhizospheric soil and enhancing the solubility of phosphorus and making it available for plants and enhancing nutrition. The phosphate solubilizations by PSB also help in the production of organic acids that act as the chelators for the displacement of metals[30].

A significant increase in the growth of various crops such as wheat, chickpea, maize, and tomato has been reported globally by the use of biofertilizers. Also, the biocontrol of diseases among crops is reported by the usage of PSBs as biofertilizers. To meet increasing food demand, the conventional methods of farming using an excess of phosphorus lead to soil pollution, eutrophication, and several other side effects. The microbes having the capacity to solubilize and mineralize P can enhance the nutritional quality of food and food products that are ultimately good for human health. Such microbes can increase the yield of a variety of foods and applications of such microbes to seeds/crops/soil can improve world food production. This knowledge transfer from the scientists to the farmers for the utilization of PSBs is of major significance[30, 53].

8. Effect of phosphorus on human body cells and tissues

Teeth and bones have 85% of the body's phosphorus [54]. Among the essential elements, Phosphorus is one of them and it is a vital component of all sorts of tissue in organic and inorganic form and helps in the maintenance of the normal functioning of cells. Inorganic phosphates are an important component of the energy currency of living organisms e.g. Adenosine tri-phosphates (ATP). Inorganic phosphates are the important substrate donor for various biosynthesis like DNA and RNA synthesis and have a major role in cell signaling, maintenance of membrane integrity and regulation of cellular metabolism. Organic phosphate can be metabolized into inorganic phosphate by conversion into mono and di-hydrogen phosphate [55]. Phosphorus has a major role in the composition of the skeleton and membranes of cell organelles[56]. The imbalance concentrations of phosphate in plasma are also an indication of disorders of calcium metabolism. The concentrations of these phosphates become the marker element to find out disorders during the biochemical profiles as an imbalance of phosphate can lead to serious and fatal complications [4].

The diseases like renal failure, diabetes, atherosclerosis and aging are more often associated with vascular calcifications. Vascular calcifications is leads to atherosclerosis which is finally responsible for myocardial infarction. Some of the authors also reported calcifications related to plaque rupture and some finds no effect on it [57]. It was thought that the calcified fibrous cap can protect plaque from rupturing which acts as the barrier[58]. The small and diffuse spotty or speckled deposits of calcium can make plaque stress and instability in atherosclerosis[59], unlike larger plate-like calcium deposits that results in stable plaques in atherosclerosis. The complex of calcium responsible for calcifications is hydroxypatite $[Ca_{10}(PO_4)_6(OH)_2]$ and it can deposit into arteries and result in diseases like atheroscleris, diabetes and chronic kidney diseases, etc. There are three sorts of vascular calcification and it is categorized based on their locations such as intimal, medial and valvular[60].

The lesions of atherosclerosis along with lipid deposition and inflammations are involved in intimal calcifications. The calcification without inflammations observed in the middle layer of vessels on the edges of elastic lamellae is supposed to be medial calcification or arterial medial calcification or Mönckeberg's sclerosis[61]. The intimal and medial calcifications are more commonly involved in the cardiovascular events related to end-stage renal diseases leading to cardiovascular mortality[62]. Arterial wall distensibility can be changed by calcium deposits in large blood vessels involved which increase pulse wave velocity by increasing stiffness of blood vessels[63]. Calcifications can lead to fatal complications like hypertension, left ventricular hypertrophy, compromised coronary perfusion and heart failure by unregulated vascular stiffness[64].

The phosphate homeostasis system is well developed in mammals as phosphate maintenance and balance are important with respect to a normal healthy life. The elimination of phosphate from the metabolism by the kidney is positive regulation of phosphate balance while an excess of phosphate is responsible for pathogenesis like bone disorder related to chronic kidney disease (Figure 3). Recent reports suggest that the concentration of phosphate has no role in toxic effects on the cardiovascular system and aging process[65].

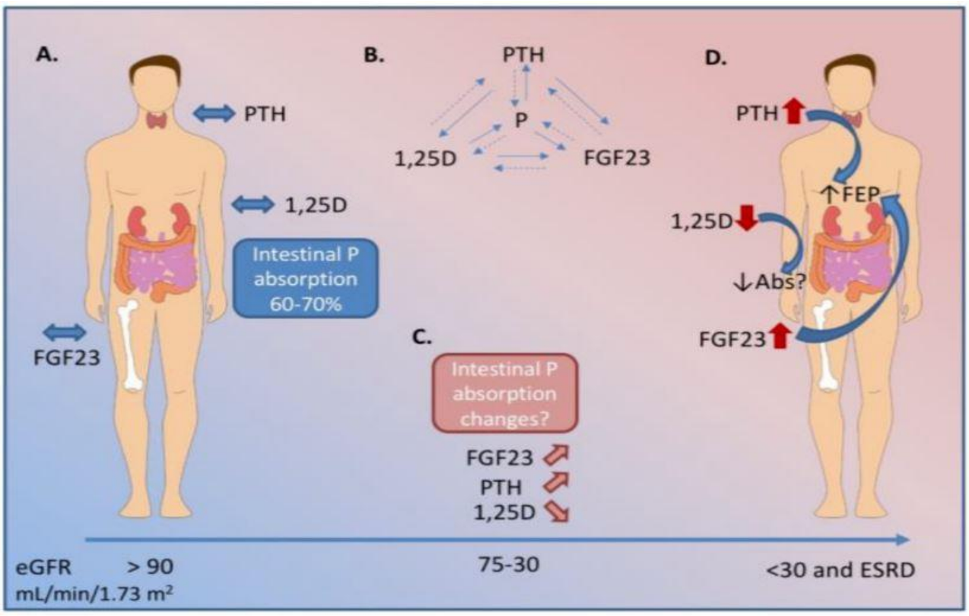

Figure 3. Hormonal regulation of phosphorus in chronic kidney disease; (fibroblast growth factor 23 (FGF23), parathyroid hormone (PTH), and 1,25-dihyxdroxyvitamin D (1,25D), chronic kidney disease (CKD), and CKD-Mineral Bone Disorder (CKD-MBD)) [66].

9. Future Perspectives

Along with modernization and urbanization, some factors such as decreasing soil productivity, global warming, energy crisis, and environmental hazards threaten sustainable agriculture practices, hence the PSB as the bio-fertilizer best sought-after environmentally friendly approach to mitigate these problems. PSM has a significant role in the solubilization of phosphate and the maintenance of mineral requirements of plants. Among PSM, PSB has a significant role in the mineralization and solubilization of P making it available to the plants in comparison with phosphate solubilizing fungi[67].

PSB has an essential contribution towards agriculture with the maintenance of nutrition requirements of the plants as the PGPR. Further research is needed for a better understanding and to find out better PSB which can be readily available as bio-inoculants for improved quality plant productivity. Extensive investigations are needed to find out better species of the PSB as biofertilizers to increase plant productivity under field conditions. With modernization and urbanization, there is increased demand for food with increasing populations. Hence the development of PSB is a promising option to meet agriculture challenges. Researchers also have scope to find an excellent alternative to chemical fertilizers as the environment-friendly approach with PSB as a biofertilizer[68].

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All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Informed Consent

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Ethics approval and consent to participate

No actual animal studies were performed in the present investigations.

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