Review Article

Phosphorus Availability in Lowland Agricultural Fields of India - An Overview

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Abstract

Phosphorus (P) is almost never found in elemental state owing to its highly reactive nature. It is available at a concentration of about 1000 mg per Kilogram in the Earth's crust. Various soil types such as acidic, lateritic, calcareous etc are characteristically low in bioavailable phosphorus due to their veritable P-fixation rates. At the same time it also is quintessential to living organisms, being a structural component of nucleic acids and ATP as well as aiding in many physiological and biochemical processes. Hence, an adequate supply of phosphorus in the soil and water is required to sustain life on earth. Phosphorus factions play major roles in the solubility and transformation of phosphorus in various soils, thus governing the management of phosphorus fertilization based on soil types. Various microbial symbioses such as with bacteria, fungi etc are responsible for the solubility of phosphorus from Apatite and related minerals but are solely not adequate in many cases to overcome the dearth in supply of bioavailable phosphorus. As we are aware that eutrophication in water bodies has transcended as a major environmental issue in dire need of resolution in recent decades, the prudent usage of phosphorus in agriculture was never more a mandate than now. In this context the data on the availability of phosphorus in various Indian soils is very important given the agriculture buttressed economy of the country and may serve as future reference while formulating policies for remedying ecological ailments.

Keywords: Phosphorus; Solubilization; Agriculture; Nutrient; Eutrophication; India

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Introduction

Phosphorus (P) is generally incorporated by plants through the root system from soil solution as orthophosphates, chiefly $H_2PO_4^-$ and HPO_4^{2-}, the latter to a somewhat lesser degree. As this depends on several innate factors, the precise recovery following an initial application of P-fertilizer can get affected. As stated by [1], the lowest concentration of P which the soil P content can get reduced to at the rhizosphere of terrestrial plants is around 1 μM. Since roots in the rhizosphere only exploit about 25 % of the topsoil, the P-contents there needs to be replenished often through fertilization to meet the nutritional demands of crops cultivated in such soils, as was observed by [2]. Nutrients acquisition by plant roots follows two different paths [3] - mass flow (depends largely on the rate of water flow through the roots) and diffusion (the main process of nutrient mobilization across a concentration gradient). Diffusion depends on the absorption capability of the roots, creating a sink to which nutrient can get pooled [4] and even this process is heavily reliant upon the soil characteristics in addition to plant metabolism [5].

A sub-continental country like India is bestowed with a diverse array of soil types which is largely responsible for the plethora of agricultural produce obtained. At the same time phosphorus availability is limited (around 50%) in majority of the arable soil types found in India due to the P-fixation (as well as buffering) capacity of the various soils, none more so than in acidic soil, (mostly resultant of leaching of base forming cations) which incidentally dominates the global cultivable lands and is a matter of great concern due to its adverse effect on crop productivity [6].

Red (or omnibus group) and lateritic soils occupy an area of about 3.5 lakh sq. Km and 2.48 lakh sq. Km (1 lakh = 100,000) respectively, accounting for more than 26 % of the total arable land area (1.597 million sq. Km) of India. Productivity of these soils is usually low because of their clastic crystalline origin, sandy texture, moderate to high porosity, low organic matter content, low cation exchange capacity (CEC), low water retention and acidic products in reaction as well as inadequacy of nitrogen (N), phosphorus (P) and potassium (K), along with the presence of some micronutrients in toxic concentrations [7].

Since the lateritic soils are acidic in nature and characterized by high P-fixing capacity; most of the water-soluble P administered to such soils is transformed to relatively insoluble inorganic phosphates of calcium (Ca), aluminium (Al) and iron (Fe), thus reducing the available P immediately. However, as the intensity factor of these soil solutions diminishes with time, the inorganic P fractions may gradually contribute to the nutrition pool for the crops [8].

On the other hand, available chemical extractants are selective in dissolving only one or more factions of inorganic P and thus differ in their efficacies in extracting available P over a physico-chemically diverse soil group. Under widespread soil conditions and agronomically acceptable fertilization rates, the P precipitation reactions with soil clay fractions (and oxides) render the P relatively immobile in soil. That is why the low P-fertilizer efficiency is often countered through high dosage of fertilizer application but, it should not be the only option for better cultivators. Increasing availability of added P to the plants through inorganic fertilization is of supreme importance for enhancing productivity and food security for the projected population during the next century [9].

The release of bound or fixed P through the action of phosphate solubilizing microbes by chelation with secreted low molecular weight organic acids into solution in a soil and its mobilization and transformation revolve around the movement of released phosphorus as well as phosphorus containing compounds in soil and thus can be made available to various other microbes and ultimately to plants via surface waters these are quite different aspects of phosphorus biogeochemistry and should not be considered the same. It is important also to point out that solubility of phosphorus is solely not the most important aspect while adding phosphatic fertilizer to the soil, as transformation and mobilization of the element also needs to be diligently considered; hence it can be stated in light of phosphorus biogeochemistry that in a broader sense solubilization, dissociation and the resultant incidentals are all integral stages in mobilization of phosphorus [10].

There have been many studies dealing with benefits of silicon and phosphorus fertilization on the productivity of aerobic rice cultivation. During the research, [11] used four P (Diammonium Phosphate or DAP [$(NH_4)_2HPO_4$]) and Si (Calcium Silicate [$CaSiO_3$]) gradients with factorial design (FRBD). Dual benefit of Si and P nutrition in overcoming stress caused by both biotic and abiotic agents was evidenced in the reduced incidence of shoot borer in rice and similar the trends were recorded by [12] in lateritic soil where the submerged rice were grown in a large area. Lowest yields were recorded in absence of silicon fertilization. The same findings were reported [13] in that the similar rates of applications of phosphorus and silicon had yielded significantly higher dry matter over the experimental control at 60, 90 days from sowing and at harvest. Effectiveness of Si in higher yield was also recorded by [14] and [15] who had reported increased leaf area and yield in rice.

The experimental findings by [16] highlighted the critical limit of phosphorus calculated by a scatter diagram plotted with Olsen's extractable P; and relative yield and relative P uptake indicated that soils in paddy fields at the sites in Andhra Pradesh had responded to phosphate application to the soil in spite of relatively high P content, thus underlining complexities of P biogeochemistry as P uptake magnitude was higher than the dry biomass yield [17]. [18] have recorded in vertisols of Maharashtra the critical limit of Olsen's P_2O_5 determined by scatter diagram and reported significant relation among dry matter yield and relative yield with soil Olsen's P and P content of soybean crop. Response of phosphatic fertilizers vary between the air dried soil and submerged soil as increase in P content in submerged soils at times become sufficient or rice production whereas in others there P fertilization becomes a must, as was observed by [19].

In India, The surface soils of pastures, mono and double-cropped land show high available P status as compared to fallow grazing lands, eroded soil and orchard soils which are normally devoid of P in most cases and this fact can be attributed to the fact of accumulation of P through regular P fertilization in the former group of soils. Although invariably at a depth of 22 cm from the surface almost all soils were observed to possess poor P contents, as was reported by [20]. Constant manuring and crop planting can increase Ca-P and Al-P contents in soil, a feature attributable to not only artificial fertilization but microbe induced solubilization of P; but it was also observed that Fe-P dominated over may such soils, which could have been due to intense weathering [8] [21]. The degree of weathering and the stage of soil maturity as well as the availability of various phosphates and their relative dominance over each other were well explained by [22].

The primary aim in this context should be to increase the available P contents in the soil though the application of biological entities as much as possible with only needed human interventions. Microbiological interactions such as with many bacteria (both phosphate solubilizer as well as other plant growth promoters) and fungi (mainly various arbuscular mycorrhizae) at the potential rhizosphere of crop and other plants have been previously shown to increase the P-contents to a significant amount. The additives such as cow dung manure, P containing minerals in the soil can greatly expedite these processes and enrich the soil faster, particular when need for agricultural purpose [23]. Addition of earthworms have been observed in many studies to greatly increase phosphate, phosophodiesterase, pyrophosphatase as well as dihydrogenase activities, pointing to the greater solubilization, accumulation and availability of P in the soil [24].

The present review focuses on some of the more crucial aspects of P in Indian soils such as its mobility and availability in submerged soil, microbial influence of soil P availability, P fractionations, and effect of drying and wetting of soil on P mobility and availability along with few other relevant aspect to provide readers and future workers with a reference to organize their studies and also cultivation as well as selection of soil and crop by agrarians.

Phosphorus in Submerged Soil

Numerous studies have been performed on the mechanism and effect of P adsorption and release from waterlogged soil [25-28]. Submerged soils undergo thermal stratification leading to a decline in the level of oxygen and reduction in oxygen level helps in increasing the concentration of water soluble P. The water soluble P increases 100 times in a lake [29] and 50 times in interstitial water of reduced sediments [30]. The loss of P in flood prone areas depends on the frequency of flooding and the variations in the depths of water column above the soil under waterlogged conditions [31]. Under anoxic conditions remineralization of P takes place because of sulphate reduction and the release of P from P sink in the sediment increases the concentration of phosphates into the overlying or adjoining water column.

There are various fractions of inorganic phosphorus such as Fe-P, Al-P, Ca-P, Mg-P (least) which are mostly get adsorbed with iron and manganese hydrous oxides, phosphates by the strength of anion exchange on clay and hydrous oxides including the organic forms of phosphorus [32]. The concentration of water soluble P in acidic soil get increased under submerged state due to the hydrolysis of phosphates of Fe and Al and anion exchange on clay and hydrous oxides of Fe and Al, it is important to point out that too, it helps in releasing the adsorbed and chemically bonded P with Fe^{3+} and Fe^{2+}. Many earlier researchers had observed that solubility of the P in basic soil like alkaline and calcareous soils appears to be controlled by the solubility of hydroxyl-apatite [33] and which is found same in reduced acidic soils by adsorption on kaolinite, montmorillonite and saturation of cations leading to precipitation of their hydrous oxides [34, 35]. The observation [36] recorded in the soil survey that the available P content in soils of Marathwada region of Maharashtra was ranged from 5.37 to 17.05 kg ha^{-1} with a mean value of 10.58 kg ha^{-1}. According to nutrient index value, the available P content of soils of Basmat tahsil was low in fertility. It might be attributed due to calcareous nature of soil as it causes P fixation.

The status of available P and transformation of inorganic P fractions in continuous rice growing soils of Andhra Pradesh under air-dried and submerged soil conditions was recorded by [37]. The abundance of inorganic P fractions ($mg.kg^{-1}$) in air dried soils was found in the sequence of Ca-P > Al-P > Fe-P > Reductant Soluble (RS)-P > saloid-P and under submerged soil conditions Ca-P > Fe-P > Al-P > RS-P > saloid-P. Fe-P was found to be the most important inorganic P fraction which could contribute more to phosphate availability to rice, followed by Al-P fraction. High Ca-P was observed in the soils due to continuous application of higher doses of superphosphate or DAP and the same trend was observed in submerged soils, although here the increase in Ca-P could have been due to conversion of insoluble tricalcium phosphate to more soluble mono or dicalcium phosphate and mineralization of organic P under submerged conditions [38]. An increase of higher proportion of Fe-P than the other P fractions in submerged soils might have been due to transformation of insoluble ferric phosphate to more soluble ferrous phosphate caused by changes in soil pH [39]. The increase of reductant-soluble P fraction on water logging might be due to an increase of soil pH which increases the rate of mineralization of organic P and decreased sorption of organic P compounds by hydrous oxides. Almost the trend was same in the air dried soil and submerged soil only there was differences found in the Fe-P and Al-P in both types of soil.

Hence it can be stated that the Olsen's extractable P in submerged soils and modified Olsen's extractable P in air-dried soils showed highly significant correlations with plant-growth as compared to other methods. Soil test methods thus need to be standardized bearing in mind the nutrient uptake of crop which was found to be more reliable than yield because the nutrient uptake was less influenced by the factors other than availability of added nutrients and it also revealed the extraction pattern of the plant throughout the growing season.

A similar study was recently performed on the transformation of P under intensive rice and allied cropping systems in acidic submerged soils of Odisha [40] where the authors have reported the gradual increase of soil pH in postharvest fields through lime input in spite of the removal of basic cations. There was also a simultaneous, although insignificant, but positive build up of N and P in the soils. In their study the authors had fractionated P in two broad groups, viz. inorganic-P (constituting about ~72%-86% and ~76%-81% of the total P in surface soil and subsoil respectively) and organic-P (~14%-28% and ~19%-24% of the total P in surficial and subsequent soil layers respectively). The sequence of various P pools observed in the abovementioned study was in order of Fe-P > RS-P > Al-P > Ca-P > Occluded-P > saloid-P (in surface soil up to 15 cm) and RS-P > Fe-P > Ca-P > Occluded-P > Al-P > saloid-P (subsurface soil up to 30 cm).

The same study also revealed the decline of organic-P in subsoil under cropped and fertilized conditions with less mineralization and uptake by crop. It was believed that transformation of phosphorus was greatly affected by root biomass and exudation. In a study performed by [41], the dominance of RS-P in acidic soils of aggressively cropped rice fields of West Bengal was observed. This was attributed mainly due to the presence of sesquioxides. There was an observed increase in saloid-P, Fe-P and RS-P but decrease in Al-P, occluded-P and Ca-P fractions of the available P pool. Reduction was observed in all inorganic-P fractions with increasing depth, except in RS-P. Thus the study had concluded that under rice based cropping system on submerged acidic soils, RS-P might be more important than others in P uptake by crops and can be used as index of potential release of P in surface/subsurface soils under reducing condition [42]. All the inorganic fractions of P had negative correlations with soil pH apart from saloid-P in the P poor subsurface soils, an observation corroborating a previous study by [43].

In the study, Bray's extracted P was found to be positively correlated with Fe and Al-P, indicating major contribution of both Fe and Al towards the available P pool in the surface soil; while Al-P was reported to be the more significant contributor in the subsurface soil layers. It could also be stated from the study that in the surface layers inorganic Fe-P associations had governed much of the uptake of available P, a role played by Al-P in the subsurface layers. Thus, there should be a carefully planning while adding inorganic-P and organic-P fertilizers in the soil as the uptake depends on various factors such as interaction among different fractions of P depending on pH, particularly in acidic soils.

Microbial influence on Phosphorus availability

The use of microbes, especially bacteria, to enhance the bioavailable content of P in soil, particularly for the betterment of crop yield, was perhaps first substantiated by [44] where the findings clearly indicated that pure cultures of soil bacteria could increase P nutrition with the mutual increase in available P through solubilization of precipitated or sorbed calcium phosphates, the bacteria being referred to as phosphate solubilizing bacteria (PSB). Since then there have been many studies (e.g. [45, 46] focusing on the influence of microbes in P fractionation and mobilization as well as on categorisation of such microbes based on their mode of action. In spite of the very many studies on the potential usage of microbes to enhance crop production through increased P availability, not many of the methods have found themselves in large scale practice barring the use of phosphate solubilizing fungal species, especially by arbuscular mycorrhizal fungal (AMF) species [47]. Apart from the intended aim of increasing bioavailable P in soil, these microorganisms also synthesize phytohormone which most definitely aid in expediting plant growth [48].

India being agriculture dominated has also reported many studies on the use of soil microbes for yield enhancement through greater nutrient availability. Since about 98% of the crop land available in India suffers from low available P, generally there is a greater trend of using inorganic P fertilizers in these areas. This has and will lead to accumulation of heavy metals in the soils in addition to calcium sulphate deposition as well as emission of fluorine as highly volatile HF, not to mention the rapid depletion of the naturally occurring rock phosphate [49], which comes along with such fertilizers as contaminants and adulterants. Thus, it has never been more imperative to switch to more ecofriendly and economically feasible options in fertilizing the soil than now and microbially enhanced soil P availability is among such paths to tread more readily.

The response were recorded [50] with varying rock phosphate and DAP (both @) 30 kg P ha^{-1}) under a dual inoculation of PSB and AMF, along with solo inoculations of the two, where it was observed that the application of rock phosphate in presence of PSB and AMF had resulted in the highest content of available P (62.94 µg g^{-1} soil). Incidentally this was a two folds increase over the recorded response with DAP with an available P concentration of 31.93 µg g^{-1} soil. In this study the efficiency of PSB to release Ca bound P into soil solution was evaluated and it was observed that the higher values for stable HCl-P fraction indicated the high P fixation capacity of the test soil. In most of the treatments, availability of P declined with the aging of the crop. It was observed that the DAP, with inoculation of PSB and AMF, when compared with un-inoculated rock phosphate showed higher available P values at both levels of applied P. However, seed inoculation with *Pseudomonas striata* in combination with rock phosphate @ 15 kg P ha^{-1} (RP15) and 30 kg P ha^{-1} (RP30) resulted in higher P values when compared with AMF inoculation at same levels of rock phosphate. However, the dual inoculation of PSB and AMF along with RP30 enhanced the available P content of soil by 61.67% in RP30+ PSB and 89.63% in RP30+AMF treatment which was found to be significantly higher compared to other treatments. Microbial inoculation certainly improved the available P content of soil over their respective controls.

On a comparative note it could be stated between both the inoculants tested however, the effect of PSB for improving availability of P was more pronounced as to AMF. It was also observed that, the sodium hydroxide extractable P fraction showed a reverse trend compared with sodium bicarbonate extractable P fraction. The peak value for this fraction at harvest was recorded in DAP15 (@ 15 kg P ha^{-1}), followed by the combination of RP30 + PSB. HCl-P fraction was found as the most stable P fraction that not usually available to the plants. The higher values for this fraction were recorded at initial stage followed by a decline at harvest stage; this might be the reason why the uptake of the available P content might have declined at the initial stage of the crop, as previously observed [51]. Application of 30 kg P ha^{-1} through RP + PSB +AMF showed higher reduction of P content in this fraction. This might have been the case where initially the solubilised P was reincorporated in the cells of the inoculated microbes during the lag phase of their growth and once they had acclimatised to the ambient conditions, the rate of solubilization had increased.

It is assumed that P availability to plants decreases with increasing strength of the chemicals used in the fractionation procedure. From the above discussion, it may be summarized that the bicarbonate-extractable-P fraction contributes most to plant available-P, while hydroxide-P and acid-extractable P fractions are the moderately or poorly available to plants. Integrated application of 30 kg P ha^{-1} rock phosphate with inoculation of PSB and AMF not only improved the sodium bicarbonate extractable P fraction in rice soil but also enhanced the enzymatic activities of soil. This treatment also increased P use efficiency of rock phosphate in aerobic rice.

Nowadays fungi such as PSF are being popular for their relatively higher potential to improve the availability of P in soil at a relatively low cost. Due to their non-specificity for plant and soil association, *Penicillium spp.* have a broad agro-ecological range, indicating their potential to be developed as inoculants for a range of plant production systems [52]. Nowadays, researchers are focusing on using them as inoculants to enhance P mobilization in soil. Works by [53] and [54] focused on *Penicillium bilaii* to increase production of wheat (*Triticum aestivum*). The results had shown that wheat seeds inoculated with *P. bilaii* had received increased availability of soil P by almost 18%, enhanced production of root hairs and improved root growth were also noticed compared to non-inoculated plants. The results documented by [55] in their study that, the seed inoculation with *P. bilaii* and other species in combination with the 100% recommended dosage of chemical inorganic P had improved the P uptake in maize (*Zea mays*) at harvest as well as plant biometric parameters.

Microbial inoculation can bring changes in Microbial Biomass P (MBP) values and it plays an important role in increasing the source of P for plants. It was [9] reported in mustard crop grown with PSF seed inoculation @ 5.302 g kg^{-1} seed and seed inoculation @ 10.604 g kg^{-1} seed that with two dosage levels of P @ 50% and 100% P of RDF the MBP values had become significantly higher after 60 days of incubation. However, at harvest of the crop only PSF seed inoculation @ 5.302 g/kg seed+ 100% P ha^{-1} could maintain its relatively high MBP values, at till the 120^{th} day of inoculation. It was [56] also observed the same results with Chickpea (*Cicer arietinum*), where they used *Bacillus megaterium* as the inoculant and recorded response on MBP values after 30 days of crop growth. Whatever the results [9] reported that, the MBP values for wheat crop were much higher than mustard crop. The variation in MBP values may be attributed to rate of fungal application on specific crop seeds and higher the rate of fungal based product application, more were the recorded MBP values. Availability of soluble P during initial stages of crop growth helped in microbial proliferation leading to assimilation of P by microbial biomass.

From these studies it can be stated that our efforts should be towards the basic management of P for which we have to focus on the ambient or fixed P to dissolve in the soil solution and also to overcome the fixation of applied P-fertilizer by using modified fertilizers and also to optimise the number of splits as per the specific requirement of the crops. Both the options are known and feasible as microorganisms play a vital role in releasing inorganic P from both organic and inorganic P sources present in soil or added exogenously [9].

Soil Phosphorus Fractionation

Over the years a number of P extraction techniques have been employed to obtain soil inorganic and organic P. Among them the relatively easier and more widely used methods are extraction of P with the help of either water or bicarbonates. Fractionation method of inorganic P used in agriculture laboratories nowadays mostly follows the technique fashioned by [57], which itself is a modification over the P-fractionation scheme of [58].

The techniques usually in practice in this regard are: 1. Extraction P in solution by shaking 1 g soil in 30 ml of 0.05M Calcium Chloride ($CaCl_2$) for 16 h followed by centrifugation, filtration and estimation of P in the filtrate; 2. Obtaining Sodium bicarbonate bound P or $NaHCO_3$-P, by shaking the residue obtained from method 1 in 30 ml of

0.5M $NaHCO_3$ for 16 h, followed by centrifugation, filtration and estimation of P in the filtrate; 3. Procuring inorganic P in Sodium Hydroxide or NaOH-Pi by vigorous agitation of the residue from (2) in 30 ml of 0.1 M NaOH for 16 h, then centrifuging, filtering, and measuring P in the filtrate after acidifying with 5 ml concentrated hydrochloric acid (HCl); 4. Extraction of organic P by NaOH or NaOH-Po by digesting 5 ml of the filtrate from (3) in 6 ml of concentrated Sulfuric acid (H_2SO_4) for 1 h, followed by cooling and adding 5 ml of Hydrogen Peroxide (H_2O_2), and reheating until the residue becomes white. The P content is then determined in the digest and Po is obtained by subtracting the NaOH-Pi from it (according to [59]). Extraction of acidified P by shaking the residue from (3) in 30 ml of a 1:1 mixture of 1M HCl / 1M H_2SO_4 and measuring the P content in the filtrate following centrifugation and filtration, and 6. Obtaining of Residual P by refluxing the soil residue from (5) in 6 ml of a 5:2 mixture of concentrated Nitric acid (HNO_3) and Perchloric acid ($HClO_4$); here the P content is determined from the digest by adhering to the protocol of [59], an improvement to the original perchloric acid extraction process of [60].

The colorimetric estimation of P is the filtrate or digest is normally carried out by following the ascorbic acid method [61] with neutralization using dilute HCl and NaOH wherever necessary. The neutral pH is indicated by the slight yellowish color of the solution in the presence of a p-nitrophenol indicator. Absorbance of P is determined at a wavelength of 712 nm by using a UV-Vis spectrophotometer. The extraction of Pi in soils heavily fertilized with phosphate fertilizers favours the technique where P extraction takes place using $NaHCO_3$ compared to NaOH mediated extraction process. However, it was also observed in those same studies that concentration of Po extracted using bicarbonate was lowest in comparison to others [62, 63].

The water soluble P (W-P) showed a decrease in its content while the bicarbonate extractable inorganic P is found to increase with crop maturity. However, dose of fungal inoculation showed variability as far as the availability of W-P was concerned [57]. The inorganic P availability of the soil exhibited an increasing trend when seeds were inoculated with PSF compared with un-inoculated crop [9]. In a recent study by [64], decrease in W-P in mustard cultivated soil with crop maturity was observed which might be due to P sorption capacity of soil and P uptake by crop. It was observed that in mustard grown soil, $NaHCO_3$-P values increased consistently with higher rate of fungal based formulation. However, the peak $NaHCO_3$-P value of was registered in 100% P ha^{-1} but the values declined with increasing the rate of fungal inoculant by >2 fold in most of fungal inoculated treatments compared. Improved availability of $NaHCO_3$-P in PSF seed inoculation emphasized the role of phosphate dissolving fungal inoculants in mobilizing chemically fixed soil P [55]. The decline in P with crop growth underlined the P uptake by plants. However, NaOH-P was the most abundant fraction of P recorded in mustard grown soil and declined with crop maturity in all the treatments irrespective of the dose of added P. The Pi was found to be high with 30 kg P_2O_5 ha^{-1} as chemical P in combination with fungal inoculation compared to 60 kg P_2O_5 ha^{-1} coupled with subtle differences among fungal inoculations [56]. Contrarily, wheat grown soil registered much lower values for NaOH-P compared to mustard grown soil and showed the highest NaOH-P fraction. When ready availability of $NaHCO_3$-P in mustard grown fields was low, the NaOH-P was found in high concentration, only to be declining sharply with the rise in availability of the former. NaOH-P was not a static fraction in either mustard or wheat grown soil, rather it declined under cropping in spite of its ready availability being comparatively low than $NaHCO_3$-P. The decrease of the moderately labile P could be due to its transformation into labile P fractions followed by transportation by surface runoff.

Apart from the above discussed P fractions, there is one called 'mineral P' which can be extracted by HCl-P. In this method almost all types of inorganic P get extracted; even the normally recalcitrant ones or the ones that are not NaOH soluble P. It was [65] recorded that HCl-P represents the mineral P, since the Fe or Al-P that remains unreacted with NaOH is soluble in acid. This P is least available to plants. It was found [66] that HCl-P is increased by application of fertilizer-P. However contradictory results had previously been reported where P application had no discernible effect on HCl-P in Brazilian soil [67]. The most stable fraction of HCl-P was low in mustard grown soil compared to that in wheat grown soil and values increased with crop maturity. The increase in HCl-P indicated the presence of Ca-containing minerals. HCl-P may act as a buffer to available P in presence of fungal inoculants as it is mineralized P. The decline in HCl-P content under mustard soil might be due to conversion of HCl-P to an available P after application of highest rate of inoculated fungi where greater H^+ ions released through root activity could have helped helps in solubilizing the slowly soluble HCl-P and residual forms of P.

The distributions of different soil P fractions were observed to be influenced by both rates of chemical P added and fungal inocula. Some significant changes were illustrated in inorganic P fractions due to fungal inoculation. Accordingly, the Since W-P and SB-P are considered as the most available fraction, these, though analyzed separately were combined together as W-P+SB-P to determine the available P fraction. The relatively muffled increase in available P fraction of wheat grown soil towards maturity indicated the high P nutritional requirement of the crop. Re-distribution of soil P was reported to be either due to the solubilisation of inorganic P by microbial process in secretion of organic acids or mineralization of organic P present in soil. And it could also be due to conversion of soil P to microbial biomass P followed by subsequent release of P in soil on microbial lyses and decomposition.

Wetting and Drying Impact on Phosphorus Availability

The transformation of P from the biomass to soil solution is a three phase process. In the first phase, the P must be released from the microbial biomass to be available for transport, a form of mobilization known as solubilization [68] [69]. Then in the second phase the solubilised P is integrated within the soil with the aid of hydrological processes. Finally, in the third phase, the solubilised and mobilized P present in the soil gets transported from soil to the immediately superficial film of water or the water column [10]. The governing factors maintaining the P transformation phases are the degree, duration, and rate of drying–rewetting and freezing–thawing of the soil. However, there are other factors of both extrinsic and intrinsic nature that are equally significant in P transformation in alternating wet and dry soils. Most important intrinsic factors are soil structure, soil chemistry, soil type, vegetation status, and microbial spatial distribution and the extrinsic factors of more immediate importance are small scale hydrological features.

As a group these factors construct the discourse of hydropedology since water plays the most important role in the pedogenic processes as catalyst within soil and also as solute transporter. Not only the availability of the P is influenced by the rewetting of a dried soil but also the extent of P leached from the soil gets determined. It had [10] attributed the differences in P concentrations in leachate caused by the different rates of rewetting largely to the ability and chance of the existing viable microbes to recycle the solubilised P, which would increase with rewetting time. Chances for plants to get solubilised P become higher with longer rewetting and thawing rates due to increased residence time of microbially derived P in the soil prior to being leached. In addition, the rate of rewetting and leachate flow initiation also affect the ability of the soil to absorb any released P, a factor which gets affected by the soil chemistry and the chemistry of the P compounds being mobilized.

Most of the work in this regard focus on the ability of microbes to release mineral P by producing organic acids, which either reduce the pH of the soil and directly dissolve the mineral P, or cause chelation of iron and aluminium ions associated with P, at the same time rendering the mineral P available to plants. However, very few studies recognize the use of non-P-solubilising soil bacteria as biofertilizers due to their ability to assimilate and subsequently release P upon their demise. Phosphate is readily adsorbed on soil and so it is considered immobile. However, many organic P compounds such as sugar phosphates and phosphate diesters have weak sorption capacity and are therefore more likely to leach, although higher order inositol phosphates are strongly retained in soils. Intrinsic factors such as the death of microbes contribute to the rise in P content in the soil due to desiccation upon the loss of ambient moisture and lyses of cell caused by osmotic shock upon rewetting. These help release the biomass associated nutrients in the soil [70]. It has also been well documented that the concentration of released Po into soil solution following a dewatering and drying period were higher than Pi [71-74]. However, as soil microbes and higher plants compete for the same P resources, enhanced assimilation of P through microbial activities underlines the ephemeral benefits to plants through greater availability of P in sequentially dried and wetted soils [75]. Under waterlogged anaerobic conditions, rates of microbial turnover and mineralisation are very low compared to aerobic ones. This in turn leads to a reduced rate of nutrients mineralization, which directly affects the availability of nutrients such as P to plants [76]. Intermittent irrigation followed by spell of dryness actually allows the soil to become less anaerobic and considerably aerobic thus facilitating mineralisation as well as P availability.

Constant application of different phosphatic fertilizers for a longer period of time apparently seems to increase Olsen's available P, except in the case of rock phosphate addition [77]. Along with this, it was reported that maximum available P was found with DAP application followed by UAP, SSP, nitrophosphate and least amount was found in the rock phosphate application. It was also observed that water soluble source figured superior results over the source which is insoluble in water. After estimation of fractions of phosphorus from soil, Ca-P was found to be dominant fraction in the inorganic-P followed by aluminium bound phosphate, iron bound phosphate and Saloid-P, respectively. All types of sources were responsible for the increment in the Ca-P fraction of the total inorganic P but Al-P fraction was found highest with SSP, followed by DAP and in case of Fe-P fraction, DAP was found highest followed by UAP then SSP and least in the rock phosphate. Dominance of Ca-P in calcareous soil may be attributed to the presence of the higher amounts of exchangeable and soluble Ca-phosphates. The findings showed that the Ca-P fraction is the major fraction observed in all types of P sources and need to be studied more to understand the solubilisation of fractions of inorganic P present in the soil to increase bioavailable P to crops.

Conclusion

Phosphorus is one of the most important non-substitutable macronutrients for plants. Almost all the phosphorus applied to agriculture comes from mined rock phosphates, but this source is non-renewable. With increasing demand for food and need for food security, the time has come to venture onto avenues that enable us to increase the phosphorus yield as well as its availability to crop plants of various ecoregion. This is even more of a necessity in countries like India as she is the second most populous nation in the world and majority of her agricultural lands are poor in naturally available phosphorus reserves. Laterites dominate the Indian agricultural landscapes and they are acidic in nature; moreover it has been shown many a times that these soils possess high P-fixing capacities. Most of the water-soluble P added to such soils is transformed into relatively insoluble inorganic compounds of phosphates of Ca, Al and Fe thus it reduces the available P immediately. It is quite obvious that only solubility of phosphorus is not enough in this context, as process like mobilization and transformation of soluble P into the soil solution has to be focused because excessive and concomitant application of inorganic phosphorus enriched fertilizers have been documented to slowly but surely increase Fe-P, AI-P and Ca-P as compare to the non-fertilized soils.

Earthworms were observed to facilitate in increased activities of acid phosphatase, alkaline phosphatase, phosphodiesterases, pyrophosphatases and dehydrogenases due to greater microbial explosion, greater enzyme creation and accumulation in the soil surrounding substance which help in dissolution into the bioavailable forms from the bound phosphorus. Silica application has made known capable increase in phosphorus availability in the soil. The plenty of inorganic phosphorus (P) fractions in air dry soils was found in most of the soil type in the sequence of descending order Ca-P > Al-P > Fe-P > reductant soluble-P > saloid-P and under submerged soil conditions the trend was quite interchanged in case of iron and aluminium phosphate which is as follows Ca-P > Fe-P > Al-P > reductant soluble-P > saloid-P based on studies across various crop fields of India. Iron-bound phosphate was found to be the most important contributory inorganic P fraction to phosphate nutrition of rice, followed by Al-P fraction. Microbial inoculations, usually bacteria and fungi, have been observed to play important role in increasing the source of P for plants as sole application or in conjunction with inorganic/organic phosphorus sources with no significant loss in their efficacies as phosphorus liberators throughout a cropping cycle. Even in their deaths, they have shown to increase the contents of phosphorus for future crops in otherwise phosphorus poor soils.

The objective of the present review is to look at the scenario and constraints faced in agriculture regarding the dearth in bioavailability and to highlight possible mitigative measures through modification of fertilization techniques and resources and at the end it can be said that the report has delivered so and has the potential to be of use to relevant workers.

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