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Strategies to Improve Phosphorus Availability in A Sustainable Agricultural System

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Abstract:-Phosphorus (P) limitation is a key challenge for crop productivity in major parts of the world, as P is least mobile and highly fixated in soil. To circumvent phosphorus deficiency, chemical fertilizers are used; however these are rapidly absorbed in the soil and not accessible for crops creating a need for more P fertilizer. Moreover, substantial amount of P is lost through runoffs and contributing to eutrophication is water bodies. Globally P is mined from geological sediments, and these non-renewable resources are being used up at an alarming rate and projected to become relatively a scare resource in the near future. Such a scenario is a threat to sustainable crop production around the world. Therefore, there is a necessity for efficient and well managed use of P in agricultural system. This review is an effort to provide a summary of strategies that can be employed to improve P availability in soil to plants. Agronomic interventions like band placement of fertilizers, conservation tillage and use of cover crops improves P use efficiencies in farming systems. Soil P management options like organic amendments and composting increases bioavailability of P. Soil microbes can also play an significant role in supplying P to plants in a sustainable and eco-friendly way. Finally, use of crops or crop genotype having necessary traits that aids improved performance under P stress is an alternative option for sustainable crop production.

Keywords*:- *Phosphorus, Sustainability, Efficiency, Management, Agronomic, P-efficient cultivars.

I. PHOSPHORUS AS A MAJOR PLANT NUTRIENT

Phosphorus (P), next to nitrogen, is the second most important macronutrient that significantly affects plant development and metabolism [1]. Phosphorus plays a vital part in a multitude of life processes, including photosynthesis, respiration, energy generation, nitrogen (N) fixation, nucleic acid synthesis, membrane synthesis and stability, glycolysis, carbohydrate metabolism, membrane synthesis and stability, cell-signaling, enzyme activation/inactivation and redox reactions [2], [3]. Balanced phosphorus nutrition improves many aspects of plant development including flowering, fruiting, shoot growth and root growth[4], [5].

II. PHOSPHORUS BIOAVAILABILITY IN THE SOIL

P is rather scarce in the biosphere: at 1180 ppm, it is eleventh place in the lithosphere, and at a mere 70 ppb, its thirteenth place in sea-water [6]. P is quite abundant in many soils, total P in the soils range between 200-430 mg/kg [7]. The soil P can broadly group into organic and inorganic form. The soil solution which is the major source of P for the plant roots contain P generally not higher than 10 µM in a favorable pH of 6.5, even in fertile soils [8], [9]. The level of inorganic phosphate (orthophosphate; Pi),the only form of P that is bio-available to the plants, is largely not available for uptake by the plant roots due to unique properties of P –slow diffusion rate at plant-soil interface and high chemical fixation in soils [10], [11]. P is an active element and thus has strong tendency to forms insoluble complexes with cation such as Al and Fein low pH soil and with Ca and Mg in high pH soil conditions condition [12], [13].

The organic form of P, mainly present as phytate, may account for more than 50% of total P in many soils [15]. These forms cannot be directly used by the plants. Phytate must first be converted to mineral P form which then can contribute to overall Pi pool. Further the availability of Pi to the plants is determined by the phosphate sorption isotherm for that soil. Due to multiple biogeochemical factors, plant roots are exposed to quite low Pi concentration in soil solution [16].

The fraction of bio-available P and its concentration in the soil solution is usually unable to fulfill the normal crop requirements in an intensive agricultural system [17]. The quantity of P present in the soil solution represents only a small fraction of plant needs, and the remainder must be obtained from the solid phase by a combination of abiotic and biotic processes. The processes involved in soil P transformation are precipitation-dissolution and adsorption-desorption which control the abiotic transfer of P between the solid phase and soil solution, and biological immobilization-mineralization processes that control the transformations of P between inorganic and organic forms [9]. So, phosphate deficiency is one of the major factors limiting plant growth and productivity in many agricultural ecosystems [18]. It is estimated that around 70% of the global land, including acidic and alkaline, appropriated for agriculture suffers from P deficiency. This has severely limited crop output by more than 30 – 40% [19].

Phosphorus deficiency is usually overcome by the use of inorganic fertilizer, and rock phosphate is the key constituent in its production. Crop production remains highly reliant on the use of P fertilizers derived from rock phosphate. There is an ever increasing demand of these finite sources and it is estimated that at current rate of consumption global reserves of rock phosphate may be exhausted within 50–100 years [20]. Thus, rock phosphate is the backbone of our current global food and feed production and its continuous and reliable supply is vital for international security,but there has been a growing concern among concerned stakeholders for more sustainable and fair use of P resources in agriculture. More importantly, there has been consensus to increase the efficiency with which P fertilizers are used in farms [20], [21].

However, even when P fertilizers are added to the soil to improve soil fertility, about 70–90% of the P fertilizers is quickly adsorbed in the soil matrix and becomes chemically ‘fixed’ as various soil P compounds of low solubility thus significantly contributing little to crop production [22], [23]. This suggests that soil P fertilization alone is not a viable strategy to improve crop productivity in many P deficient soils [24]. Also, the continuous and careless use of inorganic chemical P fertilizers, eventually leads to the degradation of soil fertility by disrupting microbial diversity, and therefore reducing crop productivity [25].

In many developing countries, P fertilizer use is little compared to developed countries because it is still expensive input [26], and there is an imperative necessity to improve the conditions of agricultural farms so that high productivity can achieved even in conditions with limited P availability [27]. Even under a well-organized P fertilization arrangement, plant roots do not acquire more than 30% of the applied P, and the rest is lost due to fixation in the soil, microbial activity and erosion. This situation has led to the overuse of P fertilizers, which coupled with overuse of nitrogen fertilizer, has resulted in the enrichment of water bodies with nutrients and thus resulted in severe eutrophication and toxic algal blooms threatening loss of biodiversity in large scale [28], [29].

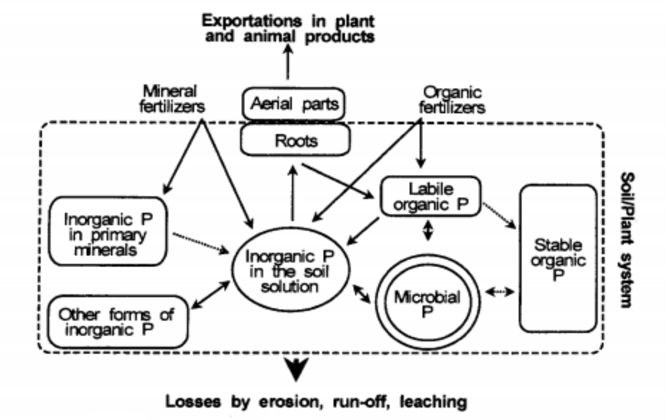

Fig 1:- The soil P cycle (adapted from [14])

So, the problem of phosphorus management is a multifaceted. So any approach to increase P-use efficiency in agricultural system must address the necessity to decrease the rates of P-loss, erosion or accumulation, if significant changes are be realized in the efficiency with which dwindling P resources are used. Throughout this review, strategies to improve P availability in a sustainable agricultural system are highlighted.

III. STRATEGIES TO IMPROVE PHOSPHORUS AVAILABILITY TO PLANTS

A number of strategies have been documented to improve the phosphorus availability in soils including, (A) Agronomic practices, (B) Organic amendments (C) Composting (D) Arbuscular mycorrhizal fungi (E) Phosphate solubilizing microbes and (F) P efficient cultivars.

A. Agronomic practices

Nutrient use efficiency and nutrition uptake could be improved by means of good agronomic practices which can decrease the accumulation of nutrients in the soil and thus improving its bio-availability [11]. Agronomic practices can decrease phosphorus fixation in soils and enhance the phosphorus availability [30]. A number of agronomic practices have shown to greatly improve on efficient use of P fertilizers on agricultural farms [31], [32].

- *For Band Placement of Fertilizers*

Fertilizer application method influences the speciation of P fertilizer reaction product [33]. Band placement of phosphorus fertilizers is a better agronomic strategy to keep phosphorus available for plants. When phosphatic fertilizers are randomly broadcasted on soil surface or mixed with soil, it interacts with more soil elements and immediately transformed to insoluble complexes with calcium fraction of calcareous soils [11], [34]. Applying P fertilizers in band placements is more effective in decreasing P-fixation and thus improving the efficiency of fertilizers in P fixing soils. Band placement causes significant drop in the volume of interaction between the soil and fertilizer thus decreasing the P fixation [35]. Band placement ensures P fertilizer is in accessible form for extended time period and thus P-up take is improved. Increased crop yield and P accumulation in the plant tissues are reported in canola [36], wheat [37], [38] with band placement as compared with broadcast method of P application. Greater efficiency of band placement of fertilizer use has been credited to placement of P fertilizer in soil at a location where contact of P with active roots of the crop plant is possible. The band placement increases the probability of root surface to be in immediate vicinity with the fertilizer which is more important than improved P availability [39].

Deep–banding methods, placing fertilzers deep below the soil surface, are suggested for cereal crops grown on soils in alkaline calcareous soil with heavier texture and overall rainfall in the growing season is lower. Banding below the seed allows emerging radicle and seminal roots to be in immediate contact with the fertilizer [40]. The band placement of P fertilizer in or immediate the seed-row and maintenance of soil levels of P through long-term fertilizer supervision are among the management practices that can be implemented to increase P nutrition in agricultural system. [41], [42].

- *Conservation Tillage Practices and Use of Cover Crops*

Conservation tillage practices and the use of cover crops are promoted as best agricultural practices to conserve P. Conservation tillage maintains a minimum of 30% crop residue on the field and includes no till or minimal tillage methods [43]. Conventional tillage practices of mixing of surface and subsurface soil increase P adsorption [44], [45]. Conservation tillage encompasses methods of incorporating into the soil all crop residues that remain following harvest. These practices have been found to lower overall P losses, compared to conventional tillage practices [43], [44]. Conservation tillage practices offer many benefits to a farm field including; reduced soil erosion and particulate bound P export by decreasing the volume of surface runoff [46], [47].

Cover crops can increase nutrient use efficiency and reduce nutrient loss from leaching and erosion. Cover crops enhances the total root volume in agricultural system, thus increasing the surface area by which nutrients are absorbed and the total volume of plant root exudates [48]. Cover crops release rhizo-deposits such as carboxylates, allowing uptake of soil P that is not accessible to other plants [49]. Integration of P-mobilizing plant species as cover crop or intercrop or in rotation is also most promising approach. Cover crop usually utilize soil P fraction that is not accessible to the main crop, thus minimizing competition for plant-available P. There is good evidence that some plant species such as Lupinus albuspossess a remarkable ability to solubilize sparingly soluble soil P [30], [50]. The cover cropped soils also shows enhanced uptake of P thorough higher rates of root colonization by mycorrhizal fungi [51].

B. Organic Amendments

Organic amendments are known to improve soil fertility. Many soil characteristics such as pH, electrical conductivity, organic content and humus fraction greatly improve upon addition of organic amendments [52], [53]. The issue of P limitation can possibly be resolved by the gradual addition of organic amendments to soil; however, the quantity, quality and management of this practice are fundamental factors that affect P availability [54]. The addition of organic residues can improve soil conditions thus improving the overall plant available P [55]. Organic amendments gradually convert native chemically fixed soil P to chemical forms which are more available after decomposition [56]. This process is accompanied by liberation of CO_2, which in soil solution readily converts into H_2CO_3. The resulting weak acid further facilitates the dissolution of primary P-containing minerals present in the soil [57]. Organic acids released during microbial decomposition also assists to release soil mineral P. In soils with high P-fixing capacities; organic compounds formed during decomposition processes may improve P availability by covering P adsorption sites or via anion exchange. Organic matter also contains large quantities of organic P and upon mineralization; Pi is released into the soil solution [53].

Organic amendments such as farmyard manure (FYM) increase microbial load and thus increasing microbial activities in soils [58]. Soil microbe’s actions diverse source of organic waste matter, decompose it and produce many organic acids [59]. Microbes also assist in mineralization of organic matter thereby slowly releasing nutrients to crop [60]. Repeated incorporation of green manures has shown to improve many soil physical parameters that positively influence plant growth such as decrease in soil bulk density, increase in soil compactness and moisture holding capacity. Positive changes in soil physical properties further help to increase P uptake by facilitating root spread in the soil and increasing mycorrhizal growth [61], [62].

Inorganic fertilizer can be combined with organic amendments to increase the crop production and reduce thus reliance on the external outputs. Use of inorganic P fertilizer in combination with FYM is found effective in augmenting the efficiency of inorganic P fertilizers by reducing P fixation soil, promoting its bioavailability in the soil and making it available in the soil for longer time period [63]. Rock phosphate has low solubility in neutral and alkaline soils [64] whereas its solubility is higher in acidic soils [65]. Solubility of rock phosphate can be increased by co-composting rock phosphate with organic amendments such as manure or plant residue [66], [67]. This increase in bio available P in rock phosphate can be explained by the release of organic acids during decomposition of organic materials [68].

C. Composting

Composted organic waste materials are known for increasing crop productivity compared to raw ones as they greatly improve soil physical, chemical and biological properties [69], [70]. During compost preparation, the raw organic matter undergoes physical, chemical and biological transformations, which result in greater proportions of stabilized organic matter. These stabilized organic matters decompose slowly releasing N and P to the soil [71], [72].

Composting is a better technique to increase bioavailable P and thus improve P nutrition from raw organic materials of diverse nature and sources. The process of composting is accompanied by substantial decrease in the natural rate of P conversion into insoluble inorganic compounds - Al-P, Fe-P and Ca-P. Soil organic component increases during composting process which facilitates increases in soil microbial activity and diversity. The fresh supply of humic material significantly increases the number of native bacterial communities residing in the soil and also millions are added. The exothermic nature of composting also facilitates establishment of diverse bacterial habitat. All these microbial communities feast on organic matter thus decomposing them. This decomposition process releases organic acids. Some of these organic acids assist in improving symbiotic association with root colonizing fungi. Symbiotic associations with root colonizing fungi further assist by improving nutrition acquisition rate from the soil.

The process of composting also facilitates conversion of native insoluble P sources. During the process, CO2 is released, which chemically reacts with soil solution to form carbonic acid, resulting in dissolution of insoluble P minerals. All these physical, chemical and biological processes occurring simultaneously in the compost help to provide P nutrition to the growing plant in a sustainable manner [74].

D. Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (AMF) are abundant soil dwellers existing in close symbiotic associations with the root system of most plant species. AMF have a long evolutionary relationship with plants- more than 400 million years, and such long relationship has forged many beneficial effects. Many studies have confirmed the favorable role of the AMF symbiosis on plant P uptake. Increased AMF colonization with the host plant roots has repeatedly shown to increase nutritional uptake [75]. AMF play an important role in P modifications and increases its bio-availability in soils [76]. AMF seems more relevant pathway for P uptake in cereal plants such as wheat. AMF extending their fine hyphae, thus increasing the surface area exposed to the soil, aid in plant P uptake than is possible by the plants root system alone [75], [77]. The benefits of the symbiosis can be observed as either increase in total P uptake by the plant roots or increase in P concentrations in the plant tissues. The chief mechanism involved appears to be a spatial one, the AM hyphae tapping soluble P (and other nutrients) beyond the P-depletion zone that develops around root as they absorb P from the soil solution. There are also some evidences of AMF assisted decrease in soil pH thus favoring the mineralization of phytate (an organic P source) and consequently increased bio-availability of P for AMF uptake and subsequent transfer to their host plant [78]. Other influence of AMF towards plant P uptake is through increased activity of acid phosphatase enzymes [79]. The hyphae of AMF fungi store polyphosphates enzymes in their vacuoles. These enzymes can selectivity cleave P linked with organic phosphates and convert into inorganic form. This process occurs in arbuscules of AMF and transported as inorganic P into the host plant across the plasma membrane of cells. Furthermore, AMF plays more significant role in P nutrition under starvation condition, contributing up to 77% uptake compared to only 49% under high P supply [80].

E. Phosphate Solubilizing Bacteria

The accrued P in farm soils due to repeated use of inorganic P fertilizers is so much that it is estimated to sustain the crop production with maximum yield for about 100 years [81]. Soil microorganisms have the potential to utilize these resources as they have the unique trait to convert insoluble P sources to bioavailable form. Many rhizospheric microorganisms that inhabit at plant-soil interface have shown this ability and thus increase crop production [82]. Many strains of bacteria and fungi have been isolated from the soil and rhizospheric region, and their unique trait examined as studied under laboratory and field conditions [83]. Many of these microbes are isolated by traditional cultural techniques with species of Bacillusand Pseudomonas bacteria [84], and Penicillium andAs per gill us fungi being dominant [85]. These phosphate solubilizing microorganisms can be used as bio-fertilizer to circumvent phosphorus deficiency. In addition, many microbes involved in P solubilization also improve plant growth by improving the efficiency of biological nitrogen fixation, increasing the bio-availability of other trace elements such as Fe, Zn, etc. and by release of plant growth promoting substances [74]. As such these phosphate-solubilizing microorganisms (PSM) has great potential in supplying the need P to plants in a more sustainable and eco-friendly way [25].

Phosphate solubilizing microorganisms have many traits and by array of mechanisms assists in mineralization of nutrients including P which is released from organic matter and made available for plants. Some of these traits are production and release of organic acids, enzymes, hormones and biologically active substances. These PSM have been reported to influence nutrient uptake, plant growth and yield [86]. Additionally, P-uptake is also enhanced by release hormones and many biologically active substances which stimulate plant root growth [87]. Many mechanisms by which these PSM acts are discussed in details.

- *Phosphorus Solubilization through Organic Acids and Chelation:*

Many PSM, through direct mechanism, produce and release wide array of oranic acids. These acids help to solubilize the rock phosphate. These acids lowers the pH and facilitates P release. [88]. Organic acids like gluconate, oxalate, acetate, lactate, citrate, tartarate,ketogluconate, succinate, glycolate, etc. [25]. The production of organic acids by PSB has been well documented. These organic acids function by chelating mineral ions, and thus release P into solution [89]. The quantity and nature of the organic acid released by the microorganisms also affect P solubilizing ability. Phenolic acids and citric acids were found to be less effective than aliphatic acids in P solubilization. In many bacterial species, gluconic acid production was the major cause of mineral phosphate solubilization [90].

Gram negative bacteria are often most efficient mineral P solubilizers, and the principal mechanism involved is the release of organic acids. Gluconic acids and α-ketogluconic acid are the most responsible for inorganic phosphate solubilization [91]. In many reports, direct oxidation of glucose in the periplasm of Gram negative bacteria produced gluconic acid [92]. In the direct oxidation pathway of glucose, the enzyme glucose dehydrogenase and gluconate dehydrogenase orient to the outer face of the cytoplasmic membrane and are able to oxidize the substrate in the periplasmic space. As a result, the organic acids diffuse freely outside the cells releasing high quantities of soluble phosphate from mineral phosphates, by supplying both hydrogen ions and metal complexing organic acid anions [88] [93].

- *Mineralization of Organic Compounds:*

Organic P can constitute anything between 4–90% of the total soil P, thus it very important to release this locked organic P though mineralization process back into the soil [94]. Many soil microbes effectively releasing P from the organic pools by mineralization [95]. Microbes carry out mineralization of organic P through extracellular enzymes like phosphatases and phytases and slowly release nutrients to crop. The organic P compounds need to be degraded by microbes before the inorganic P is free and can be utilized by the plants. Environmental factors strongly influences microbial mineralization of organic P. Mild alkaline condition favors the mineralization process. Enzyme phytase is responsible for the mineralization of soil organic P by phytate degradation [96]. Another promising step involves mobilization of phytate to make it more accessible to the plant roots. The excretion of organic acid anions, citrate and to a lesser extend oxalate, seems to be an important way to make phytate P available to the plants.

Bacteria	Achromobacter sp., Aerobactor sp., Agrobacterium sp., Alcaligenes sp., Bacillus sp., Bradyrhizobium sp., Brevibacterium sp., Citrobacter sp., Erwinia sp., Flavobacterium sp., Nitrosomonas sp., Micrococcus sp., Nitrobacter sp., Pseudomonas sp., Nitrosomonas sp., Micrococcus sp., Nitrobacter sp., Rhizobium sp., Thiobacillus sp., Xanthomonas sp.
Fungi	Aspergillus sp., Candida sp., Cladosprium sp., Helminthosporium sp., Morteirella sp., Micromonospora sp., Oideodendron sp., Penicillium sp., Phoma sp., Pythium sp., Rhizopus sp., Mucor sp.,
Actinomycetes	Actinomyces,, Streptomyces
Cyanobacteria	Anabena sp., Calothrixbraunii, Nostoc sp., Scytonemasp

Table 1. Diversity of phosphate solubilizing microorganisms

Various non-specific acid phosphatases released by phosphate solubilizing microbes hydrolyze organic P to inorganic forms [97]. One of the major enzyme in the mineralization of organic-P in soil is acid phosphatases. Increases in rhizospheric pH and production of the organic acids which are competing for sorption sites are some of the mechansims which solubility of organic P is increased [98]. Rhizosphere phosphatases play an important role in the release of P from organic soil P, for subsequent uptake by plants [99].

F. *Phsophorus Efficient Cultivars*

P efficiency is a genetic trait of plant species or cultivars to have the ability to yield maximum even under P-limiting condition [100]. In response to P limitation, it becomes imperative and some species and cultivars of plants to evolve with innovative ways to overcome such limitation and increasing the capacity of a plant to uptake more P even under limiting condition, and also to synthesize greater biomass per unit P taken up. The mechanisms that enhances plant P uptake efficiency include development of large and shallow root system [101], modification of root architecture [102], more root hairs and thinner roots [103], more secondary and tertiary root [104], increasing root exudates (enzymes and chelators, low molecular weight organic acids, hydrogen ions) [105],expression of high affinity P transporters, and association with AMF [106] all of which contribute to improved P uptake efficiency of the plant. Enhancing the above morphological, physiological, biochemical, and molecular adaptation mechanisms expression in P limitation condition through conventional plant breeding and use of modern genetic engineering tools can lead to improved P use efficiency in crops.

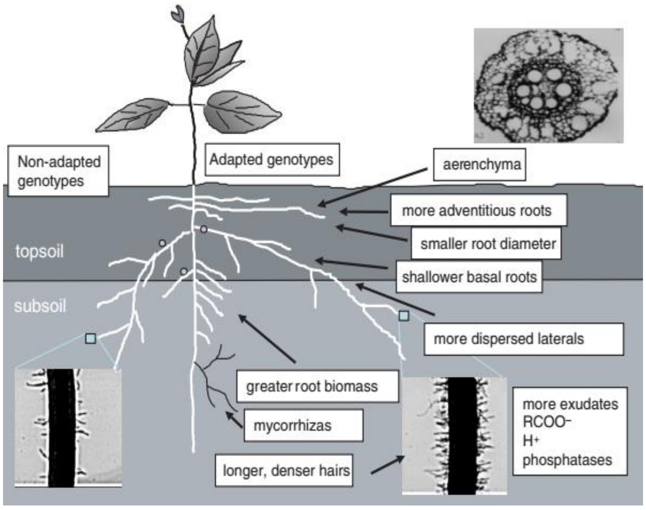

Fig 2. Root adaptations to low phosphorus availability [27]

The possibility of exploiting the genotypic difference in plants in absorption and utilization of P to increase efficiency of P fertilizer in farms has received great attention in recent years owing to scarcity of resources [107]. Phosphorus efficiency can be divided into P acquisition efficiency (PAE) and P utilization efficiency (PUE). PAE refers to the ability of plant to uptake P from soils, and PUE is associated with internal mechanism associated with conservable use of absorbed P at the cellular level. P efficiency in plants can be realized through increasing P acquisition and/or utilization [108], [109]. Plant roots play the dominant role in increasing P acquisition efficiency. The most significant traits are root architecture and morphological characteristics. A shallower root system with lateral root branching and lengthy root hairs may be advantageous for phosphorus acquisition by occupying huge soil volume [110]. Generally, P efficient cultivars show greater total biomass, higher root shoot ratio, increased rhizo-deposits and root hair density, surface scavenging lateral roots, and thinner root system under P deficient environment [101]. Acidification of the rhizosphere and the exudation of phosphatases and organic anions may also enhance P acquisition [48]. Nutrient uptake phenotype is a complex trait and is under the control of a multi-connected regulatory network linking many genes. The identification and exploiting such tightly regulated genes is a daunting challenge [111].

Hydroponic systems are nowadays routinely used in the study of plant nutrition as it allows the researcher to analyze and monitor the growth without disrupting the plant. It allows easy manipulation of the growing condition as temperature, pH, nutrient composition, and aeration. However, hydroponic system may have impact on general plant development; therefore pot trails and field experiments are still needed to validate the outcomes [112]. Pot trails and field trial are vital to consolidate our understand P use efficiency. After identification P efficient cultivars and the elite traits associated to it, one can apply modern molecular technique to further accelerate the breeding process [113].

IV. CONCLUSION

This paper outlines different strategies to overcome P deficiencies in agricultural systems. Modern intensive agricultural systems are relying too much on external outputs and non-renewable resource, and if significant improvements are not introduced to the way we presently use P resources, farms outputs will be surely suffer in near future. P scarcity is likely to have many undesirable effects related to food security and thus global peace and stability, and many smallholder farmers are more likely suffer in developing country. Therefore, better understanding of soil P and diverse interactions occurring at the soil and soil-plant interface is vital to preserve the natural P level in the soil such that agricultural yield and ecology is well taken care of. Extensive research is needed in various aspects of agricultural systems, and better strategies advanced to face the challenge of improving P nutrition of plants while increasing crop productivity in an ecological and sustainable way.

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