Review Article

STRATEGIES TO ENHANCE THE EFFICIENCY OF PHOSPHATE FERTILIZERS

ABSTRACT

Phosphorus (P) is a crucial nutrient for crop growth, but its unavailability due to fixation in the soil significantly hampers crop productivity. A low efficiency of P utilization, ranging between 10-20%, results in accumulation of P in the soil, and continuous fertilization exacerbates this degree of P fixation. Given that rock phosphate, the primary source of inorganic phosphorus, is a finite resource, there is a looming risk of its depletion in the near future. Consequently, it is essential to enhance the P use efficiency of native soil resources to counteract the dwindling use of raw materials for P fertilizer production. To address this challenge, various innovations and technologies have been developed and are increasingly being adopted in agriculture worldwide. These innovations aim to reduce the conversion of soluble P from conventional phosphate fertilizers into unavailable forms in the soil. One such solution is the use of enhanced-efficiency fertilizers, which include a range of phosphate fertilizers designed to inhibit P fixation. These fertilizers come in different forms, such as chemically modified, controlled-release, blend, multifunctional, and synergistic phosphate fertilizers, each contributing to improved P availability and utilization by plants.

Keywords: P fixation, P use efficiency, controlled release, coated fertilizers, P availability

INTRODUCTION

Phosphorus (P) is an obligatory nutrient for plant development and growth that plays an important role in metabolic processes and has structural, energetic, and regulatory functions [1]. Phosphorus deficiency affects the opening of stomata, resulting in stunted growth, dirty-dark green and erect leaves, reduced tillering and decreased root mass. In general, less P is available in soil due to slow diffusion and high fixation. Research reports indicate that P deficiency may reduce yield by up to 17% [2], depending upon the intensity of deficiency. Only 10–20% of the phosphorus applied through fertilizers is absorbed by plants, as the majority of the phosphorus is quickly fixed or precipitated into inaccessible forms and is available to succeeding crops. Owing to the increasing global population, the demand for inorganic P fertilizers continues to increase annually at a rate of 2.5 - 3.0%, and by the year 2030, this demand is estimated to reach its maximum potential [3].

Phosphorus use efficiency (PUE) is defined as the yield increase per kg of P fertilizer added and is related to environmental factors, soil, and crop management. PUE can be improved by the application of slow-release and controlled-release fertilizers, cultivation of improved varieties, band application of fertilizers, P fertigation, site-specific nutrient management (SSNM), integrated nutrient management (INM), integrated plant nutrient management (IPNS) and the application of biological inputs. The identification of desirable crop plants for adaptation to low-P-input environments may enhance crop productivity and reduce the reliance on costly synthetic P fertilizers [4]. Improving the efficiency of phosphorus (P) fertilizer for crop growth requires enhanced P acquisition by plants from the soil (P-acquisition efficiency) and enhanced use of P in processes that lead to faster growth and greater allocation of biomass to the harvestable parts (internal PUE).

The unavailable form of P in soil is also referred to as residual, recalcitrant, legacy, fixed, accumulated or reserved P. These legacy P become plant available and exist in various forms from labile to nonlabile pools depending on the clay minerals, organic matter and metal ions in the soil. To identify P losses, national- and regional-level P budgeting is needed to summarize the various components of inputs and outputs. However, the average global PUE for cereal cropping systems from 1961 to 2013 was estimated to be 16%, showing that the PUE is a sustainable indicator for understanding P budgets over a timeline [5]. Improved P management practices are also needed given the depletion of P fertilizer resources such as rock phosphate. To enhance the efficiency of P fertilizers, slow and controlled release fertilizers, P inhibitors, and biofertilizers can be used, but these technologies are not extensively used by farmers against nitrogen.

PHOSPHORUS FERTILIZER DEMAND

The global P fertilizer demand for 2023-2024 was forecasted to be 47.1 million metric tons (as P_2O_5), which was greater than that for 2022-2023 (46.2 million metric tons). Morocco holds approximately 50 billion tonnes (70%) of the total world P reserve (72 billion tonnes), making it a dominant force in the global P market. China has led in the consumption and mining of PRs; however, due to low reserves, the restriction of imposing excess tariffs on the exports of DAP and MAP by the Chinese government has led to a large demand on the global P fertilizer market of 5 million tonnes. Despite the amount of mining (47 Mt of P_2O_5) in 2020, only 68% (21 Mt) of P2O5 was estimated to be used for the production of phosphoric acid, P fertilizers and other sources, while the remaining 32% was lost through processing [6].

As phosphate rock (PR) remains the main source of P fertilizers, 60% of this reserve is expected to be impoverised by 2100 [7], and the agricultural sector itself utilizes 80-90% of the global P demand [8]. Although more than 15 million tonnes of phosphate fertilizers are applied each year throughout the world [8], phosphorus deficiency is still considered one of the greatest growth-limiting factors. Even if the existing rate of mining is approximately 30 Mt P per year [9], this will impose a supply risk to highly populated countries (India, China and the USA) in the near future. This implies that we are approaching a peak phosphorus level, a stage at which the supply of phosphorus fails to meet demand, which affects sustainable crop production. Hence, there is a dire need to enhance P fertilizer use efficiency to maintain global food security.

Since there is no alternative for P nutrition, running out of world PR reserves has increased the cost of P fertilizers. Additionally, a continuous decrease in the quality of the mined phosphatic rock increased the production cost. This persisting condition should double the demand for P fertilizers by 2050 [10]. Furthermore, this situation complicated the distribution of P fertilizers among low-income countries, which led to low P inputs in central Asia and sub-Saharan regions, increasing P scarcity [11]. To reduce waste from P fertilizer, improving fertilizer efficiency is essential. The fertilizers with innovations or technologies that enhance the agronomic efficiency of phosphate fertilization compared with that of conventional fertilizers are called enhanced efficiency fertilizers. This review discusses the various technologies used to enhance P fertilizer efficiency to reduce the unavailability of P nutrients.

CLASSIFICATION OF ENHANCED P FERTILIZERS

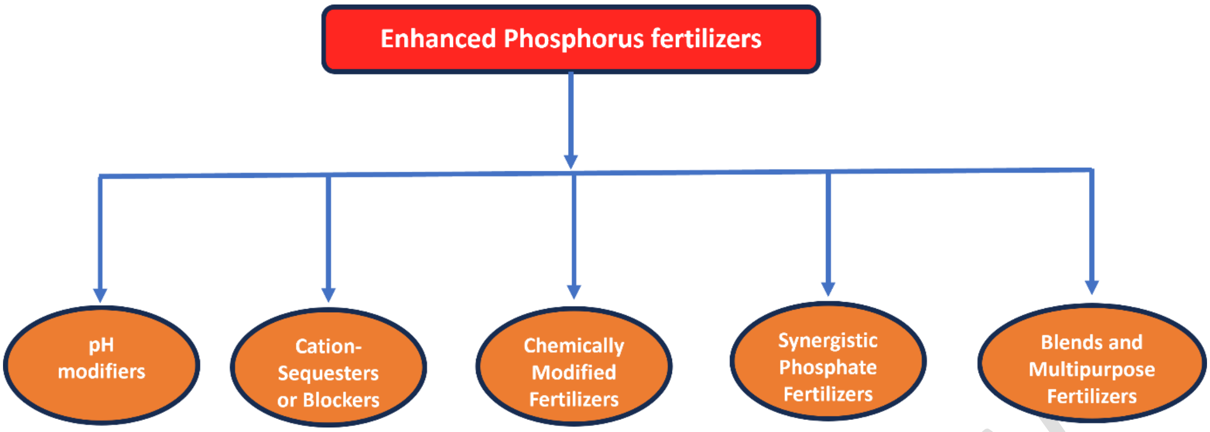

Fig 1. Classification of enhanced P fertilizers

SLOW AND CONTROLLED RELEASERS

Improving phosphorus use efficiency (PUE) involves enhancing the interaction of nutrients with active soil components. Stabilizing nutrients in the soil helps to prevent their immediate release, fixation with soil components, and the formation of insoluble precipitates. It is essential to synchronize the nutrient release kinetics of phosphorus (P) from fertilizers with crop demand and uptake. Slow-release fertilizers are developed by coating conventional fertilizers with polymers, thermostable resins, or elemental sulfur, which act as physical barriers to control P release through diffusion. The release rate is influenced by factors such as the type and thickness of coatings, soil moisture, application method, and temperature.

Coatings can be made from natural polymers such as starch, rubber, and latex or synthetic polymers such as polyvinyl chloride, polyvinyl acetate, polyacrylamide, and polyurethane. Soil moisture significantly impacts the effectiveness of controlled-release phosphate fertilizers. For example, applying fertilizers to plant furrows increases contact with soil moisture, while broadcasting reduces direct contact and prolongs the release period. Greater water penetration and granule expansion lead to increased nutrient release into the soil [12].

Controlled-release fertilizers are also affected by variations in the salt index, osmotic potential, pH, and electrical conductivity of the soil after application. Reducing the salt index and electrical conductivity is crucial because it minimizes damage to seeds, plants, and roots. pH variations can influence the availability and reactions of nutrients in the granule dissolution zone. The gradual release of soluble phosphate fertilizers through coatings can also help reduce acidification around the granules. Biodegradability is another important factor in fertilizer coating development. While synthetic polymers offer better resistance and nutrient release control, their accumulation in soil can cause pollution.

Experimentally, [13] demonstrated that coating thickness significantly influences P diffusion. For instance, castor polyurethane applied to diammonium phosphate (DAP) granules at 3% by mass or less showed similar P release to noncoated granules due to incomplete coverage. However, coatings of 4.5% to 7.5% resulted in moderate dissolution, and coatings of 9.0% or greater drastically delayed P migration in the Oxisol soil. Studies by [14] indicated that coating water-soluble triple superphosphate (TSP) with a lignin-carrageenan formulation (LGCR) reduced P release by 59.5% and 72.5% after 3 days, compared to 100% release from uncoated TSP. [15] modified a cottonseed oil-based polyurethane coating by roughening its surface with a SiO_2–diatomite hydrosol and then immersing it in a perfluorodecyl trichlorosilane solution. This process made the originally hydrophilic coating extremely hydrophobic, slowing granule hydration and delaying nutrient release.

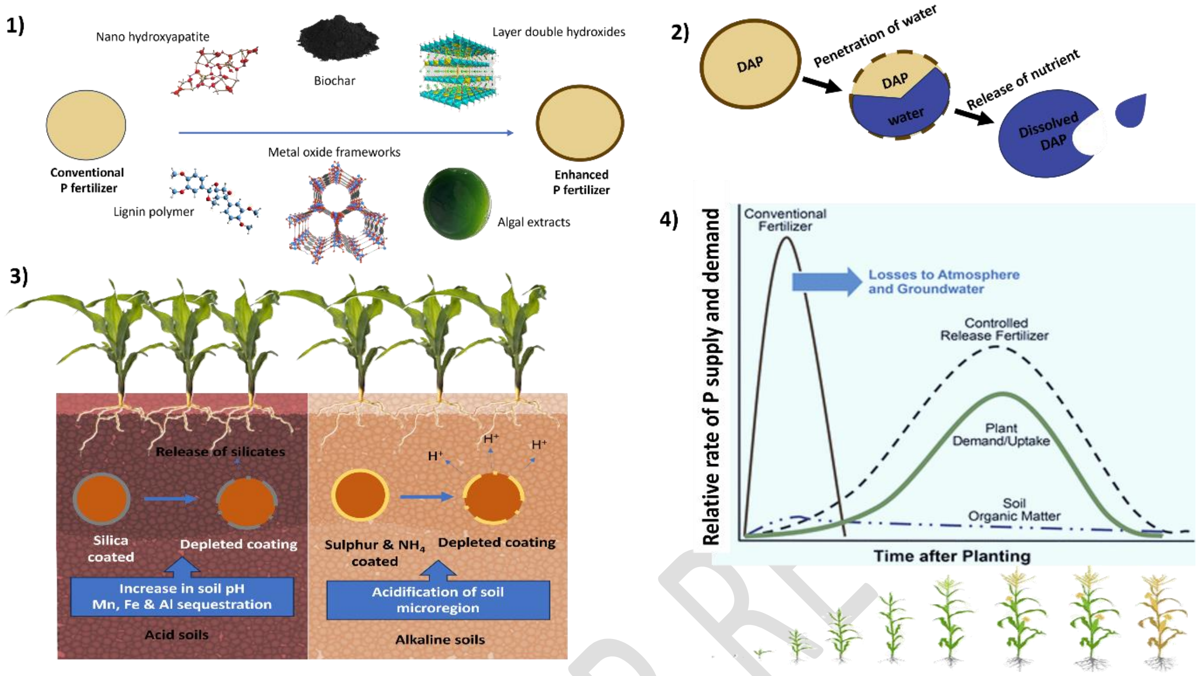

Fig 2. 1) Formation of enhanced P fertilizers 2) Release of nutrients from coated DAP, 3) Mechanism of pH modifiers under problem soils and 4) Supply of nutrient by controlled release fertilizers over the crop requirement

pH MODIFIERS

Another strategy for improving the partitioning of phosphorus (P) around fertilizer granules is to coat or cogranulate them with materials that can either acidify the surrounding soil in alkaline environments or increase the pH in acidic soils. By modifying the pH in the rhizosphere, these coatings create a microenvironment that enhances the solubility of the fertilizer, increasing the accessibility of the solubilized phosphates to plants. Materials such as elemental sulfur, hydroxides, sulfates, oxides, carbonates, and silicates are used as pH modifiers [16]. They can be applied through coating or granulation to reduce P fixation and neutralize the effects of Fe, Al, and Ca. Additionally, the dissolution of these coatings supplies essential nutrients that support plant growth.

Ammonium and elemental sulfur (S_0) are commonly used to generate protons as byproducts of microbial oxidation, thereby acidifying the soil. Conversely, silicate has been studied for its role as a proton scavenger to neutralize acidic soils. In both scenarios, the goal is to enhance P solubility by moving the soil pH toward neutral. The pH of conventional phosphate fertilizers is a crucial factor in the development of these technologies. The reactivity and quantity of pH modifiers added to fertilizer are key factors in promoting acidification around the granules.

There is a wide range of raw materials, processes, and production technologies available to alter soil pH in the microenvironment of phosphate fertilizer granule dissolution. This approach aims to improve fertilizer efficiency by creating optimal conditions for nutrient availability and uptake by plants.

CATION SEQUESTERS OR BLOCKERS

Cation-sequestering additives function by creating negative charges around phosphate fertilizer granules, which helps retain cations that typically precipitate with phosphorus (P). In acidic soils, these cations include Fe^{2+}, Al^{3+}, and Mn^{2+}, while in alkaline soils, they are Ca^{2+} and Mg^{2+}. The negative charges also help prevent the phosphate ions from being bound or adsorbed. Chelating agents, along with anionic and cationic surfactants, alter the charge balance in the area where the fertilizer granule dissolves, enhancing cation retention and blocking sites that would otherwise adsorb P.

The main chemical compounds classified as cation-sequestering agents or blockers include (a) organic acids such as fulvic and humic acids; (b) anionic and/or cationic surfactants and chelating agents; and (c) copolymers of itaconic and maleic acid. The specific ionic surfactant groups included sulfonate (RSO_3^-), carboxybetaine ($-NR_2CH_2COO^-$), sulfobetaine ($-N(CH_3)_2C_3H_6SO_3^-$), and quaternary ammonium ($-R_4N^+$).

Compared with conventional fertilizer alone, a mixture of itaconic acid, maleic acid, acrylic acid, and potassium persulfate polymerized with conventional fertilizer has been shown to increase wheat yields. The use of biodegradable maleic-itaconic polymer-coated phosphate fertilizer at two different concentrations improved phosphorus uptake by 66.7% in calcareous soil and increased the plant's fresh and dry biomass by 10.71% and 18.09%, respectively, compared with commercial diammonium phosphate (DAP) [17]. Additionally, applying humic acid P fertilizer at varying proportions of humic acid (1%, 5%, 10%, and 20%) to maize crops increased grain and plant phosphorus uptake by 6.0% to 15.4% and 6.3% to 14.0%, respectively, compared to that under normal P treatments [18].

CHEMICALLY MODIFIED FERTILIZERS

Chemically modified fertilizers are created by altering the original fertilizers through physicochemical processes during production. These modifications can improve the solubility, mobility, release timing, and absorption of nutrients by plants. With their high specific surface area per unit volume, nanomaterials facilitate the interaction between phosphorus (P) and nanomaterial surfaces for gradual release into the soil. Examples of such advanced technologies include nanoparticles, layered double hydroxides (LDHs), graphene oxide, and metal-organic frameworks (MOFs).

LDHs, also known as anionic clays, are synthesized by stacking layers of hydroxides with natural or synthetic anions. These anions are incorporated into the structure between the layers, neutralizing their negative charge, and are gradually released into the soil solution. The main challenge with these products is synchronizing the release of anions with plant uptake. A significant drawback of P-loaded LDHs is that only approximately half of the phosphorus can be desorbed within the time frame relevant to crop growth, leaving a substantial amount of P potentially unavailable in the soil [19]. Additionally, LDH structures may negatively impact the availability of other nutrients, such as sulfate, due to their affinity for various anions necessary for plant growth or the increase in soil pH observed when these products are applied. A 21-day pot trial with barley using P-loaded LDHs showed promising P uptake and yield, comparable or superior to struvite and KH_2PO_4 [20].

Graphene oxide, with its two-dimensional (2D) carbon atom arrangement, provides a high surface charge density (2600 m^2/g), making it suitable for retaining and gradually releasing phosphorus. The challenge for using graphene oxide in fertilizers lies in increasing its P retention capacity and reducing its currently high cost, which limits its use in the fertilizer industry. [21] demonstrated through a small column study and application to three different soils that graphene oxide gradually releases phosphorus over time compared to more common water-soluble fertilizers.

Metal-organic frameworks (MOFs) are porous materials designed to release nutrients into the soil through chemical breakdown, microbial degradation, and hydrolysis. These frameworks are gaining popularity in scientific research aimed at developing new phosphate fertilizers for agriculture. [22] synthesized an oxalate-phosphate-amine metal-organic framework (OPA-MOF) containing 12.5% phosphorus, aiming to create a fertilizer that slowly releases both nitrogen in the form of urea and phosphorus as oxalate degrades. Wheat pot trials in a Rhodic Ferralsol plant harvested at six weeks after sowing and at maturity showed that, compared with the control and urea-only treatments, OPA-MOF increased yield and biomass but performed slightly less effectively than triple superphosphate (TSP) and urea + TSP amendments.

SYNERGISTIC PHOSPHATE FERTILIZERS

The enhancement of the efficacy of conventional fertilizers can be achieved through the supplementation of nutrients, microorganisms, nanoparticles, or biostimulants. Adding a magnesium source to phosphorus (P) fertilizers can increase phosphorus mobilization within plant cells, as magnesium acts as an active transporter of P. Additionally, algae extracts and humic substances can improve soil structure, enhance the solubilization of micronutrients, and stimulate root and microorganism development. The combined use of biofertilizers and biostimulants, such as humic acid, can increase the solubilization efficiency of P fertilizers, improving nutrient uptake by crops.

Microorganisms employ various strategies to solubilize phosphorus, including the exudation of citric and gluconic acids, alteration of rhizosphere pH, and mineralization of organic phosphorus. It is crucial to note that laboratory results do not always replicate field conditions. The challenge lies in selecting resilient microorganisms that efficiently solubilize the unavailable phosphorus fraction in the soil and determining the percentage of phosphorus solubilized by microbial activity.

Polysaccharide-enriched extracts (PEEs) from the red seaweed *Schizymenia dubyi* have been used as coating materials for controlled-release triple superphosphate (TSP) fertilizers at different concentrations (1.8% and 2.5% w/v) over four application cycles [23]. The best results were observed with the 2.5%-C4 formulation, which released 75% of the phosphorus over 5 to 7 days, compared to 2 days for the uncoated TSP. This trend was consistent with the soil release kinetics and weight loss. Additionally, compared with the uncoated fertilizers, the coated fertilizers improved soil water retention by more than 4% over a 28-day period.

BLENDS AND MULTIPURPOSE FERTILIZERS

An effective strategy for reducing the costs associated with high-efficiency fertilizers and optimizing phosphorus (P) release for different crops is the use of integrated blends. This involves combining conventional fertilizers with advanced technologies to enhance fertilizer efficiency, which is particularly beneficial for mixed cropping systems. The blend should be formulated in specific proportions tailored to the crop and its P release requirements. For example, a blend might consist of a physical mixture of conventional monoammonium phosphate (MAP) with controlled-release MAP granules. The conventional MAP component, being water soluble, meets the crop's immediate phosphorus needs, while the controlled-release MAP provides a gradual P supply controlled by the coating characteristics that influence the release duration.

Generally, the costs of these fertilizers vary based on the raw material expenses, production technologies, and proximity to the consumer market. Fertilizer prices typically follow this ascending order: conventional fertilizers < fixation inhibitors ≤ synergistic fertilizers ≤ blends < controlled-release fertilizers ≤ chemically modified fertilizers ≤ multifunctional fertilizers

ALTERNATIVE PHOSPHORUS SOURCES

PHOSPHITE (PHOSPHOROUS ACID)

Phosphites (Phis) are a reduced form of phosphates (Pis) generated from phosphorous acid ($H_3PO_3^-$), and they frequently mix with nonmetallic cations such as potassium, sodium, calcium, or ammonium. The names 'phosphite' and 'phosphonate' are used to describe salts generated from phosphorous acid. Reduced P fertilizers (H_3PO_3, Ca-Phi) were initially applied to red clover (*Trifolium pretense L.*) and ryegrass (*Lolium spp.*), where the fodder yield decreased with Phi compared to that of Pi but remained similar to that of the control [24]. Fortunately, the residual Phi/Pi reaction was tested, and soybean (*Glycine max L.*) production was greater in Phi- and Pi-treated soil than in untreated soil, suggesting that the remaining Phi was oxidized to Pi. In field trials under P-deficient soil, foliar Pi and Phi caused a 29% increase and an 18% drop in biomass output in corn, respectively [25]. Phi is stored in plant cell vacuoles in the same way as phosphate (Pi), but it cannot be metabolized as a P source. Phi oxidation is the only approach for improving Phi as a P source for crops, and this conversion is performed by soil bacteria.

AMMONIUM POLYPHOSPHATE

Ammonium polyphosphate (APP) is one of the most popular forms of liquid P fertilizer on the market today. The OPs contained approximately one-quarter to one-half of the ortho phosphate (OP) and the remainder of the polyphosphate (PP) (e.g., pyrophosphate, triphosphate). The condensed forms of P are typically hydrolysed to OP by enzymes released from soil microorganisms and plant roots. [26] demonstrated that the presence of PP, even at low concentrations in liquid formulations as ~10% of total P, may dramatically reduce P precipitation as Ca-P relative to technical grade MAP in a calcareous soil. This advantage is not apparent, and PP application may even be detrimental in some iron- and aluminum-rich acid soils where inner-sphere complexation is the dominant mechanism of fixation [27, 28]. The effects of the transformation of fractions and the fate of poly-P in calcareous soils with ammonium polyphosphate (APP) on maize growth were studied, and the results showed that the maize seedling total dry weight increased by 42.4% in the APP-3.8-90% treatment, while the soil available P, Fe, and Zn concentrations increased by 22.7%, 6.5%, and 16.7%, respectively. The soil labile P forms of resin-P, $NaHCO_3$-P and NaOH-P in the APP-3.8-90% treatment were 91.6%, 24.4% and 27.6% greater, respectively, than those in the MAP treatment, while the soil HCl-P(Ca-P) concentration decreased by 7.2% [29].

STRUVITE

Struvite, magnesium ammonium phosphate ($MgNH_4PO_4{\cdot}6H_2O$), is a white crystalline material with approximately equal molar concentrations of Mg, NH_4, and PO_4 [30]. Struvite has been shown to be a slow-release fertilizer P source that can be recovered from both solid and liquid wastes [31]. Chemically precipitated (CPST) and electrochemically precipitated struvite (ECST) have been extensively evaluated for their potential use as alternative, blended fertilizer-P and -N sources compared to other commercially available fertilizers, including TSP, MAP, DAP, and RP [32]. The diffusion distance of struvite from the point of application in soils with varying pH followed the order of neutral > acid > calcareous, while lability favoured acid > neutral > calcareous. The solubility of struvite increases as the pH decreases [33]. Studies have reported similar plant growth from struvite, whereas several studies have reported the reduced agronomic effectiveness of struvite compared to that of commercially available P fertilizers.

Compared with the WS-P concentrations among ECST and MAP, DAP, and TSP under soil conditions near field capacity, struvite showed greater potential for use as a sustainable fertilizer-P source. The use of ECST and CPST, along with MAP, DAP, and TSP, on irrigated rice showed similar results to those of conventional fertilizers, indicating that struvite could be used as an alternate P fertilizer [34]. Multiple studies have investigated the response of potato yield to P inputs, with the control treatment showing lower potato yield. Potato yield and P uptake was comparable between 100% TSP and TSP+ struvite at the same rate, except at one site where struvite at a greater proportion reduced yield owing to lower P uptake [35]. Overall, the use of struvite could be a sustainable means to address long-term global P scarcity.

TABLE 1 - EFFECT OF ENHANCED P FERTILIZERS ON DIFFERENT CROPS

Enhanced P fertilizer	**Crop**	**Condition**	**Summary of results**	**Reference**
Coating of MAP with natural, synthetic and peat humic organic acid (PHO)	Maize	Green house	Agronomic efficiency (AE) of P applied as controlled-release sulfur-coated MAP (CSRF) was 3% to 13% higher compared to MAP, with maize showing a 41% increase in apparent P recovery on PHO-treated MAP.	[36]
Biochar-based slow-release P fertilizer (BBSRPF) produced from a corn stover-derived biochar (CSB)	Spinach	Green house	The P-BC treatment increased bioavailable soil P by approximately 72% compared to F and BC treatments. Additionally, spinach plants showed significant increases of approximately 29% in P, 52% in N, 33% in K, 20% in protein, 21% in ascorbic acid content, and approximately 25% in yield with P-BC treatment.	[37]

Lignin extracted from olive pomace (OP), barley straw (BS) and wood shavings (WS) coating for triple super phosphate (TSP) fertilizer	Wheat	Pot	100% P release occurred from uncoated TSP within 3 days, whereas release ranged from 16.9% (TSP@L-OP) to 33.4% (TSP@L-BS) for coated treatments. Improved shoot biomass was evident with coated TSP treatments, reaching up to 57.8% (TSP@BS), 78.1% (TSP@WS), and 93.7% (TSP@OP), compared to uncoated TSP.	[38]
Humic acid-enhanced phosphate fertilizer (HAP)	Maize	Hydroponic culture	Dry biomass, phosphorus uptake, nitrogen uptake, and average phosphorus absorption rates increased significantly by 14.7–27.9%, 9.6–35.1%, 17.9–22.4%, and 22.1–31.0%, respectively.	[39]
Controlled Release Rock Phosphate	Wheat	Green house	Polyvinyl alcohol-coated product (2% coating) released P gradually, aligning with plant P demand and resulting in greater biomass yield, P uptake, and recovery in wheat.	[40]
HA-enhanced phosphate (HAP) fertilizer	Wheat	Pot	Grain yields with HA-enhanced phosphate (HAP) were 0.23%–13.21% higher compared to other treatments. Adding 0.5%–5.0% HA to phosphate fertilizer increased wheat yield, P uptake, fertilizer use efficiency, and soil available phosphorus.	[41]
Carbond P (CBP) fertilizer	maize	Glass house	Biomass yield and total P uptake were significantly higher with CBP, but decreased with increasing organic matter content.	[42]
Polymer Coated Dap	wheat	field	Applying 100% of the recommended P rate as polymer-coated DAP increased plant height by 4%, biological yield by 39%, grain yield by 29%, agronomic efficiency by 58%, and recovery efficiency by 130% compared to uncoated DAP	[43]
Humic acid-enhanced phosphate fertilizer (HAP)	Maize	Pot	Maize biomass and root distribution area treated with localized hydroxyapatite	[44]

			(HAP) were 12.9% and 29.7% higher than with conventional phosphate (CP). Root biomass positively correlated with soil available phosphorus.	
Hydroxyapatite nanoparticles	wheat	Glass house study	Transport experiments revealed that 5% of nanohydroxyapatite (n-HAP) leached in Andisol and less than 1% in Oxisol, whereas bulk hydroxyapatite (bulk-HAP) remained immobile in both soils. Phosphorus uptake and plant-derived P from fertilizers ranked as follows: triple superphosphate (TSP) > n-HAP > bulk-HAP.	[45]

CONCLUSION

Phosphorus management in agricultural soils is never simple, and one single solution cannot solve the issue of providing all crops in all soils with optimal fertility with minimal loss to the environment. 4R management practices with enhanced-efficiency phosphate fertilizers for proper fertilizer use can reduce P losses in agricultural systems, resulting in increased yield and quality of crops. This increase in fertilization efficiency should always be associated with increased economic profitability and reduced environmental effects, in accordance with the concepts of sustainability and a circular economy. The main challenge for innovation is to convert existing fertilizer knowledge into patents and scholarly papers on fertilizer-specific technology to increase consumer access to this information. However, numerous field-scale trials are needed to determine whether these fertility systems can be extremely practicable in the future.

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