ADVANCES FOR IMPROVING PHOSPHORUS USE EFFICIENCY IN AGRICULTURE

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 fertilizersis unavoidable. There are clear prospects and it is now critical to prioritize a concerted effort to increase phosphorus usage efficiency.

Key word:soil nutrient, plant grow ,Fertigation, vertisols, fertilizers, Grain yield, NPK

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, phosphaticfertilizers 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.

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.

Rehim*et al.* (2010) discovered that band application of P increased the P content of the straw and grain, resulting in higher P uptake. 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

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	Rehim*et al.* (2011)
				With FYM- 13.62	
		150 kg/ha P_2O_5	Wheat	31.177	Ghafoor (2016)
2	Soil amendments	NPKSCa	Wheat – maize cropping system	85.00	Qaswar*et. al* (2020)
3	Fertigation	Fertigation	Maize	24.7	Iqbal*et al.* (2013)
		RD of P through fertigation at 1st irrigation	Maize	17.00	Javid*et al.* (2015)
4	Plant Strategies				
a	Root foraging strategies	At low P	Soybean genotype	-	Vandamme*et al.* (2012)
b	Soil phosphorus mining strategies	Citric acid treatment		-	Tsado*et al.* (2014)
c	Transgenic approach	*ex::phyA-3* gene	Tobacco	-	George *et al.* (2004)
		osavp1dox gene	Rice	-	Gaxiola*et al.* (2011)
5	Nano-fertilizers	ZnONanoparticles (1000µg) in pure culture		-	Tarafdar*et al.* (2012)

		Nano ZnO (10 ppm)	Clusterbean	-	Raliya and Tarafdar (2013)
		Nano ZP @ 100 %	Peanut	ARE of P - 32.90	Hagab*et al.* (2018)
6	Phosphate solubilizing micro-organism	100% RDP with PSF	Wheat	Total P uptake - 25.7 kg/ha	Ram *et al.* (2014)
		20 kg P_2O_5 kg/ha + PSB + VAM	Mungbean	ARE of P - 12.49	Yadav (2017)
7	Integrated nutrient management	FYM @ 10 t/ha under finger millet-groundnut rotation	Finger millet based cropping system	ARE of P - 18.85	Shilpa and Vasanthi (2021)
8	Controlled release fertilizers	Polymer coated DAP at 50% rate of the recommended dose	Wheat	ARE of P - 55.76	Sobia*et al.* (2017)
		liquid paraffin coated products used in wheat field	Wheat	P release- 97.3 mg P /kg soil	Sarkar*et al.* (2018)
9	Management practices	Interculture + Gliricidia cover + maize stover @ 20 kg P_2O_5/ha	Maize-chickpea cropping system	7.21	Chaudhary*et al.* (2018)

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. (Singh *et al*., 2000; Delong *et al*., 2001; Imtiaz*et al*., 2003 and Alam*et al*., 2003).

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 as indicated by studies such as those conducted by Sultani*et al*. in 2004 and Alam*et al*. in 2005.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. This observation aligns with the findings of Ghafoor in 2016, who noted a significant increase in P concentration in wheat grains with higher P application rates to the soil. These results are consistent with the findings of Rehim*et al*. in 2010 and Sushanta*et al.* in 2014, who reported that total P uptake by wheat increased with increasing P fertilizer application.

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^+ 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.Qaswar*et al*. (2020) 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. 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.

Papadopoulos (1994) reported that in calcareous soil having high pH, fertigation was superior to conventional soil P application. Alam*et al*. (1998), Latif and Iqbal (2001), Latif*et al*. (2002), Alam*et al.* (2003), and Hussein (2009) also demonstrated the fertigation as a more efficient method of nutrient management than broadcast method. Phosphorus applied by fertigation resulted in improving the P efficiencies as compared to its soil mixing at sowing. Latif*et al*. (2001) discovered that 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. 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 (Iqbal*et al*. (2013). 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.

Javid*et al.* (2015) discovered that phosphorus uptake by grain, stalk and total was greatest when the recommended dose of P was administered *via*fertigation rather than broadcast. As outlined by Memon*et al.* in 2011, 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. Similarly, studies by Latif*et al.* in 1997 and Hussein in 2009 revealed that 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. 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 as highlighted by Lynch in 2007.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. These factors have been extensively reviewed by researchers like Gahoonia and Nielsen in 2004, Lambers*et al.* in 2006, Lynch in 2007 and Ramaekers*et al.* in 2010. These root characteristics can result from either inherent features expressed regardless of environmental conditions or genotype-specific responses to the environment.

In a study conducted by Vandamme*et al.* in 2013, 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. 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. Research by Jones *et al*. in 2003 and Palomo*et al*. in 2006 highlighted the significant impact of organic acid secretion (including compounds like citric, tartaric and oxalic acids) from plant roots. 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, as noted by Hue *et al*. in 1994.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. According to a study by Tsado*et al.* in 2014, organic acids have varying degrees of effectiveness in mobilizing P with citric acid being the most effective followed by tartaric acid and oxalic acid.

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, as indicated by Turner *et al.* in 2002.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, as noted in studies by Hayes *et al*. in 2000, Richardson *et al*. in 2000 and 2001, Celi*et al*. in 2001 and Idriss*et al*. in 2002. 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.

In a study conducted by George *et al*. in 2005, 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. 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.

In a study by Gaxiola*et al*. in 2011, 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. 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, as noted by Diaz and Rosenberg in 2008 and Donner and Kucharik in 2008.

5. Nano-fertilizers

In a study by Tarafdar*et al.* in 2012, the impact of ZnO nanoparticles on the activity of phosphatases produced by two different fungi was demonstrated. Aspergillusterreus CZR1 showed an increase in the secretion of both acid and alkaline phosphatase in the presence of ZnO nanoparticles. Aspergillusflavus 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 Aspergillusterreus 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 Aspergillusterreus CZR1 and Aspergillusflavus 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 nanoZnO 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, as explained by Tarafdar and Claassen in 2003. In a study by Raliya and Tarafdar in 2013, 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. This suggests that nanoZnO application can enhance the activity of P-mobilizing enzymes thus benefiting the availability of phosphorus for plant growth from organic sources.

According to a study by Hagab*et al.* in 2018, 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. 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.

6. Phosphate solubilizing micro-organism

Ram *et al.* in 2015 conducted a study that demonstrated an increase in phosphorus (P) content in grain when phosphate-solubilizing fungi (PSF) were applied, 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.It's worth noting that other researchers, such as Rodríguez and Fraga in 1999 and Gulati*et al.* in 2007, have also reported similar increases in P uptake in various crops when phosphate-solubilizing bacteria (PSB) were introduced.

Yadav*et al.* in 2017 conducted an observation where they found that increasing the phosphorus level from 0 to 20 kg/ha resulted in the highest agronomic efficiency and apparent recovery of phosphorus. 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. These findings align with the results of earlier studies by Tanwar*et al.* in 2003, Rathore*et al.* in 2010 and Kumawat*et al.* in 2013 on urdbean, as well as Singh and Sekhon in 2007 on mungbean. When seed and soil were both inoculated with phosphate-solubilizing bacteria (PSB) and vesicular-arbuscularmycorrhiza (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, as explained by Kumar *et al.* in 2014.

7. Integrated nutrient management practices

In a study conducted by Shilpa and Vasanthi in 2021, the relationship between grain yield and the total amount of phosphorus applied was examined. They 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, as discussed by Chandrakala in 2014. 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. Similar findings were reported by Tarik and Mani in 2017 and Zhu *et al.* in 2012.

8. Use of controlled release fertilizers

Sobia*et al.* in 2017 found that the agronomic and recovery efficiency of phosphorus (P) increased as the rates of polymer-coated DAP (Di-ammonium Phosphate) fertilizer decreased. The highest increase in P agronomic efficiency was observed when polymer-coated DAP was used compared to uncoated DAP application. Similarly, Zahrani in 2000 and Hopkins *et al.* in 2008 reported that the maximum recovery efficiency was achieved with polymer-coated DAP as opposed to uncoated DAP application.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 by Sarkar*et al*. in 2018, it was observed that 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. 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. Gordon and Tindall, in their study in 2006, noted that the release of nutrients from controlled-release fertilizers can depend on soil type and moisture movement through porous materials. The nutrient release from such fertilizers tends to be gradual and synchronized with the nutrient requirements of plants

9. Effect of management practices

Chaudhary*et al.* in 2018 found that 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. Similar results were reported by Kushwah*et al.* in 2016 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_5applied.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_5applied 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.

Nadeem*et al.* in 2018 observed that 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_5per hectare (W4 x F2). Following closely was the post-emergence application of Isoproturon and carfentrazone ethyl with 150 kg of nitrogen and 100 kg of P_2O_5per 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 (Hernandez *et al.* 2020; Hernandez and Olivares, 2019). 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 (Olivares, 2016; Hernandez *et al*. 2018; Hernandez and Olivares, 2020). 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 (Araya-Alman*et al.* 2020; Campos 2023; Lobo *et al.* 2023). 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 (Rey *et al*. 2022; Olivares, 2023). 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 (Olivares *et al.* 2022a; Olivares 2022). 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 (Montenegro *et al.* 2021a; Olivares *et al.* 2022b). 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 (Montenegro *et al.* 2021b; Rodriguez *et al*. 2023).

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.

REFERENCE :

Alam, S. M., Iqbal, Z. and Latif, A. (1998).Comparison of Phosphate fertilizer application methods for berseem. In: Proceeding Symposium Plant Nutrition Management for Sustainable Agricultural Growth. pp. 239-241.Islamabad, Pakistan.

Alam, S. M., Shah, S. A. and Akhter, M. (2003). Varietal differences in wheat yield and phosphorus use efficiency as influenced by method of phosphorus application. *Songklanakarin J. Sci. Tech*., **25**(1): 175-181.

Alam, S. M., Shah, S. A. and Iqbal, M. M. (2003). Varietal differences in wheat yield and phosphorus use efficiency as influenced by method of phosphorus application. *Songklanakarin J. Sci. Technol*. **25**(2):175-81.

Alam, S. M., Shah, S. A. and Iqbal, M. M. (2005).Evaluation of method and time of fertilizer application for yield and optimum P-efficiency in wheat.*Songklanakarin J. Sci. Technology*,**27**(3): 457-463.

Araya-Alman, M., Olivares, B. and Acevedo-Opazo, C. (2020). Relationship Between Soil Properties and Banana Productivity in Venezuela's Two Main Cultivation Areas. *J Soil Sci Plant Nutr*.**20**(3): 2512-2524.

Campos, B.O. (2023). Fusarium Wilt of Bananas: A Threat to the Banana Production Systems in Venezuela. In: Banana Production in Venezuela. The Latin American Studies Book Series.Springer, Cham.

Celi, L., Presta, M., Ajomne-Marsen, F. and Barberis, E. (2001) Effects of pH and electrolyte on inositol hexaphosphate interaction with goethite.*Soil Sci. Soc. Am. J*. **65**(1): 753-760.

Chandrakala, M. (2014).Status and revalidation of phosphorus requirement for finger millet-maize cropping system in soils of Eastern Dry Zone of Karnataka, Ph.D. Thesis, University of Agricultural Sciences, Bangalore, Karnataka, India.

Chaudhary, R. S., Somasundaram, J., Mandal, K. G. and Hati, K. M. (2018).Enhancing water and phosphorus use efficiency through moisture conservation practices and optimum phosphorus application in rain fed maize–chickpea system in *vertisols* of central india. *Indian J Agric Res.***83**(6): 79-84.

Delong, R. E., Johnson, W. F. and Correll, M. D. (2001). Influence of phosphorus fertilizer on phosphorus uptakes and grain yields of wheat following rice. Research Services Arkan.*Agric. Expt. St*., pp. 480.

Diaz, R. J. and Rosenberg, R. (2008).Spreading dead zones and consequences for marine ecosystems.*Science*.**321**(2): 926–928.

Donner, S. D. and Kucharik, C. J. (2008). Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proc. Natl. Acad. Sci. USA*. **105**(1): 4513–4518.

Gahoonia, T. S. and Nielsen, N. E. (2004) Root traits as tools for creating phosphorus efficient crop varieties. *PlantSoil*.**260**(3):47–57.

Gaxiola, R. A., Edwards, M. and Elser, J. J. (2011).A transgenic approach to enhance phosphorus use efficiency in crops as part of a comprehensive strategy for sustainable agriculture.*Chemosphere*.**84**(2): 840–845.

George, T. S., Simpson, R. J., Hadobas, P. A. and Richardson, A. E. (2005). Blackwell Publishing, Ltd. Expression of a fungal phytase gene in Nicotianatabacum improves phosphorus nutrition of plants grown in amended soils. *Plant Biotechnol. J*.**3**(1): 129–140.

Ghafoor, A. M. R. (2016). Effect of Phosphorus Fertilizer Application on Some Yield Components of Wheat and Phosphorus Use Efficiency in Calcareous Soil.*J. Dyn. Agric. Res*.**3**(4): 46-52.

Gordon, W. B. and Tindall, T. A. (2006). Fluid P performance improved with polymers. *Fluid J*. **14**(2): 12–13.

Gulati, A., Rahi, P. and Vyas, P. (2007).Characterization of phosphatesolubilizing fluorescent Pseudomonas from the rhizosphere of seabuckthorn growing in the cold deserts of Himalayas.*Curr.Microbiol*.**56**(1): 73–79.

Hagab, R. H., Kotp, Y. H. and Eissa, D. (2018). Using nanotechnology for enhancing phosphorus fertilizer use efficiency of peanut bean grown in sandy soils. *J. Adv. Pharm. Educ. Res.* **8**(3):59-67.

Hayes, J. E., Simpson, R. J. and Richardson, A. E. (2000) The growth and phosphorus utilization of plants in sterile media when supplied with inositol hexaphosphate, glucose-1-phosphate or inorganic phosphate. *PlantSoil,* **220**(1): 165-174.

Hernandez, R., Olivares, B., Arias, A., Molina, J. C. and Pereira, Y. (2020). Eco-territorial adaptability of tomato crops for sustainable agricultural production in Carabobo, Venezuela. Idesia, **38**(2):95-102.

Hernández, R. and Olivares, B. (2019).Ecoterritorialsectorization for the sustainable agricultural production of potato (Solanumtuberosum L.) in Carabobo, Venezuela.*Agricultural Science and Technology*.**20**(2): 339-354.

Hernández, R., Olivares, B., Coelho, R., Molina, J. C. and Pereira, Y. (2018). Spatial analysis of the water index: an advance in the adoption of sustainable decisions in the agricultural territories of Carabobo, Venezuela. *RevistaGeográfica de América Central*.**60**(1): 277-299.

Hernández, R. and Olivares, B., (2020). Application of multivariate techniques in the agricultural land's aptitude in Carabobo, Venezuela.*Tropical and Subtropical Agroecosystems*, **23**(2):1-12.

Hopkins, B. G., Rosen, C. J. and Shiffler, A. K. (2008). Enhanced efficiency fertilizers for improved nutrient management: Potato (*Solanumtuberosum*) crop management. *Plant Management Network*.

Hue, N. V., Ikawa, H. and Silva, J. H. (1994).Increasing plant available phosphorus in an ultisol with yard waste compost.*Commun. Soil Sci. Plant Anal*. **25**(1): 3292-3303.

Hussein, A. H. A. (2009). Phosphorus use efficiency by two varieties of corn at different phosphorus fertilizer application rates. Res. *J. Appl. Sci*. **4**(2):85-93.

Idriss, E. E., Makarewicz, O., Farouk, A., Rosner, K., Greiner, R., Bochow, H., Richter, T. and Borriss, R. (2002) Extracellular phytase activity of Bacillus amyloloquefaciens FZB45 contributes to its plant-growth-promoting effect. *Microbiology*, **148**(3): 2097–2109.

Imtiaz, M., Shah, S. K. H., Khan, P., Saddiqui, S. H., Memon, M. Y. and Aslam, M. (2003).Response of wheat genotype "SI-91195" to increase N and P levels, and their ratios under agro-climatic conditions of Sindh.*Pak. J. Soil Sci.*,**22**(3): 58-63.

Iqbal, Z., Yaqub, M. Muhammad Akram, M. and Ahmad, R. (2013). Phosphorus fertigation: A technique for enhancing P fertilizer efficiency and yield of wheat and maize. *Soil Environ*. **32**(2): 146-151.

Javid, S., Majeed, A., Sial, R. A., Ahmad, Z. A., Niaz, A. and Muhmood, A. (2015). Effect of phosphorus fertigation on grain yield and phosphorus use efficiency by maize (*zea mays* L.) *J. Agric. Res*. 53(1).37-47.

Jones, D. L., Dennis, P. G., Owen, A. G. and VanHees, P. A. W. (2003).Organic acids behavior in soilsmisconceptions and knowledge gaps.*Plant Soil*.**248**(1): 31 – 41.

Kumar, S., Tomar, S. and Tomar, T. S. (2014).Integrated phosphorus management in blackgram (*Vignamungo*) in western utter pradesh during summer season.*Ann. Agric. Res*.**5**(3): 290- 297.

Kumawat, P. K., Tiwari, R. C., Golada, S. L., Garhwal, R. K. and Choudhary, R. (2013). Effect of phosphorus sources, levels and bio-fertilizers on yield attributes, yield and economics of blackgram (*Phaseolusmungo*) *Legume Res*.**36**(3): 70- 73.

Kushwah, S. S., Damodar-Reddy, D,,Somasundaram, J., Srivastava, S. and Khamparia, S. A. (2016). Crop residue retention and nutrient management practices on stratification of phosphorus and soil organic carbon under soybean-wheat system in *Vertisols* of Central India. *Commun Soil Sci Plant Anal*.**47**(21):2387–2395.

Lambers, H., Shane, M. W., Cramer, M. D., Pearse, S. J. and Veneklaas, E. J. (2006) Root structure and functioning for efficient acquisition of phosphorus: matching morphological and physiological traits. *Ann Bot.***98**(2):693–713.

Latif, A. and Iqbal, M. M. (2002).Fertigation techniques. In: Proc. of the workshop on "Technologies for Sustainable Agriculture", Sept. 24-26, 2001, NIAB, Faisalabad, Pakistan. pp.155-59.

Latif, A., Alam, S. M., Hamid, A. and Iqbal, Z. (1997). Relative efficiency of phosphorus applied through broadcast incorporation, top dressing and fertigation to crops. *Pak. J. Soil Sci.***13**(1):15-18.

Latif, A., Alam, S. M., Iqbal, Z. and Shah, S. A. (2001). Effect of fertigation applied nitrogen and phosphorus on yield and composition of maize. *Pak. J. Soil Sci*. **19**(2): 23-26.

Latif, A., Iqbal, Z., Ali, S. and Iqbal, M. M. (2002). Comparison of fertigation with farmer's practice for evaluating phosphorus fertilizer-use efficiency in maize.*Pak. J. Soil Sci*.**21**(1): 102-105.

Lynch, J. P. (2007) Roots of the Second Green Revolution. *Aust J Bot.***55**(2):493–512.

Lobo, D., Olivares, B., Rey, J. C., Vega, A. and Rueda-Calderón, A. (2023). Relationships between the Visual Evaluation of Soil Structure (VESS) and soil properties in agriculture: A meta-analysis. *Sci. Agropecu*, **14**(1):67-78.

Montenegro, E., Pitti, J. and Olivares, B. (2021a). Adaptation to climate change in indigenous food systems of the Teribe in Panama: a training based on CRISTAL 2.0. Luna Azul. **51**(2) :182 - 197.

Montenegro, E., Pitti, J. and Olivares, B. (2021b). Identificación de los principalescultivos de subsistenciadelTeribe: un estudio de casobasado en técnicasmultivariadas. Idesia.**39**(3): 83 - 94.

Memon, M. S., Shah, J. A., Khan, P., Aslam, M. and Depar, N. (2011). Effect of phosphorus fertigation in wheat on different soils varying in $CaCO_3$ levels.*Pak. J. Bot*. **43**(6):2911-2914.

Nadeem, M. A., Tanveer, A., Maqbool, R., Abbas, T. and Farooq, N. (2018).Efficacy evaluation of fertilizers and weed control practices to mitigate weat nutrient and yield losses.*PlantaDaninha*, **36**(1): 1806-1810.

Olivares, B. (2016). Description of soil management in agricultural production systems in the Hamaca de Anzoátegui sector, Venezuela.*La Granja: Revista de Ciencias de la Vida*.**23**(1): 14–24.

Olivares, B.O., Calero, J., Rey, J.C., Lobo, D., Landa, B. B. and Gómez, J. A. (2022a). Correlation of banana productivity levels and soil morphological properties using regularized optimal scaling regression. *Catena*, 208: 105718.

Olivares, B.O. (2023). Evaluation of the Incidence of Banana Wilt and its Relationship with Soil Properties. In: Banana Production in Venezuela. The Latin American Studies Book Series.Springer, Cham.

Olivares B. (2022). Machine Learning and the New Sustainable Agriculture: Applications in Banana Production Systems of Venezuela. *Agric. Res.* **42**(2): 133 - 157.

Olivares B, Vega A, Calderón, M. A. R., Rey, J. C., Lobo, D., Gómez, J. A., Landa, B. B. (2022b). Identification of Soil Properties Associated with the Incidence of Banana Wilt Using Supervised Methods. *Plants*, **11**(15):2070.

Palomo, L., Claassen, N. and Jones, D. L. (2006).Differential mobilization of P in the maize rhizosphere by citric acid and potassium citrate.*Soil Biol. Biochem*. **38**(3): 683-692.

Papadopoulos, I. (1994). Use of labeled fertilizers in fertigation research. In: Proc. of an international symposium on nuclear and related techniques in soil-plant studies. October 17-21. p. 399-410. Vienna, Austria.

Qaswar, M., Dongchu, Li., Jing, H., Tianfu, H., Ahmed, W., Abbas, M., Lu, Z., Jiangxue, D., Khan, Z. H., Ullah, S., Huimin, Z. and Boren, W. (2020). Interaction of liming and long-term fertilization increased crop yield and phosphorus use efficiency (PUE) through mediating exchangeable cations in acidic soil under wheat–maize cropping system. *Scientifc Reports*.10:19828.

Raliya, R. and Tarafdar, J. C. (2013).ZnO Nanoparticle Biosynthesis and Its Effect on Phosphorous-Mobilizing Enzyme Secretion and Gum Contents in Clusterbean (*Cyamopsistetragonoloba* L.).*Agric Res*. **2**(1):48–57.

Ram, H., Malik, S. S., Dhaliwal, S. S., Kumar, B. and Singh, Y. (2015). Growth and productivity of wheat affected by phosphorussolubilizing fungi and phosphorus levels. *Plant Soil Environ*. **61**(3): 122–126.

Ramaekers, L., Remans, R., Rao, I. M., Blair, M. W. and Vanderleyden, J. (2010) Strategies for improving phosphorus acquisition efficiency of crop plants. *Field Crop Res*. **117**(2):169– 176.

Rathore, D. S., Purohit, H. S. and Yadav, B. L. (2010). Integrated phosphorus management on yield and nutrient uptake of urdbean under rainfed conditions of Southern Rajasthan, *J. Food Legumes*, **23**(2): 128-137.

Rehim, A., Ranjha, A. M., Rahamtullah, and Waraich, E. A. (2010).Effect of phosphorus application and irrigation scheduling on wheat yield and phosphorus use efficiency.*Soil Environ.*,**29**(1):15-22.

Rey, J. C., Olivares, B. O., Perichi, G. and Lobo, D. (2022).Relationship of Microbial Activity with Soil Properties in Banana Plantations in Venezuela.Sustainability 14, 13531.

Richardson, A. E., Hadobas, P. A. and Hayes, J. E. (2000) Acid phosphomonoesterase and phytase activities of wheat (*Triticumaestivum* L.) roots and utilization of organic phosphorus substrates by seedlings grown in sterile culture. *Plant Cell Environ*. **23**(2): 397-405.

Richardson, A. E., Hadobas, P. A., Hayes, J. E., OHara, C. P. and Simpson, R. J. (2001a) Utilization of phosphorus by pasture plants supplied with myo-inositolhexaphosphate is enhanced by the presence of soil microorganisms. *PlantSoil*, **229**(1): 47–56.

Rodríguez, H. and Fraga, R. (1999): Phosphate solubilizing bacteria and their role in plant growth promotion. *Biotechnol. Adv*. **17**(2): 319–339.

Rodriguez-Yzquierdo, G., Olivares, B. O., Gonzalez-Ulloa, A., Leon-Pacheco, R., Gomez-Correa, J. C., Yacomelo-Hernandez, M., Carrascal-Perez, F., Florez-Cordero, E., Soto-Suárez, M. and Dita, M. (2023).Soil Predisposing Factors to Fusariumoxysporumf.spCubense Tropical Race 4 on Banana Crops of La Guajira, Colombia.*Agronomy*, 13, 2588.

Sarkar, A., Biswasa, D. R., Dattaa, S. C., Roya, T., Moharanaa, P. C., Biswasa, S. S. and Ghosh, A. (2018). Polymer coated novel controlled release rock phosphate formulations for improving phosphorus use efficiency by wheat in an Inceptisol.*Soil tillage res.***180**(1): 48-52.

Shilpa, and Vasanthi, B. G. (2021). Phosphorus use efficiency as affected by long-term manuring and fertilization under finger millet based cropping systems in acidic Alfisols. *J Pharm Innov.***10**(4): 1120-1123.

Singh, B., Bishnoi, S. R. and Dhillon, N. S. (2000).Response of Pearl Millet to phosphorus in soils of variable fertility.*J. Indian Soc. Soil Sci*., **48**(4): 845-847.

Singh, G. and Sekhon, H. S. (2007). Effect of sowing methods and fertilizer application on growth and yield of kharifmungbean (In) National Symposium on Legumes for Ecological Sustainability: Emerging Challenges and Opportunities, 3-5 Nov. IIPR, Kanpur.

Sobia, N., Muhammad, Y., Muhammad, N. and Rashid, A. (2017).Use of controlled release phosphatic fertilizer to improve growth, yield and phosphorus use efficiency of wheat crop.*Pak. J. Agri. Sci.,***54**(4): 541-547.

Sultani, M. I., Shaukat, M., Mehmood, I. A. and Joyia, M. F. (2004). Wheat growth and yield response to various green manure legumes and different P levels in pothowar region. *Pak. J. Agri. Sci.,***41**(3-4): 102-108.

Sushanta, S., Bholanath, S., Sidhu, M., Sajal, P. and Partha, D. R. (2014).Grain yield and phosphorus uptake by wheat as influenced by long-term phosphorus fertilization.***Afr. J. Agric***. *Res*.**9**(6):607-612.

Tanwar, S. P. S., Sharma, G. L. and Chahar, M. S. (2003). Effect of P and biofertilizer on yield, nutrient content and uptake by blackgram (*Vignamungo*).*LegumeRes*., **26**(1): 39-49.

Tarafdar, J. C. and Claassen, N. (2003) Organic phosphorus utilization by wheat plants under sterilized condition.*BiolFert Soils*.**39**(1): 25–29.

Tarafdar, J. C., Agrawal, A., Raliya, R. Kumar, P., Burman, U. and Kaul, R. K. (2012).Zno nanoparticles induced synthesis of polysaccharides and phosphatases by *Aspergillus*fungi. *AdvSciEng Med.* **4**(1): 324–328.

Tarik, M. and Mani, P. K. (2017).Effect of organic amendments on rice yield trend, phosphorus use efficiency, uptake and apparent balance in soil under long- term rice-wheat rotation.*J Plant Nutr*.**40**(9):1312- 1322.

Tsado, P. A., Lawal, B. A., Eze, P. C., Igwe, C. A., Okolo, C. C. and Tswanya, M. (2014). Phosphate Mobilization by Addition of Organic Acids in Two Soils of the Nigerian Guinea Savanna.*Asian J Agric Food Sci*. **2**(5): 434-441.

Turner, B. L., Papházy, M. J., Haygarth, P. M. and McKelvie, I. D. (2002) Inositol phosphates in the environment.*Phil. Trans. R. Soc. London B: Biol. Sci*.**357**(1): 449–469.

Vandamme, E., Renkens, M., Pypers, P., Smolders, E., Vanlauwe, B. and Merckx, R. (2013). Root hairs explain P uptake efficiency of soybean genotypes grown in a P-deficient Ferralsol. *Plant Soil*.**369**(1):269–282.

Yadav, M., Yadav, S. S., Kumar, S., Yadav, H. and Tripura, P. (2017). Effect of Phosphorus and Bio-fertilizers on Yield, Nutrient Content and Uptake of Urban (*Vignamungo* (L.)Hepper).*Int.J.Curr.Microbiol.App.Sci*.**6**(5): 2144-2151.

Zahrani, S. (2000). Utilization of polyethylene and paraffin waxes as controlled delivery systems for different fertilizers. *Ind. Eng. Chem. Res*. **39**(2): 367-371.

Zhu, X. K., Li, C. Y., Jiang, Z. Q., Huang, L. L., Feng, C. N. and Guo, W. S. (2012). Responses of phosphorus use efficiency, grain yield, and quality to phosphorus application amount of weak-gluten wheat, *J Integr Agric*. **11**(7):1103-1110.