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Advances for Improving Phosphorus Use Efficiency in Agriculture

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

An impending crisis is the continuous availability of phosphate fertilizers, which underlie global food production. The rock phosphate deposits on which the world depends are not only finite but many are polluted and many are located in geopolitically unstable locations, implying that significant changes will be required to maintain food supply for an increasing global population. There is no single solution, but a combination of phosphorus management measures is required not just to extend the life of the remaining non-renewable rock phosphate sources, but also to result in a more efficient, sustainable phosphorus cycle. Improving the effectiveness of fertilizer applications to agricultural land, as well as a better understanding of phosphorus cycling in soil-plant systems and the interplay between soil physics, chemistry and biology in conjunction with plant characteristics are among the solutions. The finite nature of rock phosphate supply and the development of other sources of phosphorus fertilizers is unavoidable. There are clear prospects and it is now critical to prioritize a concerted effort to increase phosphorus usage efficiency.

Keywords: Soil nutrient; plant grow; fertigation; vertisols; fertilizers; grain yield; NPK.

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1. INTRODUCTION

Nutrient utilization efficiency (NUE) is a significant element in agricultural production system evaluation. Fertilizer management, as well as soil and plant water management, can have a significant impact. The goal of nutrient utilization is to improve ' overall performance of cropping systems by giving economically optimal nourishment to the crop while minimizing nutrient losses from the field. NUE addresses certain aspects of that performance but not all. As a result, system optimization objectives must incorporate both overall productivity and NUE.

Because of its numerous functional and structural roles in plants and soils, phosphorus (P) is an essential nutrient for plant growth and development. Plants absorb phosphorus as phosphate and anion from the soil solution. It is the least movable component. Because of its sluggish diffusion and high fixation in soils, P is difficult to make available to plants. A sufficient amount of soluble phosphatic fertilizer is applied to achieve maximum output. However, phosphatic fertilizers that are applied in soluble form quickly become unavailable to plants. The phosphorus requirement for optimal growth ranges from 0.3 to 0.5%.

When water-soluble P fertilizers are applied to the soil, P rapidly reacts with different soil components and becomes unavailable through precipitation, with dissolved irons, aluminum, manganese (in acid soil), or calcium (in alkaline soil) to form phosphate minerals by conversion into less soluble inorganic P fraction through fixation and retention. Desorption and dissolving reactions make the leftover portions available for future crops. Phosphorus becomes more difficult to release into soil solutions over time and as a result, the efficacy of P fertilizers in soil remains low.

2. RECENT APPROACHES FOR IMPROVING PHOSPHORUS USE EFFICIENCY IN SOIL - PLANT SYSTEMS

1. Doses and placement of phosphorus

Phosphorus application can be categorized into two primary methods: broadcast and band placement. Broadcasting involves applying fertilizer to the soil surface with or without subsequent incorporation. This method is the simplest and is ideal for high-speed operations and heavy application rates. When the fertilizer is ploughed or disked in, broadcasting ensures the most even distribution of phosphorus within the root zone and promotes increased root contact with phosphorus. It also enhances the interaction between the soil and fertilizer increasing the chances of fixation. On the other hand, band placement concentrates the fertilizer within narrow zones or bands that are maintained to provide a concentrated nutrient source. Banding is particularly beneficial in situations where soil test levels are low and there's a risk of early-season stress due to cool or wet conditions that might limit root growth and nutrient uptake. It's also advantageous for soils that tend to immobilize phosphorus in less available forms. Phosphorus can be banded before, during or after planting.

Band application of P increased the P content of the straw and grain, resulting in higher P uptake [1]. The advantage of band placement of P at higher P levels could be attributed to the fact that developing roots in band placement were in close contact with P-enriched soil near to fertilizer granules rather than broadcasted P and lower P levels. Nonetheless, owing to the little soil contect, there was adsorption in band placement over broadcast [2] [3] [4] [5].

The elevated PUE (Phosphorus Use Efficiency) observed with band placement of phosphorus as compared to broadcasting and top dressing can be attributed to the higher fixation of broadcasted phosphorus relative to that applied in bands. This fixation occurs because of the narrow soil-to-fertilizer ratio in the latter method. It's important to note that PUE is influenced by the ratio of soil to applied P [6][7]. Likewise, the higher PUE at lower P levels is likely the result of intense root competition, leading to the efficient utilization of the applied phosphorus. When P application rates are higher, plants tend to use a smaller proportion of the fertilizer P resulting in a lower PUE[8]. Significant increase in P concentration in wheat grains with higher P application rates to the soil. The total P uptake by wheat increased with increasing P fertilizer application[1][9].

2. Application of soil amendments

Alterations in soil acidity resulting from fertilization can have a significant impact on soil nutrient availability, plant growth and the overall functioning of the ecosystem. Soil acidification is indicative of the balance between acidic cations (H^+ and Al^{+3}) and base cations (Ca^{+2}, Mg^{+2}, K^+

Table 1. Recent approaches for improving phosphorus use efficiency in soil - plant system

Sr. No.	Approaches	Treatments	Crops	PUE (%)	References
1	Placement and Dose	Band placement	Wheat	Without FYM- 9.37 With FYM- 13.62	[1]
		150 kg/ha P_2O_5	Wheat	31.177	[8]
2	Soil amendments	NPKSCa	Wheat – maize cropping system	85.00	[10]
3	Fertigation	Fertigation	Maize	24.7	[17]
		RD of P through fertigation at 1st irrigation	Maize	17.00	[18]
4	Plant Strategies				
a	Root foraging strategies	At low P	Soybean genotype	-	[25]
b	Soil phosphorus mining strategies	Citric acid treatment		-	[29]
c	Transgenic approach	*ex::phyA-3* gene	Tobacco	-	[36]
		osavp1dox gene	Rice	-	[37]
5	Nano-fertilizers	ZnO Nanoparticles (1000µg) in pure culture		-	[40]
		Nano ZnO (10 ppm)	Clusterbean	-	[42]
		Nano ZP @ 100 %	Peanut	ARE of P - 32.90	[43]
6	Phosphate solubilizing micro-organism	100% RDP with PSF	Wheat	Total P uptake - 25.7 kg/ha	[44]
		20 kg P_2O_5 kg/ha + PSB + VAM	Mungbean	ARE of P - 12.49	[47]
7	Integrated nutrient management	FYM @ 10 t/ha under finger millet-groundnut rotation	Finger millet based cropping system	ARE of P - 18.85	[54]
8	Controlled release fertilizers	Polymer coated DAP at 50% rate of the recommended dose	Wheat	ARE of P - 55.76	[58]
		liquid paraffin coated products used in wheat field	Wheat	P release- 97.3 mg P /kg soil	[61]
9	Management practices	Interculture + Gliricidia cover + maize stover @ 20 kg P_2O_5/ha	Maize-chickpea cropping system	7.21	[63]

and Na^+) capable of neutralizing the acidic cations. This balance largely relies on the presence of exchangeable calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions. As the concentration of H+ ions increases, the levels of base cations decrease as ecosystems develop.

Soil acidification can lead to adverse effects, such as the depletion of essential base nutrients and increased solubility of aluminum (Al), iron (Fe) and manganese (Mn), which in turn can potentially cause toxicity in plants. Compared to fertilizer treatments without lime application and fertilizer with lime application considerably boosted P absorption and P usage efficiency (PUE) during different fertilisation years [10]. P uptake increased by 154%, 461%, 472%, 717%, 1168% and 1236% under NP, NPK, NPKS, NPCa, NPKCa and NPKSCa fertilisation treatments, respectively. PUE in the above treatments was 20.7 kg/kg, 66.2 kg/kg, 64.4 kg/kg, 105.1 kg/kg, 187.6 kg/kg, and 185.0 kg/kg on average during the years. The application of quicklime had a noteworthy impact on improving Phosphorus Use Efficiency (PUE) and crop yield. This was achieved by raising soil pH and increasing the presence of base cations, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}), while also reducing the levels of exchangeable aluminum (Al^{3+}). The most substantial increase in crop yield and PUE was observed in treatments involving the application of both NPK fertilizer and calcium (NPKCa) or NPK fertilizer with straw and calcium (NPKSCa). This improvement was attributed to the retention of soil organic carbon (SOC) by straw and the mitigation of soil acidification through liming. However, it's important to note that liming resulted in a decrease in the availability of soil phosphorus in the NPKCa treatment and the NPKSCa treatment when compared to the treatments involving only NPK fertilizer (NPK) and NPK with straw (NPKS), respectively.

3. Fertigation

P-Fertigation represents an innovative agricultural technique where nutrients in the form of a solution are introduced into irrigation water, enabling rapid delivery to the crop roots. This method serves as an efficient means of controlling the timing and precise placement of fertilizers leading to enhanced fertilizer utilization efficiency by reducing nutrient losses due to leaching and minimizing fixation of nutrients in the soil in less available forms. In essence when dry P fertilizer is applied to the soil surface, it tends to be used inefficiently resulting in excessive P fixation in the soil. This means that crops utilize less of the phosphorus, leading to increased production costs. This issue is particularly pronounced in regions where the soil has originated from volcanic ashes. P-Fertigation on the other hand involves the practice of injecting P fertilizers into the flowing water of an irrigation system offering a more efficient and effective way to deliver phosphorus to the crops.

Calcareous soil having high pH, [11] fertigation was superior to conventional soil P application. The fertigation as a more efficient method of nutrient management than broadcast method [12][13][14][15][16]. Phosphorus applied by fertigation resulted in improving the P efficiencies as compared to its soil mixing at sowing. When a lesser dose of nitrogen was combined with a full dose of P and delivered through fertigation, the P absorption was equal to that of a full dose of N and the same dose of P [13]. It demonstrates that crop benefitted the most from balanced P supply by fertigation. During three cropping seasons, P uptake by fertilisation was substantially higher than P uptake by broadcast technique [17]. Over the three crop seasons, fertigated applied P led to increases in mean P-uptake, agronomic efficiency, and P utilisation efficiency of 17, 65 and 90%, respectively, over broadcast technique. Fertigation had a P use efficiency of 24.70%, whereas broadcast application had a P use efficiency of 13.03%. These results demonstrated that fertigated P application outperformed the broadcast technique.

Phosphorus uptake by grain, stalk and total was greatest when the recommended dose of P was administered *via* fertigation rather than broadcast [18]. A low recovery of broadcasted phosphorus indicates a relatively high level of P fixation, where applied phosphates are transformed into less accessible forms due to the alkaline and calcareous nature of the soil [19]. Maize plants that received P in solution form during the initial irrigation had significantly higher phosphorus content compared to those that received P through broadcasting at sowing [20][16]. The increased Phosphorus Use Efficiency (PUE) observed at lower P levels can be attributed to strong root competition which results in the efficient utilization of applied P fertilizer. Fertigation offers several potential advantages, including enhanced fertilizer utilization efficiency, the flexibility to apply fertilizers at optimal times in line with crop demands, increased crop yield and improved produce quality.

4. Plant strategies

A) Root foraging strategies

Phosphorus use efficiency can be achieved in two main ways: (i) by enhancing P uptake efficiency which refers to the ability to maintain P uptake levels under suboptimal P availability conditions compared to optimal P availability, or (ii) by improving P utilization efficiency which involves using the acquired P for biomass production. Among these approaches, focusing on enhancing P uptake efficiency is considered the most promising [21]. Increased P uptake efficiency is linked to various root characteristics, including: (i) root growth and architecture, such as the root-to-shoot ratio, distribution among different root types and root angles; (ii) root morphology, which encompasses factors like root diameter, the development of root hairs and the presence of aerenchyma; (iii) processes in the rhizosphere, such as soil acidification, phosphatase activity and the release of organic acids; and (iv) symbiotic relationships with mycorrhizal fungi [21][22][23][24]. These root characteristics can result from either inherent features expressed regardless of environmental conditions or genotype-specific responses to the environment.

It was observed that when phosphorus levels were low, the soybean genotypes Namsoy4m and Nyala displayed the highest biomass accumulation and total phosphorus uptake while the Pan-872 genotype exhibited the lowest performance in these aspects [25]. Interestingly, when phosphorus levels were high, P utilization efficiency was lower for all genotypes but this decrease was not influenced by genotype. The variations in phosphorus uptake efficiency among these genotypes were predominantly associated with differences in the development of root hairs and to a lesser extent, the extent of colonization by mycorrhizal fungi. It's worth noting that the situation in field conditions may be more complex, as other root traits like root angles and branching could potentially impact phosphorus uptake in addition to the factors observed in this study.

B) Soil phosphorus mining strategies

Organic acids play a crucial role in soil chemistry, particularly in the mobilization of various phosphates in the soil. The significant impact of organic acid secretion (including compounds like citric, tartaric and oxalic acids) from plant roots [26][27]. This secretion serves as a major mechanism for enhancing phosphorus (P) availability in soils ultimately leading to improved crop yields. The presence of organic acids in the rhizosphere strongly influences the supply of P to plants [28]. This concept suggests that it might be feasible to replicate a plant's natural release of organic acids by artificially introducing acids into the soil. This could be especially beneficial in soils with low P levels, as it would enhance P availability. Organic acids have varying degrees of effectiveness in mobilizing P with citric acid being the most effective followed by tartaric acid and oxalic acid [29].

C) Transgenic approach

Phytases are enzymes that play a significant role in hydrolysing derivatives of inositol penta and hexakis phosphates. They are particularly interesting because phytate, a form of organic phosphorus, accounts for as much as 50% of the total organic phosphorus present in soil [30]. However, it's paradoxical that many plants have limited ability to directly acquire phosphorus from phytate when they are grown under controlled conditions. This limitation is primarily due to the low availability of phytate in soil, which occurs because of processes like sorption and precipitation reactions [31][32][33][34][35]. Additionally, the capacity of plants to exude phytase into the rhizosphere (the soil zone in the vicinity of plant roots) is restricted. In low phosphorus-absorbing growth media, such as agar or sand, plants can enhance their ability to utilize phosphorus from phytate when they are either inoculated with soil microorganisms possessing phytase activity or when purified phytase is added to the growth medium. This suggests that microorganisms and exogenous phytase can assist plants in accessing phosphorus from phytate in environments where it might otherwise be less available.

Tobacco plants were grown in soil that had been enriched with phytate. Transgenic plants that expressed the ex::phyA gene accumulated more phosphorus (P) in their shoots compared to control plants [36]. Specifically, the shoot biomass of the phyA-expressing line (ex::phyA-3) increased by 38% in comparison to control plants that were grown in soil collected from fertilized plots. Additionally, P accumulation in the transgenic plants expressing ex::phyA was significantly improved by 34% when compared to control plants in the same soil. This indicates that the genetic modification of plants to express ex::phyA led to an increased capacity for P accumulation in their shoots when phytate was present in the soil.

It was suggested that rice lines carrying the AVP1DOX gene (OsAVP1DOX) exhibited sustained shoot growth even under conditions of low phosphate (Pi) availability, specifically when Pi levels were at 10 µM, whereas the control plants grew poorly under these conditions [37]. Additionally, the AVP1DOX rice lines developed more robust root systems compared to the control plants, regardless of whether they were grown in Pi-sufficient or Pi-deficient conditions. This suggests that overexpressing AVP1 in both monocots and dicots leads to stronger root systems and an increased capacity for soil acidification under low Pi conditions. Importantly it also enhances the ability of crops to extract phosphorus under both Pi-deficient and Pi-sufficient conditions. The development of AVP1-transgenic corn with improved Pi uptake capabilities could potentially help mitigate the significant environmental impacts associated with the cultivation of this crop [38][39].

Nano-fertilizers: The impact of ZnO nanoparticles on the activity of phosphatases produced by two different fungi was demonstrated [40]. Aspergillus terreus CZR1 showed an increase in the secretion of both acid and alkaline phosphatase in the presence of ZnO nanoparticles. Aspergillus flavus CZR2 on the other hand exhibited a substantial increase of 50.8% in acid phosphatase activity and a remarkable 80.4% increase in alkaline phosphatase activity. Whether zinc was applied in the form of the normal oxide or in nano-scale oxide, it consistently led to higher levels of both acid and alkaline phosphatases. The increase in enzyme activity was more pronounced when ZnO nanoparticles were applied, and this effect was more prominent in Aspergillus terreus CZR1. It's worth noting that acid phosphatase production by both fungi was generally higher than alkaline phosphatase production.

Additionally, the study revealed that ZnO nanoparticles could significantly boost the secretion of extracellular polysaccharides by the fungi Aspergillus terreus CZR1 and Aspergillus flavus CZR2 by a substantial 8 to 9 times. The production of extracellular polysaccharides by industrial microorganisms is known to have a positive impact on enhancing the quality of the final product. Moreover, the presence of zinc (Zn) as a structural component in phosphorus (P)-mobilizing enzymes such as phosphatases and phytases led to the hypothesis that the application of nano ZnO may promote increased secretion of P-mobilizing enzymes. These enzymes play a crucial role in the mobilization of native phosphorus for plant nutrition from otherwise unavailable organic sources [41]. It was demonstrated that the activity of P nutrient-mobilizing enzymes, including phytase, acid phosphatase and alkaline phosphatase in the rhizosphere, was significantly increased when nano-ZnO was sprayed at a concentration of 10 mg/L on 2-week-old clusterbean plants, compared to ordinary-sized zinc oxide and control conditions [42]. This suggests that nano ZnO application can enhance the activity of P-mobilizing enzymes thus benefiting the availability of phosphorus for plant growth from organic sources.

The apparent recovery efficiency of phosphorus (P) at a 100% application rate was found to be 18.40% for soluble P (SP), 32.90% for nano zinc phosphate (NZP) and 23.70% for zinc phosphate (ZP). Interestingly, when only 50% of the recommended rate was applied from the nano source, the recovery efficiency was higher than when 100% of the ordinary source was used in both the first and second seasons [43]. This suggests that NZP can serve as a promising and cost-effective alternative source of phosphorus compared to other conventional sources. Consequently, using NZP could lead to a reduction in the quantity of applied fertilizers, which, in turn would contribute to increased profitability for farmers.

5. Phosphate solubilizing micro-organism

An increase in phosphorus (P) content in grain when phosphate-solubilizing fungi (PSF) were applied [44], but this increase was observed only when no additional P was added (0% P level). Interestingly, this increase in P content in grain was similar to that in cases where 50% of the recommended P was applied with no PSF. Furthermore, the study found that the total P uptake in both grains and straw was significantly higher in the presence of PSF compared to when PSF were not used but this effect was particularly pronounced at the 0% P level. On average, the use of PSF increased P uptake by approximately 11.6% under the 0% P treatment. This increase in P uptake with the application of PSF was likely due to the greater availability of P in the soil, facilitated by the solubilization of inorganic P fractions [45][46] and increases in P uptake in various crops when phosphate-solubilizing bacteria (PSB) were introduced.

Increasing the phosphorus level from 0 to 20 kg/ha resulted in the highest agronomic efficiency and apparent recovery of phosphorus [47]. However, beyond this point, as the phosphorus supply increased up to 60 kg/ha, there was a significant decline in these parameters. This suggests that an excessive supply of phosphorus may lead to the regulation of the starch/sucrose ratio in source leaves and reproductive organs. The positive effect of phosphorus on fruiting and the improved translocation of important metabolites to the parts of the plant contributing to yield could be responsible for the increased grain yield [48][49][50] in urdbean and [51] in mungbean. When seed and soil were both inoculated with phosphate-solubilizing bacteria (PSB) and vesicular-arbuscular mycorrhiza (VAM), they recorded significantly higher agronomic and apparent recovery efficiencies compared to other treatments. This enhanced efficiency is likely due to the increased solubilization and mineralization of organic phosphorus and the improved availability of nitrogen and phosphorus [52][53].

6. Integrated nutrient management practices

The relationship between grain yield and the total amount of phosphorus applied was examined and [54] found that the partial factor productivity of phosphorus (PFPP) was notably higher, ranging from 24.28 kg/kg in the case of finger millet mono-cropping to 110.50 kg/kg in finger millet-groundnut rotation. Agronomic efficiency and apparent recovery of phosphorus were also significantly higher in the finger millet-groundnut rotation system. In general, it was observed that phosphorus use efficiency was much higher when lower rates of phosphorus were applied and it decreased as the rate of nutrient application increased. Plots receiving organic inputs had lower levels of available phosphorus compared to those with integrated applications of manures and fertilizers. This could be attributed to the enhanced response and more efficient utilization of applied phosphorus by finger millet in the latter plots. Beyond a certain point, further phosphorus application became non-beneficial and uneconomical, as the plants absorbed a smaller proportion of the applied phosphorus, with the rest becoming fixed in the soil [55]. The study also noted that higher phosphorus use efficiency in the case of organically maintained treatments might be due to increased biomass production compared to the nutrient input supplied and improvements in soil physico-chemical and biological properties resulting from the use of organic farmyard manure (FYM) and rotational cropping [56][57].

Use of controlled release fertilizers: The agronomic and recovery efficiency of phosphorus (P) increased as the rates of polymer-coated DAP (Di-ammonium Phosphate) fertilizer decreased [58]. The highest increase in P agronomic efficiency was observed when polymer-coated DAP was used compared to uncoated DAP application. Similarly, the maximum recovery efficiency was achieved with polymer-coated DAP as opposed to uncoated DAP application [59][60]. This effect is likely due to the slower and gradual release of nutrients from coated fertilizers. Such controlled release can be beneficial by reducing the frequency of application and minimizing the negative effects associated with overuse of fertilizers.

In a study of polyvinyl alcohol-coated controlled-release rock phosphate fertilizers (CRRPFs) released a higher amount of phosphorus measuring 116.5 mg/kg, in comparison to the liquid paraffin-coated products, which released 97.3 mg P/kg of soil [61]. In contrast, uncoated commercial DAP (Diammonium Phosphate) released a considerably higher amount of P, with 326.9 mg P/kg of soil. This suggests that the choice of coating material for controlled-release fertilizers can significantly affect the release of nutrients, with polyvinyl alcohol-coated CRRPFs outperforming liquid paraffin-coated products in P release. The release of nutrients from controlled-release fertilizers can depend on soil type and moisture movement through porous materials [62]. The nutrient release from such fertilizers tends to be gradual and synchronized with the nutrient requirements of plants.

7. Effect of management practices

The highest phosphorus use efficiency (PUE) value of 7.21 kg/kg P_2O_5 applied was recorded under the MCP4 treatment, which involved intercropping, Gliricidia cover and maize stover in a cropping system [63]. Similar results were reported in a soybean-wheat system under Vertisols in Central India. Conversely, the lowest PUE value was recorded under MCP1, which was the control treatment with a value of 4.0 kg/kg P_2O_5 applied [64]. A comparison of PUE values across various moisture conservation practices (MCPs) for different P doses revealed that P_{20} had a higher PUE of 5.55 kg/kg P_2O_5 applied and this was statistically similar to the PUE under P_{40} doses (5.30 kg/kg P_2O_5) applied. The integration of moisture conservation practices along with proper root-enhancing phosphorus nutrition contributed to successful chickpea cultivation in a rainfed maize-chickpea system.

The maximum nitrogen and phosphorus uptake by wheat, measuring 107.4 and 25.58 kg/ha, respectively, was achieved with manual hoeing and the application of 150 kg of nitrogen and 100 kg of P_2O_5 per hectare (W4 x F2) [65]. Following closely was the post-emergence application of Isoproturon and carfentrazone ethyl with 150 kg of nitrogen and 100 kg of P_2O_5 per hectare (W3 x F2). The minimum nitrogen and phosphorus uptake by wheat was found in the weedy check with no fertilizer application (W1 x F0). Maximum fertilizer use efficiency was attained with the post-emergence application of Isoproturon and carfentrazone ethyl, and this was statistically similar to the results obtained with manual hoeing. The lowest fertilizer use efficiency was observed in the weedy check. As the fertilizer dose increased, nutrient uptake by both wheat and weeds increased. However, the increased nutrient losses due to higher weed uptake at higher fertilizer rates can be effectively mitigated through appropriate weed control practices. Among the various fertilizer doses and weed control practices, the combination of higher fertilizer rates and manual weed control resulted in the highest NPK use efficiency and grain yield, followed by the use of higher fertilizer doses. Therefore, achieving efficient fertilizer use can be accomplished through effective weed control practices. To achieve higher grain yield and better fertilizer use efficiency, it is essential to control weeds along with the use of higher fertilizer levels.

This review holds significant scientific relevance in the context of sustainable agriculture and food security. Phosphorus is an essential nutrient for plant growth and is commonly supplied to crops through fertilizers [66] [67]. However, inefficient phosphorus use in agriculture can lead to environmental problems, such as water pollution, and economic issues for farmers. By systematically summarizing the latest advancements in phosphorus use efficiency, this review can help bridge the gap between fundamental research and practical agricultural applications [68][69][70]. Understanding how to maximize the utilization of phosphorus in crop production not only improves agricultural productivity but also reduces the environmental footprint, a critical concern in modern agriculture [71][72][73]. Furthermore, as phosphorus reserves are finite and non-renewable, optimizing its use is pivotal for long-term food production sustainability.

In comparison to current studies on soil quality and productivity with artificial intelligence (AI) and machine learning (ML) algorithms, this review provides a specialized focus on a crucial aspect of nutrient management [74][75]. While AI and ML have become valuable tools for assessing soil quality and predicting crop yields, their application in optimizing phosphorus use efficiency is an area that requires greater attention [76][77]. Integrating the findings of this review with AI and ML models can provide a comprehensive approach to enhancing sustainable agriculture. By employing these advanced technologies, farmers and researchers can create precision agriculture strategies that not only consider soil quality and crop productivity but also the efficient use of essential nutrients like phosphorus [78][79]. This combination of expertise can lead to more environmentally friendly and economically viable agricultural practices, ultimately contributing to food security and the preservation of our natural resources ([80] [81].

3. CONCLUSION

From the forgoing discussion some agronomic practices like application of phosphorus through band placement with appropriate rate, application of soil amendment (lime in acid soil), fertigation, INM, nano fertilizers and CRF with some management practices *viz*; moisture conservation and weed management helped in improving PUE. Besides these, some plant strategies *viz*; root foraging, P mining and transgenic approaches enhanced P availability. Among all the approaches use of nano sources of fertilizers and CRF were found with highest PUE owing to the minimized the pollution hazard as well as slower and gradual release of P from coated fertilizers helped in term of reduced frequency of application and also minimized the negative effects associated with over dosage.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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