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Phosphorus and Phosphate Solubilizing Bacteria under Rice Rhizosphere – a Review

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ABSTRACT

Phosphorus is an important macronutrient next to nitrogen, which is involved in many essential physiological functions. The inadequate supply of phosphorus will reduce crop yield. Phosphorus fixation is the most wide spread problem, almost all soils based on its soil reaction the quantum P fixation occurs. Rhizosphere is main portion which participate or regulate the nutrient elements uptake especially phosphorus. Rhizosphere of rice is entirely different from other crops as that it is typically cultivated in flooded soil, resulting in oxic and anoxic zones. Manipulating this zone will enhance the phosphorus solubility through solubilizing microorganisms. Phosphate solubilizing bacteria playing a vital role in phosphorus solubilization and enhances the P availability in soil solution through various mechanisms especially releasing of organic acids and enhancing enzymatic activities. Phosphatic fertilizers combined with phosphate solubilizing bacteria within the rice rhizosphere in acidic, neutral and alkaline soil conditions significantly have interaction with other nutrient availability in soils and improves nutrient uptake which in turn enhances the rice production.

KEY WORDS: Phosphorus, phosphate solubilizing bacteria, rice, rhizosphere, solubility

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1. INTRODUCTION

The rhizosphere is the zone of soil surrounding the root which is affected by it. The significance of the rhizosphere arises from the release of organic material from the root and the subsequent effect of increased microbial activity on nutrient cycling and plant growth. In the rhizosphere the quantities and the types of substrates are different from those in the bulk soil and this leads to colonization by different populations of bacteria, fungi, protozoa and nematodes. Other physicochemical factors which can be different in this region are acidity, moisture and nutrient status, electrical conductivity and redox potential. The association between organisms and roots can be beneficial (water uptake, soil stabilization, growth promotion, N_2 fixation, biocontrol, antibiosis, symbiosis), harmful (infection, phytoxicity) or neutral (nutrient flux, free enzyme release, attachment, allelopathy, competition) these effects often depend on soil conditions and therefore must be regarded as variable. Interactions that are beneficial to agriculture include mycorrhizae, legume nodulation and production of antimicrobial compounds that inhibit the growth of pathogens. Clearly the goal in manipulating the rhizosphere must be to increase the balance of beneficial effects as the rhizosphere is deeply affected by fertilization.

Soil zone extending outward up to 1 cm from root surface depending upon plant type, soil moisture and texture is called rhizosphere. It generally considered at 2 mm distance from the root surface known as rhizoplane. Researchers have shown that the influence can be up to 10 mm [1].Rhizoplane affects the nutrient availability as well as microbial population. Rhizosphere is the area around a plant root that is inhabited by a unique population of microorganisms (hot spot of micro flora), influenced by the chemicals released from plant roots. Plant roots continuously excrete root exudates consisting of ions, free oxygen, water, enzymes, mucilage and a diverse array of carbon-containing primary and secondary metabolites [2]. From 10 % up to 44 % of the photo synthetically fixed carbon is excreted by the root [3.] Organic acids, sugars, amino acids, lipids, coumarins, flavonoids, proteins, enzymes, aliphatics and aromatics are examples of the primary substances found at the soil–root interface which are a key factor for the enrichment of specific microbial populations in the rhizosphere. The accumulation of various substances into soil is called rhizodeposition and represents the key process by which carbon is transferred from living plants into soil subsystem of the larger ecosystem [4]. Rhizodeposition increases the energy status of the surrounding soil. This is reflected in the R/S ratio i.e. the biomass of microbes in rhizosphere (R) in relation to that in bulk soil (S). This ratio is generally greater than one. Therefore, Rhizosphere can be best defined as the volume of soil around living roots, which is influenced by root activity [5]. The rhizosphere is a densely populated area in which the roots must compete with the invading root system of neighboring plant species for space, water, mineral nutrients, and soil-borne microorganisms, including bacteria, fungi, and insects feeding on an abundant source of organic material [6]. Thus, root–root, root-microbe, and root-insect communications are likely of continuous occurrence in this biologically active soil zone, but due to the underground nature of roots [7], these intriguing interactions have largely been overlooked [7]. Root-root and root-microbe communication can either be positive (symbiotic) to the plant, such as the association of epiphytes, mycorrhizal fungi, and nitrogen-fixing bacteria with roots or negative to the plant, including interactions with parasitic plants, pathogenic bacteria, fungi, and insects [8]. It determined the nutrient conversion of non labile pools to available form, which is helpful to enhance biochemical activities and nutrient uptake in plants. The plant species belonging to gramineae, solanaceae and leguminoseae families had higher rhizosphere effect on soil available phosphorus (P) and biological properties than those belonging to cruciferae and compositae [9].

Phosphorus (P) is the second most important plant nutrient after nitrogen. Its accessibility is low in soils because of P fixation as insoluble phosphates of iron, aluminum and calcium [10]. About 98% of Indian soils are deficient in phosphorus, as the concentration of free phosphorus, i.e. the form available to crop plants, even in fertile soils, is generally not higher than 10 µM even at pH 6.5, where it is most soluble [11]. Deficiency of P is the most important chemical factor restricting plant growth and chemical phosphatic fertilizers are extensively used to get optimum yields. Soluble forms of P fertilizer are easily precipitated as insoluble forms leading to extreme and repeated applications of P fertilizers to crop land. Therefore, P availability form soils to the plants are a key to sustain higher yields [12].Application of P aided in more vigorous root development, early tillering capacity, early tillers have more panicles and % of filled spikelet's and good grain quality. In Indian soils, phosphorus is available in low to medium quantity. The P deficient soils cannot sustain higher yields without P application. Therefore consumption of P in India has increased progressively from 0.69 million tonnes in 1951-52 to 2.8 million tonnes in 1993-94, 5.5 to 5.8 million tonnes in 2000 and projected quantity may be doubled in 2025 [13] . In soils, of the total P (0.5 %), only 0.1 % is plant available phosphorus. Efficiency of applied P fertilizer throughout the world is around 10 - 25 % [14], and concentration of bio-available P in soil is very low reaching the level of 1.0 mg kg^{-1} soil [15]. As a major growth-limiting nutrient, and unlike the case for nitrogen, there is no large atmospheric source that can be made biologically available [16]. Root development, stalk and stem strength, flower and seed formation, crop maturity and production, crop quality, and resistance to plant diseases are the attributes associated with phosphorus nutrition. Reports indicated the response of rice to P fertilization and significant increase in the P content in rice grain was observed due to increased application of P. To produce one ton of paddy grain, 11.0 kg P_2O_5 is removed from the soil. Out of the total P uptake, about 65 percent of P is absorbed by the early panicle initiation stage and about 95 percent of P uptake is completed by the heading stage. The partitioning of uptake in the case of N and P is higher in grain than in straw (3:1), whereas a greater proportion of K, Ca, Mg, Si, Fe, Mn and B remain in the straw. The S, Zn and Cu taken up are distributed about equally in straw and grain [17].

2. PHOSPHORUS UNDER RICE RHIZOSPHERE

Rice differs from most crops in that it is typically cultivated in flooded soil, resulting in oxic and anoxic zones within the rice rhizosphere that select for specific physiological groups of microorganisms with either aerobic, anaerobic or facultative metabolism [18].The microbial community of the rhizosphere was distinct from the bulk soil, but more similar than the rhizosphere communities of plants grown in different soils. Whereas soil geochemistry appears to be the primary determinant of the rhizosphere community structure, plant species[19] , cultivars [20] and growth stage [21] have all been shown to have significant additional effects. Rice is one of the most important crops in the world. However, its production is largely limited by the P deficiency in many soils, particularly in acidic and calcareous soils where P retention and precipitation is high [22]. In recent years great attention has been dedicated to enhance the phosphorus use efficiency (PUE), which is nearly 15-20 per cent. Phosphorus absorption by plants depends on its concentration gradient and diffusivity in the soil near the roots [23]. Under such conditions, root-soil interactions in the rhizosphere noticeably affect the availability of P to plants. In this relation soil microorganisms play a vital role in the dynamics of P, particularly those which are able to solubilize insoluble P forms. Root exudates that are composed of low molecular weight organic substances (LMWOS) [24] represent a significant source of easily degradable organic carbon [25]. Small additions of LMWOs such as amino acids or mono-saccharides to soil have been shown to strongly increase available phosphorus in soil [26]. Especially the glucose, which serves as an energy source to microorganisms, has a strong effect on microbial activity and phosphorus mineralization in rhizosphere region. In contrast, amino acids that are mainly used as N and less importantly as carbon (C) source by microorganisms have a smaller effect on P mineralization from organic sources [27]. Apart from the organic acids, plant roots also secrete specialized metabolites such as phyto-siderophores. Siderophores are the low-molecular mass compounds chelating iron from the rhizosphere and in the process releasing P from Fe-bound-P. Studies revealed that plant species significantly decrease all the inorganic P (Pi) fractions in the rhizosphere soil as compared to the bulk soil [28]. Soil bacteria; that belong to the genera *Pseudomonas*, *Enterobacter*, *Bacillus Penicillium*, *Aspergillus* and soil fungi solubilize insoluble phosphate [29].The mechanism involved in the microbial solubilization of P is the production of organic acids and the release of protons to the soil solution. The alkaline phosphatase activity increases from 102 to 325 % and acid phosphatase activity from 205 to 455 % in the soil adhering to the root mat as compared to the non rhizosphere soil [30].

Low N concentration and NH_4/NO_3 ratio significantly reduces P concentration in leaf; it might be due to the indirect effect of the rhizosphere pH. The decrease in rhizosphere pH significantly enhanced the utilization of H_2SO_4-soluble P by rice plants. The main mechanisms of P solubilization in the rhizosphere of rice were because of the formation of soluble citrate-metal-P complexes or chelation of metal ions that immobilize P. It was reported that the P absorption ability varied significantly among different rice genotypes [31].However, little information was available about the changes in chemical and biochemical properties in the rhizosphere of different rice genotypes and their relationships with P depletion in soils. Phosphatase in the rhizosphere was observed to be closely related to depletion or utilization of organic P in the rhizosphere of plants [32]. An increasing atmospheric CO_2 concentration speeds up the photosynthesis [33].A significant amount of root exudates are released into the soil from plant roots. It enhances the availability of phosphorus in soil solution [34]. The availability of additional phosphorus enables most plants to grow faster under elevated CO2, with dry matter production in free-air CO_2 enrichment (FACE) being increased on average by 17 % for the above ground, and more than 30 % for the below ground portions of plants [35].This increased growth is also reflected in the harvestable yield of crops, with wheat, rice and soybean showing increase in yield of 12–14 %under elevated CO_2 in FACE. Photosynthetic rate will increase under elevatedCO_2 leading to more plant growth due to more acquisition of mineral nutrients from rhizosphere soil. Also effective increase in PUE under elevated CO_2 conditions by reducing shoot phosphorus content as a component of CO_2-induced photosynthetic acclimation. In low soil phosphorus biomass N is not much increased in grasses, but it is increased by 28 %, when soil was high in P under elevated CO_2 condition [19].

3. PHOSPHATE SOLUBILIZING BACTERIA (PSB)

Under acidic or calcareous soil conditions, large amounts of phosphorus are fixed in the soil but are unavailable to the plants. Phosphobacterins, mainly bacteria and fungi, can make insoluble phosphorus available to the plant. The solubilization effect of phosphobacterins is generally due to the production of organic acids that lower the soil pH and bring about the dissolution of bound forms of phosphate. It is reported that PSB culture increased yield up to 200-500 kg/ha and thus 30 to 50 kg of superphosphate can be saved. Assimilation of phosphate from organic compounds by plants and microorganisms take place through the enzyme "phosphatase" which is present in a wide variety of soil microorganisms. Those are called subsequently as Phosphate solubilizing microorganisms (PSM). Population of PSB depends on different soil properties (physical and chemical properties, organic matter and P content) and cultural activities. Several scientists have reported the ability of different bacterial species to solubilize insoluble inorganic phosphate compounds, such as Tri-calcium phosphate, Di-calcium phosphate, Hydroxy apatite, and Rock phosphate. The bioavailability of soil inorganic phosphorus in the rhizosphere varies considerably with plant species, nutritional status of soil and ambient soil conditions. To circumvent phosphorus deficiency, Phosphate Solubilizing Microorganisms (PSM) can play an important role in supplying phosphate to plants in a more environmental friendly and sustainable manner and reduce the demand of chemical fertilizers.

Soil microorganisms have ability to convert insoluble phosphatic compounds into soluble P form for uptake by the crops [36]. There are many rhizosphere microorganisms, which are able to dissolve insoluble P. It has been found that the poorly soluble P is usually dissolved by microorganisms, which can then be converted into soluble forms by the process of acidification, chelation, and exchange reactions [37]. Phosphorus solubilizing bacteria enable P to become available for plant uptake after solubilization. Several soil bacteria, particularly those belonging to the genera *Pseudomonas* and *Bacillus* possess ability to bring insoluble soil phosphates into soluble forms by secreting acids such as formic, acetic, propionic, lactic, glucolic, fumaric and succinic. The plant growth promotion of PSM has been reported to be a combination of several other factors, such as nitrogen fixation, production of plant growth promoting substances, siderophores, HCN, lytic enzymes, competition, and control of plant pathogens and by inducing systemic resistance [38, 39].

The quantity of PSB, involved in solubilization process, is more abundant in the rhizosphere than non-rhizosphere soil and is metabolically more dynamic than from other sources. The PSB also plays a vital role in combination with chemical fertilizers, for example, single super phosphate (SSP) and PR, and application of microbial phosphatic fertilizers has been found to reduce the synthetic P levels by 25–50 % in agricultural practices [40]. Direct application of PR is mostly not effective for annual crops [41], the availability of which however can be enhanced by applying some acid-producing microorganisms: able to solubilize PR [42]. Researchers suggested that certain PSB strains were able to solubilize P; examples included were those of *Pseudomonas putida* (51 %), *P. fluorescens* (29 %), and *P. fluorescens* (62 %). *Pseudomonasstriata* and *Bacillus polymyxa* solubilized 156 and 116 mg P l^{-1}, respectively; *Pseudomonas fluorescens* solubilized 100 mg P l^{-1} containing Ca_3 (PO_4)2,92 mg P l^{-1}containing $AlPO_4$, and 51 mg P l^{-1} containing $FePO_4$. Phosphorus solubilizing microorganisms (bacteria and fungi) enable P to become available for plant uptake after solubilization. The plant growth promotion of PSM has been reported to be a combination of several other factors, such as nitrogen fixation, production of plant growth promoting substances, siderophores, HCN, lytic enzymes, competition, and control of plant pathogens and by inducing systemic resistance [38,39]. Synergistic effect of AMF and PSB strains (*Coccus* DIM7, *Streptooccus* PIM6 and *Bacillus spp*

PIS7) on P solubility from Rock phosphate (RP) and their successive uptake by maize crop at alkaline soil under green house condition [43]. Principal mechanism in soil for P solubilization is lowering of soil pH by microbial production of organic acids and mineralization of organic P by acid Phosphatase. Use of phosphorus solubilizing microorganisms alone or in combination with other beneficial bacteria and mycorrhiza as inoculants increase prospects of direct application of rock phosphate (RP) in P uptake and crop production [44].

3.1.Phosphate Solubilization By Phosphate-Solubilizing Bacteria (Psb)

3.1.1. Solubilization Of Al And Fe-Bound Soil P

The solubilization of Fe and Al takes place through the release of protons by PSB, reducing the adsorbing surface charge to make possible the sorption of negatively charged P ions. Phosphate sorption also might be decreased with the release of protons by acidification that increases $H_2PO_4^-$in comparison to HPO_4^{2-}having higher similarity to reactive soil surfaces [29]. The different forms of P, like Al-P and Fe-P, are mostly solubilized by carboxylic acids [45] by the mineral P dissolution as an effect of anion exchange of PO_4^{3-}or by chelation of Al and Fe ions associated with P [45]. This is due to high affinity of iron uptake system by root-colonizing pseudomonas which depends on the release of Fe^{3+} chelating molecules like siderophores [46]. Further, P replaced by carboxylic anions through ligand exchange from sorption complexes [29] and chelates Fe and Al ions with phosphate, and after transformation, phosphates become available for plant uptake. Different carboxylic anion lowers the P desorption potential with decrease in the stability constants of Fe- or Al-organic acid complexes (log KAl or log KFe) in the order: citrate>oxalate> malonate/malate>tartrate> lactate> gluconate> acetate> formiate [47].

3.1.2. Solubilization Of Ca-Bound Soil P

At high pH, soil P forms a complex with Ca and remains unavailable to plants. In the alkaline soil conditions, phosphatic fertilizers and its metabolites are fixed as calcium phosphates. Rock phosphate in soil is insoluble and can become soluble following the release of inorganic P to maintain plant growth [15]. Calcium phosphate solubilization occurs through the secretion of organic acids by microbes [48], and lowering of rhizosphere pH , that break down the bound forms of P like $Ca_3(PO_4)_2$; however, the buffering capacity of the medium decreases the effectiveness of PSB in releasing P from tri-calcium phosphates [49]. Thus, any microorganism that acidifies its external medium will result in some level of PS activity. In majority of the soils, proton substitution reactions are determined by microbial production of organic acids, the complexity of Ca-P chemistry and the multiplicity of microbially produced organic acids with differing numbers of dissociable protons[50].

4. PHOSPHORUS SOURCES AND PSB ON SOIL BIO-PHYSICO-CHEMICAL PROPERTIES UNDER RICE RHIZOSPHERE

Phosphorus can never be too much in the soil for plant absorption, as it is slowly absorbed and greatly needed for an overall growth and health of the crops. Apart from bio-geochemical properties of soil under rice rhizosphere, the source of P also have key role in its availability in solution and to the rhizosphere. Based on the P source applied to different soil types differ in their reactions and bio-geochemical properties under rice rhizosphere. For example, application of 50% NPK Zn + Bio-fertilizer (PSB+BGA) + FYM (10 t ha-1) shows higher organic carbon content (0. 71%) at 30 DAS and at harvest OC (0.66%) as compared to control shows lowest OC (0.62%) at 30 and at harvest OC (0.53%) however there is a slight decline in OC reported by [51]. Application of FYM (1/3) + vermicompost (1/3) + green leaf manure (1/3) equivalent to RDN with recommended FYM + microbial consortium (M) (*Azospirillum* + PSB) with soil application of bio-digester @ 2500 ha^{-1}shows the higher dehydrogenase (14.6 and 13.1 g TPF g^{-1} $soil^{-1}$ day^{-1}) and phosphatase activity (28.5 and 27.3 g pNP g^{-1} $soil^{-1}$ h^{-1}) at flowering and harvest respectively [52]. Researchers proved that application of 45 kg basal + 15 kg at tillering ha P_2O_5 through SSP shows lowest pH (8.72) EC (0.37 dSm^{-1}) while control shows highest pH (8.80),EC (0.37 dSm^{-1}) and application of 30 kg Basal +15 kg at tillering + 15kg at PI through SSP shows higher OC (0.38%) as compared to control OC (0.33)[53]. And application of phosphorus levels and inoculation of PSB strains did not cause significant variance on soil pH. The highest pH was recorded with application of 60 kg P_2O_5 ha^{-1} (5.15) and with inoculation of *Pseudomonas spp*. (5.14), respectively [54]. The organic carbon content was not significantly influenced by the application of phosphorus at different levels and PSB strains. However, the highest values were recorded when 60 kg P_2O_5 ha^{-1} (2.04%) was applied and *Pseudodomonas spp*. (2.06%) was inoculated.Use of phosphorus solubilizing microorganisms alone or in combination with other beneficial bacteria and mycorrhiza as inoculants increase prospects of direct application of rock phosphate (RP) in P uptake and crop production [55]. Increased dosage of inhibits the survival of microbes due to osmotic stress created by fertilizers and native soil inhabits influences the soil enzyme activity [56].(Bharathi *et al*., 2011). Activity and build-up of dehydrogenase and phosphatase increased with organic application [57], and any management practice that affects the biological population of soil could be expected to result in some change in soil enzyme levels [58].

5. PHOSPHORUS SOURCES AND PSB UNDER RICE RHIZOSPHERE AND IT'S INFLUENCE ON GROWTH AND YIELD

Better rhizosphere activities both under oxic and anoxic condition would significantly influence the nutrient transformations which in turn might cause the rice productivity. For example, application of 50% RD of P_2O_5 from SSP + 50 % RD of P_2O_5 from RP showed higher grain yield

(36.33g hill^{-1}), plant height (110.7 cm) and dry matter yield (33.67g hill^{-1}) as compared to control grain yield (21.33 g hill^{-1}), plant height (94.3 cm) and dry matter yield (26.83 g hill^{-1}) [59] and also higher phosphorus uptake (120.94 mg hill-1) as compared to control (86.43 mg hill^{-1}) at harvest. Application of NPK+PSB proved best in influencing growth and productivity where grain yield (4226.6 kg ha^{-1}) and straw yield (6256.67 kg ha^{-1}) as compared to control shows lower grain yield (2686.67kg ha^{-1}) and straw yield (3103.33 kg ha^{-1}) [60]. Further, application of 50% NPK Zn + Bio-fertilizer (PSB+BGA) + FYM (10 t ha-1) shows higher grain yield(32.87qha^{-1}) and straw yield (89.98 qha^{-1}) as compared to control grain yield (12.12qha^{-1}) and straw yield(75.04 qha^{-1}) [51],and application of 50 kg P ha-1 through phosphatic fertilizers and use of PSB but no vermicompost - P50 + PSB shows the higher grain yield (5.2 t ha^{-1}) than control (4.7 t ha^{-1}) [61]. Phosphate solubilizing bacteria (PSB) as biofertilizers has concurrently increased phosphorous uptake in plants and improved yields in several crop species [62] and significant response of yield and yield components of rice to different P solubilizing microbes and mineral phosphorus was realised [63].

Combined application of NPK with *Azotobacter* and PSB in rice rhizosphere i.e. application of NPK+ Azotobacter + PSB on rice crop had increased the plant height, number of tillers, number of grain per panicle, test weight (g), grain and straw yield. The maximum yield was recorded with higher dose of NPK with Azotobacter + PSB [64]. Use of PSB + BGA + FYM (5 t ha^{-1}) proved superior to PSB alone & PSB + BGA duly by positive effect on plant growth, nutrient uptake, grain yield and yield components in rice plants in the treatment inoculated with phosphate solubilizing bacteria (PSB) [65]. Application of 75 per cent NPK through fertilizers and 5 t of FYM ha^{-1} or *Azotobactor* + PSB improved the rice - wheat system productivity and stability index of system as compared to the application of 100 per cent NPK through inorganic fertilizers [66]. Effect of phosphate-solubilizing bacteria (PSB) and organic acids (oxalic and malic) on phosphate (P) solubilization from phosphate rock (PR) and growth of aerobic rice [67]. Application of PSB inoculation improved grain yield significantly and the grain yields were 14.3, 18.2 and 9.3% higher over the uninoculated control in three respective years [68].Yaser *et al*. (2011) reported that Fertilizers with PSB, *Pseudomonos fluorescence* and *Azospirillum lipoforum* have significantly increased the panicle number and harvest index and Davari and Sharma (2010) reported that combination of FYM + wheat residue (WR) + Biofertilizer (BGA, PSB and cellulolytic culture) and vermicompost (VC) + WR + biofertilizer (B) resulted in highest increase in yield attributing characters of rice and increased grain yield of basmati rice over control by 51-58 per cent [69,70].

6. PHOSPHORUS SOURCES AND PSB ON NUTRIENT AVAILABILITY UNDER RICE RHIZOSPHERE

Nutrient availability under flooded or non flooded condition depends on various factors however the activity and availability is more in rhizosphere soil when compared to non rhizosphere soil. Nutrient availability of soils differs in relation to application of various P sources and microbial activities. For example, application of 50% NPK Zn + Bio-fertilizer (PSB+BGA) + FYM (10 t ha^{-1}) shows higher available nutrients (N,P,K kg ha^{-1} 262.53,21.48 , 272.69 respectively) as compared to control shows lower (N,P,K kg ha^{-1} 239.75, 10.09, 244.89, respectively [51]. Also, application of complex fertilizer source 20:20:0 @ 250 kg ha^{-1} (on P equivalent basis) + PSB @ 2 kg ha^{-1} shows higher soil available phosphorus 27.53 kg ha^{-1} at post-harvest stage as compared to application of 100 % recommended P as SSP (313 kg SSP ha^{-1}) shows lower available phosphorus 23.53 kg / ha [71].Maximum available nitrogen, phosphorus and potassium (175.40, 6.90 and 260.40 kg/ha), respectively were recorded by the applying 45 kg basal + 15 kg at tillering ha P_2O_5 through SSP) as compared to control (116.50, 14.60 and 238.80 kg ha^{-1})[72]. Addition of organic sources i.e. (1/3rd FYM + 1/3rd poultry manure + 1/3rd vermicompost) with bio-fertilizers (*Azotobacter* and PSB) significantly improved availability of nitrogen, phosphorus and potassium [73]. Application of rock phosphate in combination with PSB increases soil microbial biomass carbon, alkaline phosphatase and dehydrogenase activity in rice based cropping system [74]. Biofertilizers application enhanced N availability through biological nitrogen fixation and solubilized the unavailable P and better P uptake in aerobic rice[75].

7. PHOSPHORUS SOURCES AND PSB ON NUTRIENT UPTAKE, USE EFFICIENCY UNDER RICE RHIZOSPHERE

Microorganisms play an important role in making nutrient transformation efficiently both in rhizosphere and non rhizosphere zone. Nutrients in soil solution made available by microorganisms which enhances its uptake and use efficiency. As several researchers stated that soil application of PSB @ 750 ml ha^{-1} along with 50% RDP (30 kg P_2O_5) recorded the higher partial factor productivity and agronomic efficiency for phosphorus in rice[76]. Use of phosphate solubilizing bacteria (PSB) biofertilizers has along with STCR based IPNS concurrently increased phosphorous uptake in plants and improved yields in several crop species especially in rice rhizosphere [77], and application of 100% RDP (60 kg P_2O_5 ha^{-1}) proved higher removal of NPK by grain (75.42, 11.79 & 15.57 kg ha^{-1}) and straw (41.38, 8.98 & 96.44 kg ha^{-1}) of rice , and combined application of PSB + BGA + FYM (5 t ha^{-1}) recorded that removal of NPK by grain and straw [78]. Combined application of bio-organics increased N in grain (30.31%) and straw (17.54%), P uptake in grain (38.21%) and straw (49.76%) and K uptake in grain (14.74%) and straw (16.81%) and protein content (19.30%) and protein yield

(30.32%) over use of PSB alone[79].Phosphorus mineralization in soil amended with RP was 6.0-11.5 mg kg^{-1}, while both soluble P fertilizers resulted in 68–73 mg P kg^{-1} at day 0, which decreased by 79–82%. The integrated use of PSB and PM with RP stimulated P mineralization by releasing a maximum of 25 mg P kg^{-1} that was maintained at high levels without any loss. The PUE of applied P varied from 4 to 29% and was higher in the treatments that included PSB [80]. Numerous studies have been conducted to evaluate the efficiency of different amendments to increase the availability and solubility of P from native and applied sources including RP. Among these, organic amendments, including animal manure, plant residues and green manure [81,82,83],composts [84,85,86], and bacterial inoculation [87,88] are considered beneficial for improving the P efficiency. Application of 100% recommended dose of nutrients on nitrogen basis (RDN) as organic manure with biofertilizers (*Azotobacter* and PSB) had the highest rice grain equivalent yield and production efficiency in rice based cropping system followed by organic nitrogen sources alone [73] , and phosphorus concentration in the shoot of rice increased constantly up to 150 mg P kg-1 soil and then declined. However, P concentration in the grain and uptake in shoot and grain increased quadratically with increasing P rates from 0 to 250 mg P kg^{-1} of soil [89].

Inoculation of PSB and the application of oxalic acid increased P uptake in aerobic rice [90].The lower specific activity (^{32}P) in the aerobic rice tissue showed a positive effect of PSB inoculation or OA application to make the bio-available P from PR and native soil sources. P uptake and crop yields have been observed after PSB inoculation with *Bacillus sp*. [38,91], *Pseudomonas* and *Bacilli* [92]. Inoculation of PSB enhanced P uptake and simultaneously increased the yield of aerobic rice. Plant P uptake, P use efficiency (PUE %), total biomass, and total protein content increased with the inoculation of PSB with CIPR and OA. In addition, PSB inoculation and the application of PR and OA significantly increased the grain yield and plant biomass of aerobic rice. The highest grain yield and plant biomass were determined when PSB was inoculated with CIPR and OA and was statistically at par with those of PSB and PR application. Further, application of triple super phosphate (TSP) at three levels (0, 30 and 60 kg ha^{-1}) and two isolated PSB (*Bacillus* sp.) strains (PSB 9and PSB 16) were significantly, showed high P solubilization (28.7 mg kg^{-1}) and plant uptake (7.94 mg kg^{-1}) by PSB16 inoculated treatments at 30 kg ha^{-1} of P_2O_5 [90]. Triple superphosphate (TSP) 50 per cent could be substituted with RP when P-solubilizing bacterial inoculants *Enterobactorgegovie*, *Bacillus pumilus*and *Bacillus subtilis* were applied with RP to wetland rice both under pot and field conditions significantly improved the PUE [93]. NPK uptake and management can be improved by the use of PSB in rice [94]. The application of PSB significantly increased soluble phosphorus and its uptake in aerobic rice genotype and use of isolated PSB strain solubilized significantly high amounts of P (20.05-24.08 mg kg^{-1}) compared to non- inoculated (19-

23.10 mg kg^{-1}) treatments [90]. The higher amounts of soluble P in the soil solution increased P uptake in plants. P applied as either SSP or PR once, at five rates (0, 20, 40, 60 and 80 kg P ha^{-1}) on a sandy clay loam soil. Results revealed that in the first year, applied PR @ 80 kg P ha^{-1} to rice recorded the highest grain yield of 7.06 t ha^{-1}, while Rock Phosphate field by more than 1 t ha^{-1} in second year compared to SSP due its residual effect[95]. Phosphorus Use Efficiency (PUE) was highest with SSP, compared to PR.

8. CONCLUSION

The foregoing broad review of literature has shown that phosphorus is a key nutritional element for rice. Phosphorus availability is restricted in soil by various factors which results in reduction of nutrient uptake and yield. Therefore, applying more P fertilizers or increasing P use efficiency is essential to meet up the crop requirements. But, declining trend of P fertilizer production sources was notified globally which raise a question of P fertilizers availability. Where use microorganisms like P solubilizers can recycle P in soil as well as enhances the availability. PSB application would be vital for P management in rice, as it is economic, efficient and a renewable source. So the use of potent phosphate solubilizing bacteria along with P fertilizers will help to boost up rice production and contribute to sustainability in agriculture.

9. FUTURE THRUST AREA

Determining biogeochemical activities under rhizosphere itself an immense task for the researchers and further manipulating and quantifying nutrient transformation could a key for enhancing crop production especially rice grown under saline condition. Many researches showed results on screening of organic compounds producing microorganisms and their utilization under normal soil condition. Hence, more precise research should be done on rice rhizosphere areas like hot spot, in –situ and site specific detection and quantification of root distribution ; deposition, induced phyo-chemical changes, characterization, various mechanisms at plant physiological and molecular level for techno-transfer towards next frontiers of rice production through management of rice rhizosphere.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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