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Review

An Integrated and Multi-Stakeholder Approach for Sustainable Phosphorus Management in Agriculture

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Abstract: Conventional agriculture relies on non-renewable rock phosphate as a source of phosphorus. The demand for food has led to increased phosphorus inputs, with a negative impact on freshwater biodiversity and food security. The importation of phosphorus fertilizers makes most food systems vulnerable to phosphorus supply risks. The geopolitical instability generated by the pandemic and the current Russia–Ukraine conflict, which has led to a 400% increase in phosphorus commodity prices, offers the international community and institutions an opportunity to embrace the global phosphorus challenge and move towards a more circular system. Here, we discuss an integrated and multi-stakeholder approach to improve phosphorus management in agriculture and increase the efficiency of the whole chain, highlighting the contribution of conventional breeding and genetic engineering, with a particular focus on low-phytic-acid (*lpa*) crops, whose grains may help in reducing phosphorus-management-related problems. In recent decades, the choice of short-term strategies—such as the use of phytase as a feed additive—rather than *lpa* mutants, has been carried out without considering the long-term money saving to be derived from *lpa* crops. Overall, *lpa* crops have the potential to increase the nutritional quality of foods and feeds, but more research is needed to optimize their performance.

Keywords: rock phosphate; phosphorus recycling; environmental sustainability; food security; low phytic acid; genetic engineering

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1. The Phosphorus Alarm

P bioavailability in intensive farming systems often limits crop productivity [1,2].

Globally, approximately 85% of phosphates produced for market are processed to produce mineral P fertilizers, 10% are used to prepare animal feed supplements, and the remaining 5% are used in a variety of chemical industries [3].

Phosphorus is obtained from rock phosphate, a limited and non-renewable resource [4]. At current mining rates, it is estimated that the reserves of rock phosphate may be exhausted in one or two centuries [5], but the quality of rock phosphate will decline over time [6].

From a geographical point of view, the mineable deposit areas are concentrated in only a few countries, some of which are considered geopolitically unstable: Morocco, Western Sahara, China, Russia, and the USA hold 85% of the world's rock phosphate reserves, and 70% is found in Morocco alone. The food systems in most countries hinge on the importation of P fertilizers, rendering them vulnerable to potential risks associated with phosphorus supply [7].

The European Union (EU) continues to import more than 90% of mineral P, and in 2020, rock phosphate and white phosphorus were identified as critical raw materials [8].

In this precarious situation, the accessibility of available P reserves and the susceptibility of the national food system to external factors can be influenced by policies, taxes, and legislation [9]. An example occurred in 2008, when the price of rock phosphate surged by

800%, leading to an escalation in fertilizer prices that adversely affected the livelihoods of numerous impoverished farmers globally [5,9]. More than a decade has passed since that peak, but in 2022 a similar situation occurred, and the prices of P fertilizers increased by 400%, mainly due to the rise in raw material prices and the COVID-19 outbreak (Figure 1). These considerations have become even more vital due to the geopolitical instability generated by the current Russia–Ukraine conflict, which puts global food security at risk, due to fertilizer shortages [10].

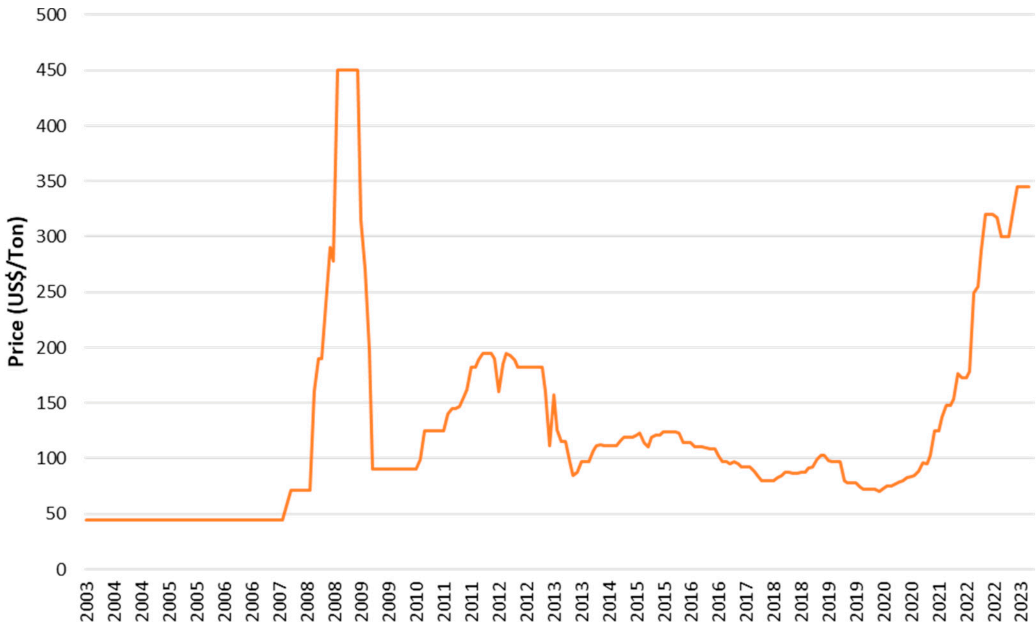

Figure 1. Rock phosphate commodity prices, 2003–2023. Data source: World Bank Commodity Price Data (worldbank.org, accessed on 1 March 2024).

Currently, one in seven farmers are experiencing significant challenges due to their inability to afford an adequate supply of fertilizers, hindering the maintenance of soil fertility, and impacting food production. In the absence of significant changes in the trend in P supply, the insufficient utilization of P fertilizer in Africa is projected to cause nearly a 30% reduction in crop yields by the year 2050 [11]. Conversely, in high-income countries, the excessive application of P fertilizer has given rise to various issues, including the rapid depletion of non-renewable P resources, escalated production costs, and numerous environmental concerns [5]. The sustainable use of phosphate is crucial for two main reasons: the dwindling supply and, paradoxically, the wasteful disposal of most produced phosphate [5]. It is well known that wasted P has resulted in widespread losses of P into water bodies, causing significant problems of water surface eutrophication in lakes, rivers, and coastal waters [12].

Unlike other current issues such as water scarcity or N management, the challenge of P shortage is relatively little studied, and only in recent years have some countries realized the importance of this problem, thanks to the pressure of many scientists and industry experts all around the world. As we are learning from the rapidly evolving climate change scenario, the solution is not immediate, and a long-term timeframe is needed: decision-makers need to look to the next 50 years—rather than the next 5 years—and they should propose a sustainable and multi-stakeholder approach for P management. Even if this time horizon may seem long, it is evident that such a linear economy of mining followed by wastage of P resources is unsustainable, and there is an urgent need to move towards a more circular system.

In this context, the aim of the present review is to provide an overview of the dynamics of P, highlighting the different opportunities and strategies that have been proposed to improve P management, reducing its waste, and improving the efficiency of the entire system. In the second part of this review, we will highlight the possible contribution of plant breeding and genetic engineering to the integrated approach, with a particular focus on low-phytate crops, little considered in P management programs, but which have a great long-term potential.

2. The Role of Soil as a Transient Compartment within the Broader Context of the Global P Cycle

Phosphorus stands as the eleventh most abundant element composing the Earth's crust, with an average concentration of 0.1% [13]. Indeed, it is found in its oxoanionic form (orthophosphate) in a limited number of minerals, such as fluorapatite and carbonate-fluorapatite in igneous and sedimentary rocks, respectively [13,14]. Despite being geochemically classified as a trace element, P is largely required by all living organisms, and its availability for plants and other organisms often limits the autotrophic production of biomass in most farmed and non-farmed terrestrial systems, often restricting ecosystem processes related to N fixation and carbon sequestration [15]. It has been estimated that the typical concentration of total P in soils ranges from 200 to 800 mg kg^{-1}; however, these values are influenced by soil age, typically being lower in older soils [16].

The current global P cycle is shaped by a low and one-way movement of the element within the lithosphere. This journey starts from rock phosphate deposits, passes through the soil, generating biological cycles, gets passed along to interconnected food chains, and concludes in water, where new sediments are formed [17].

The P present in continental apatite minerals is not usable for plants and soil microorganisms. Through chemical weathering processes occurring during soil formation events, P is released into the soil pore system in forms that can be easily dissolved and assimilated by living organisms (i.e., as inorganic phosphate ions). This process—mainly triggered by the production of respiratory CO_2 in soil (carbonation weathering) and the exudation of organic acids by plant root systems [18]—accounts for a global release of available phosphate ions amounting to approximately 1.5 Tg $year^{-1}$ [17]. Conversely, physical weathering processes affecting continental rock phosphate only yield raw fine materials that are susceptible to subsequent chemical reactions. However, a significant portion of the overall P content in the soil can be lost through surface and subsurface runoff [19], eventually reaching the oceans, where it supports other active biogenic cycles or contributes to the formation of sediments. Thus, within this logical framework, the natural soil can be perceived as an environmental compartment engaged in the ongoing transport of P from its primary source (continental rock phosphate) to freshwater systems and eventually to oceans. Consequently, the total P content along the profile of natural soil is inevitably destined to diminish over time as a result [20].

Although inorganic phosphate ions in soil solution may be taken up and assimilated by plants into organic P forms, a large proportion of P released during chemical weathering may react with other minerals, leading to the creation of less available or unavailable P forms. The entry of inorganic phosphate into the biological cycles, involving plants and soil microorganisms, itself diminishes the bioavailability of P through the temporary immobilization of the element within organic P forms, which will release the nutrient in the bioavailable form only following mineralization.

Many other processes in the soil may contribute to the genesis of additional sinks for inorganic phosphate ions released following weathering, thus reducing their bioavailability [18,20]. In acidic soils, iron and aluminum oxides may either adsorb phosphate ions onto their surfaces or surround them, producing non-occluded or occluded P forms, respectively, whereas in alkaline soils, inorganic phosphate often precipitates with calcium minerals [18,21–25].

As soil development progresses towards its final stages, crystalline oxide minerals accumulate so that occluded P and organic P fractions emerge as the primary forms of P persisting in the soil [18,20]. In such conditions, plant P nutrition mainly relies on the release of P sourced from the decomposition of organic matter in the biogeochemical cycle occurring within the upper soil layers [26,27]. Nevertheless, different plant species have evolved distinct strategies that allow them to access some less available P sources. These strategies include: (i) the secretion of phosphatase enzymes in the rhizosphere to mobilize organic P; (ii) the release of ligand-exchanging organic anions (i.e., malate, oxalate, or citrate), which desorb P from soil mineral surfaces; and (iii) the extrusion of protons into the soil solution, potentially aiding in the dissolution of calcium phosphates [28–31].

Anthropic activities have a significant impact on the soil P cycle. The impressive mining exploitation of non-renewable rock phosphate that is crucial to produce P fertilizers, which has occurred since the end of World War II, has led to an extensive movement of P from non-bioavailable forms to accessible forms within agroecosystems to support the increasing demand for food production [1,32]. Additionally, other human-related activities, such as livestock farming, which leads to the production of manure and slurry, and the generation of waste resulting from food consumption, have introduced additional routes impacting the global P cycle [17].

Since the biogenic P cycle in the soil is often not sufficient to meet the high demand for P of modern cropping systems, continuous P supplementation is essential to support the high productivity of crops. Growing consumption of inorganic P fertilizers derived from rock phosphate mining has contributed to major increases in crop yields since the 1950s [33]. Since the mid-20th century, there has been an annual growth of 3–4% in the worldwide production of P fertilizers, and significant increases in their production—ranging from 50 to 100%—are expected by 2025 [1,34].

Discrepancies between nutrients applied into agricultural soils through agronomic practices and nutrients removed through crop harvesting may lead to nutrient imbalances that can impact both the environment and crop productivity [35]. The few studies that have attempted to analyze global P flows in agricultural systems agree in showing that the current agronomic inputs of P, resulting from the use of P fertilizers and manure, significantly exceed P removals by harvested crops at the global scale, although at least 30% of the global cropland area experiences a P deficit [36,37]. In 2010, the global agronomic surplus accounted for 11.5 Tg P y^{-1} [36].

Studying the connections among P imbalance, overall crop productivity, and agronomic phosphorus use efficiency (PUE; total dry matter production per unit of applied P) offers vital perspectives on the management of P in diverse cropland areas. This analysis also enables an evaluation of the duration for which surplus P fertilization is necessary and how long the depletion of accumulated P surplus can proceed without negatively impacting crop yields. Indeed, high PUE values can be associated with either P surplus or P deficit in the soil, indicating high productivity per unit of P supplied or the dependence of crop production on soil P depletion, respectively. Conversely, low PUE values associated with a P surplus clearly indicate excessive use of P fertilizer that does not result in increased crop productivity. Finally, areas with low PUE, relatively low P fertilizer application, and low crop production, often experience different constraints related to agronomic P inputs, water scarcity, or adverse soil properties [36].

3. An Integrated Approach for Sustainable P Management

The unsustainable use of P affects water and food security, freshwater biodiversity, and human health. The growing demand for food to support an ever-growing population determines increases in P inputs within the entire food system and, consequently, losses from terrestrial sources to aquatic ecosystems. In turn, these losses cause various ecological and environmental problems through the proliferation of harmful algae in freshwater and coastal marine ecosystems, leading to a decline in biodiversity and serious risks to human health due to contaminated drinking water supplies [12]. Taking proactive measures to reduce P inputs and promote sustainable practices is crucial for the preservation and restoration of healthy aquatic ecosystems. Several authors agree that there is no single solution to improve P management, but that an integrated approach is needed to improve

P use efficiency and reduce losses along the entire food production and consumption chain [5,7]. Farmers cannot make changes without supporting actions that are also implemented throughout the food chain: an integrated and multi-stakeholder approach will be fundamental (Figures 2 and 3).

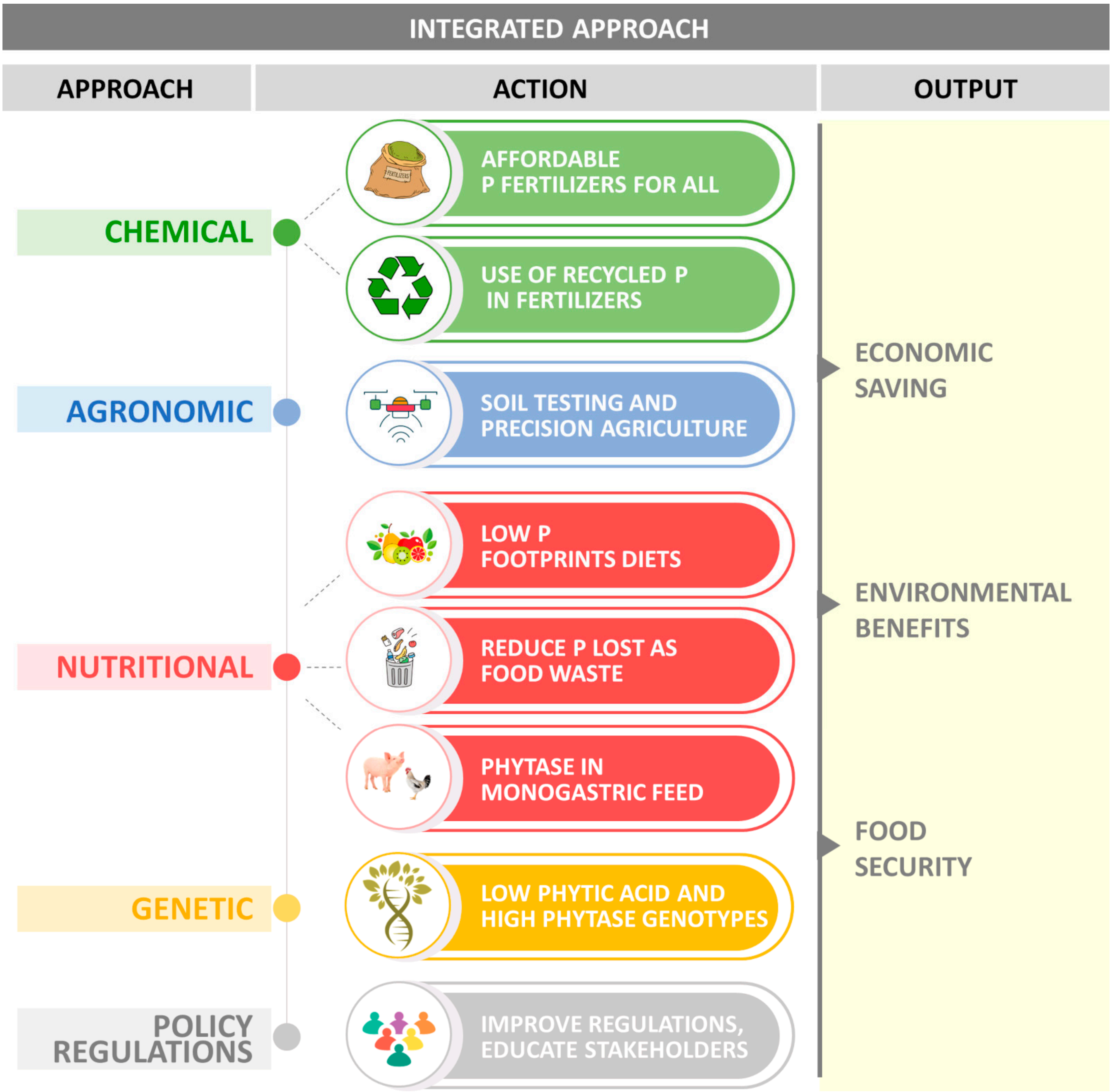

Figure 2. Schematic representation of the integrated approach. Optimal P management results in the outputs shown on the right: economic savings, environmental benefits, and food security.

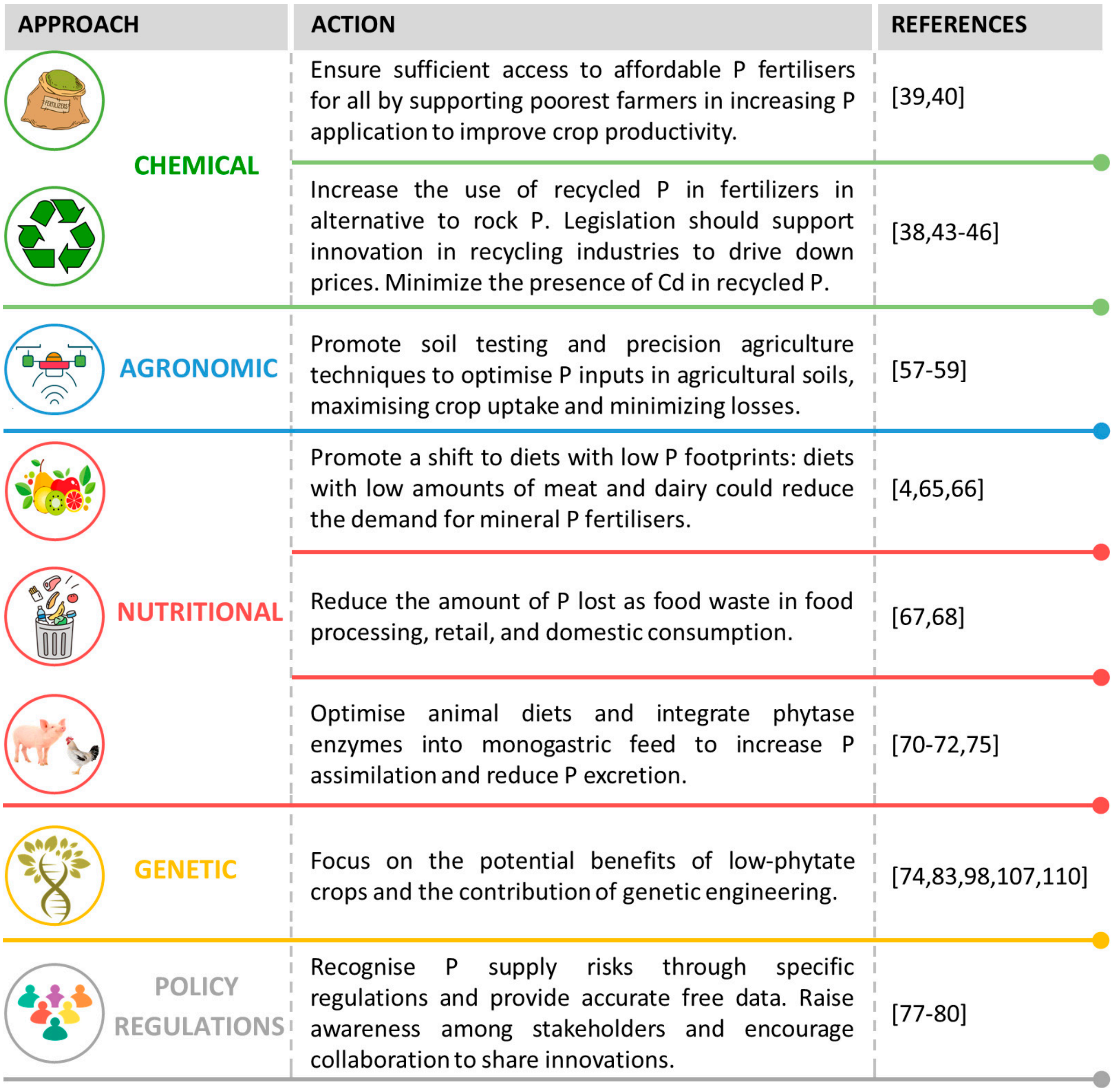

Figure 3. Strategies and actions of the integrated approach for a sustainable P management.

3.1. Chemical Approaches

Since rock phosphate is non-renewable, several possible strategies have been proposed to improve P management and limit its waste. In wealthier countries, appropriate control limits on P inputs are needed, while in many low-income countries, an increase in mineral P application is required to improve agricultural productivity and avoid the unsustainable depletion of soil P stocks. In these regions, there is an urgent need to improve access to P through various measures: investment in local P recycling systems, extension services, access to credit, and knowledge exchange to increase P use efficiency [38]. Indeed, ensuring all farmers have access to enough P to grow crops and protect them from fluctuations in fertilizer prices is a global responsibility and requires international cooperation [39]. The access to P for everybody is an essential step towards achieving the Sustainable Development Goal 2—Zero Hunger [40].

In general, the issues described above can be highly region specific: while in many regions of Europe the soils are characterized by nutrient deficiencies and a low productive capacity, in others (especially those with high livestock density), large quantities of P accumulate in soils [41]. A clear example of P imbalance is in the UK: the north-west is dominated by livestock agriculture, and eastern regions by crops. Soil P efficiency, i.e., P applied as fertilizer and manure that actually ends up in grazing or cropping, is only 47% in the north-west, but is 110% in the wastern regions, meaning that crops absorb more P than is applied. This determines an annual soil P surplus of around 14 kg ha^{-1} in the north-west and a deficit of −3.2 kg ha^{-1} in the eastern regions [42].

In this section, we would like to emphasize the importance of recovered P or other alternative P sources, especially for those countries with limited reserves of rock phosphate. Replacing mineral P fertilizers with recycled P fertilizers would help to shift reliance away from mined P sources [43]. National policies that optimize P recycling, and reduce the reliance on mineral P fertilizers, are acknowledged as pivotal for a transition to a more sustainable P future [44–46]. After the fertilizer price spike in 2008, the first European countries that started investing in the recovery of P from waste streams were Germany and Switzerland [47]. Currently, the production of P fertilizer from recycled P sources is limited and cannot financially compete with the price of rock phosphate [48]. Legislation should support innovation in P recycling industries to drive down the prices of recycled P fertilizers: for instance, it could be stipulated that fertilizers should contain at least 20% recycled P by 2030 to demonstrate green commitment across the industry [38]. In recent years, the EU has made great efforts in policy guidance and facility expansion, but new technologies need to be developed to increase the efficiency of wasted P recovery [49]. Currently, the P recycling rate worldwide is below 30%, except for in Japan and Finland, reaching 50% and 68% respectively [50].

The production of recycled P fertilizers also requires the presence of low concentrations of contaminants. Internationally, safe limits should be set for cadmium (Cd) and other harmful contaminants in all P fertilizers (mineral and recycled) and feed supplements [8,51]. In Europe, P fertilizers contribute 45% to the total Cd contamination of cultivated lands, and at the same time, 55% of Cd intake in the diet of a European consumer is related to its accumulation in the soil, supporting the paradigm that Cd-contaminated soils generally result in Cd-rich food [52]. After many years of debate, in 2019, the EU Council adopted the Regulation 2019/1009, which sets limits on the Cd content for CE-marketed P fertilizers at 60 mg/kg P_2O_5 [53]. Many authors believe that existing Cd limits need to be better enforced [51]. Contaminants can be removed during P rock processing and fertilizer production through existing measures such as blending and decadmiation, but these processes are too expensive and are not used at industry scales [54].

3.2. Agronomic Approaches

Among the possible solutions of the integrated approach, agricultural systems could also improve the management of P through various mechanisms and appropriate measures. Of the approximately 35 million tons of P applied to soils every year, less than 30% enters the food we eat [55]. Therefore, P accumulates in aquatic sediments and agricultural soils, and represents both a source of pollution for the future and an untapped resource [56]. To solve this problem, extensive soil testing is needed to guide the application of P fertilizers according to crop needs, while nutrient management planning ensures that fertilizers are applied at the right time, in the right amounts, and in the right form [57–59]. The adoption of advanced precision agriculture techniques, including the integration of Geographic Information Systems (GISs), variable rate application, and remote sensing technologies, can empower farmers to make data-driven decisions for the targeted and efficient application of P fertilizers. By leveraging real-time data on soil conditions, nutrient levels, weather patterns, and crop growth stages, these technologies enable precise and site-specific fertilization strategies. This not only reduces the risk of overapplication but also maximizes the uptake of essential nutrients by crops, promoting sustainable and environmentally responsible farming practices [58].

Another important point that should be described is represented by the 'phosphorus bank', i.e., part of the P locked in the soil, which has accumulated over decades from repeated applications of fertilizers and manures [60]. The amount of this non-bioavailable P locked in the 'bank' is many times higher than the amount measured in soil tests as being available to plants, which is used to decide fertilizer applications [42]. In recent years, many scientists have been trying to figure out how to access and manage that P: promising research suggests that inoculating plant roots with microbes (e.g., mycorrhizal fungi) may help to unlock legacy P [61,62]. Another possibility is the selection of P-efficient genotypes to access the P already stored in agricultural soils, thus improving P acquisition and P utilization efficiencies [63,64]. In fact, PUE is less than 30% in major cereals, and consequently, more than half of the P applied is lost to the environment. Research in this field should be supported, as the 'phosphorus bank' represents a great long-term opportunity.

3.3. Nutritional Approaches

Phosphorus also plays a crucial role in human and animal nutrition, and its management could be improved in several ways.

In humans, the adoption of healthy diets with low amounts of meat and dairy could drastically reduce the demand for mineral P fertilizers, thus decreasing the need for rock phosphate mining. Studies have reported that meat-based diets require 2–3 times more P fertilizers compared to a vegetable-based diet, resulting in increased P consumption through food [4,65]. Metson and coworkers reported that if all humans adopt a vegetarian diet, the requirement for mineral P fertilizers will decrease by at least 50% [66]. Even if it is not realistic for the entire population to adopt a vegetarian diet, reducing the excessive consumption of meat and dairy products can still contribute to a decrease in P demand.

Efforts should be made to minimize the amount of P lost through food waste in food processing, retail, and domestic consumption. In under-developed countries, most food waste occurs before products reach consumers, while wealthier nations waste more food in retail settings and at home [67]. Hence, instead of recycling P from food waste, the first step to save mineral P is to reduce the production of food waste, thus cutting the resources used for its production [68].

Finally, in livestock production, many nutritional strategies can greatly reduce P losses in manures. These include the optimization of P intake according to growth requirements, and the supplementation of phytase enzymes in the diet of monogastrics, thus improving P uptake from grains and reducing P excretion [69]. Many authors reported that modifying the diet composition to meet animal needs at different growth stages can dramatically decrease P excretion in cattle, poultry, and swine, without affecting animal health and performance [70–72]. However, the most widespread operation in developed countries remains the addition of phytase enzyme to the diet of monogastric animals; nevertheless, its high cost limits its application in low-income countries. Phytase is the enzyme that breaks down phytic acid (PA), the major form of P found in cereal seeds [73]. Because of its negative charge under physiological pH conditions, PA binds to inorganic cations, leading to the formation of phytate salts that have limited bioavailability. Unlike ruminants, monogastric animals lack phytase activity during digestion and assimilate only 10% of the phytate in the feed, while the remaining 90% is excreted, leading to high P concentrations in feces and urine [74]. To meet the nutritional requirements of monogastrics, farmers need to add mineral P to their diet and supplement phytase as a feed additive to make P more digestible [71,75]. This makes the phytase market the most extensive among industrial enzyme markets, whose global value exceeded $500 million in the year 2015 [76].

3.4. Policy and Regulations

All the strategies described in the previous paragraphs have highlighted that the adoption of an integrated approach is urgently needed and should be supported by precise and accurate regulations.

As a first essential step, governments need to recognize P supply risks through appropriate policies, providing accurate free data on supply and demand at a national scale. In fact, several authors reported the need for transparency on global reserves of rock phosphate [77–79]. Greater transparency requires the collaborative efforts of the different stakeholders, governments, universities, and international organizations [80]. The creation of an independent and international body is urgently needed to evaluate data regularly and to disseminate results through appropriate mechanisms, institutions, and awareness programs [69,79]. Moreover, governments recognizing P supply risks should regulate the use of phosphates in agriculture through community directives that acknowledge that deficits and surpluses of P, although different issues occurring in distinct geographical areas, require a concurrent effort to optimize the management of a common resource available in limited quantities [36]. Finally, through controls and incentives, governments must constantly monitor the implementation of directives regarding sustainability of the P supply chain [77–80].

3.5. Genetic Approaches

In cereal crops and legumes, a significant portion, usually ranging from 60% to 85%, of the overall P content is ultimately allocated to grains, so that most of the P taken up by the plants is definitely removed from the soil at harvest and only a minimal amount of the element returns to the soil with the straw [81]. Since the majority of the P stored in seeds is in the form of PA, and monogastric animals are unable to use it, it follows that most of the P removed from the soil is not assimilated but excreted in feces, contributing to malnutrition and water eutrophication [12,82]. In this situation, reducing the amount of P directed to the seeds might result in less P being removed from the soil, consequently, lessening agricultural systems' reliance on P fertilizers. In rice, SULTR-like phosphorus distribution transporter (*SPDT*) controls the allocation of P to the caryopsis. It has been shown that mutations in this gene result in a significant 20% decrease in the overall P content of the grains, without any adverse impact on yield or seed germination; furthermore, the mutation increases the amount of P that remains in the straw, consequently enhancing the quantity of the nutrient that can return to the soil through the crop residues [83–85]. However, for the sake of completeness, it is worth noting here that the first paper, to our knowledge, reporting a link between SULTR-like genes and P accumulation in seeds is credited to Ye et al. [86], which reported a comparative genomic analysis of the barley *lpa1-1* mutant.

Another approach to improve P assimilation and decrease P excretion is based on the decrease in PA in grains. As previously discussed, the use of phytase enzymes in monogastric animal diets is a common practice adopted in wealthier regions to break down PA. Recently, the rising cost of phytases (and dwindling rock phosphate supplies) have spurred interest in long-term solutions like *lpa* crops. A breakthrough in *lpa* crop development was the isolation of the mutant *lpa1-1* in maize by Raboy and colleagues [87]. In this mutant, a remarkable 60% reduction in PA associated with a proportional increase in inorganic phosphate did not significantly alter the total P content within the caryopses. Subsequently, other *lpa* mutants were identified in maize [87–90] and other major crops like barley [91–93], wheat [91], rice [94,95], soybean [96–98], and common bean [99,100]. The *lpa* mutants offer several advantages, mainly in the following: (i) improving P management in non-ruminant production; (ii) enhancing sustainability by reducing animal P waste; and (iii) increasing mineral bioavailability as a strategy to tackle mineral deficiencies. Many nutritional trials conducted on monogastric animals validated the heightened bioavailability of P and cations found in low-phytate seeds [101–103]. Moreover, *lpa*-seed-based animal diets do not require mineral P supplementation and drastically reduce the presence of P in wastes [104].

Interestingly, some *lpa* mutations not only reduce PA accumulation but also cause a significant decrease in the total P of the seeds. This is the case of the *lpa1-1* mutant of barley, in which a 50% reduction in PA is associated with a 15–20% reduction in total P; moreover, the mutation did not produce significant effects on yield [105–107]. A 20% reduction in PA has minimal impact on crop productivity but could save several hundred million dollars used for fertilizers, increasing the long-term sustainability of the entire process. The good performance of the barley *lpa1-1* mutant has led to the subsequent registration of two low-phytate barley cultivars, "Herald" and "Clearwater" [108,109].

Despite these promising results, low-phytate crops have attracted only limited interest. One key challenge is the occurrence of negative pleiotropic effects, impacting seed viability, germination, or plant performance [74]. Additionally, short-term efforts often overshadow long-term goals and benefits. However, research indicates that with sustained breeding and financial support, high-yielding low-phytate crop lines can be developed. Legume crops like the common bean and soybean have demonstrated optimal field performance and yields in low-phytate mutants [99,110].

In maize, where *lpa1-1* has been extensively studied, issues like reduced field emergence and lower yields compared to the wild type have emerged [111–113]. Researchers are working on introgressing this mutation into elite lines and selecting plants with improved field performance and stress resilience, with promising results expected from these long-term efforts. To mitigate negative pleiotropic effects and harness the nutritional advantages of *lpa* mutants, further breeding work is under way in maize and other cereals. Genetic engineering has also emerged as a promising approach, with studies targeting genes involved in the low-phytate trait using techniques like zinc-finger nucleases, TALENs, and CRISPR/Cas [83,114–117]. Phytase overexpression in seeds has shown promise and could provide active phytase action to promote the digestion of PA sources in food or feed [118–121]. In conclusion, the pursuit of low-phytate crops presents both challenges and opportunities in addressing P management, environmental sustainability, and nutritional deficiencies. While overcoming pleiotropic effects and optimizing crop performance will require ongoing efforts, the potential benefits make it a worthwhile endeavor for both conventional breeding and genetic engineering approaches.

4. Conclusions

In the present review, different strategies and opportunities have been proposed to improve P management and P use efficiency at the global level. In our opinion, these strategies need to be integrated with conventional breeding and genetic engineering with a particular focus on low-phytate crops, not yet usually considered in P management programs.

The choice of alternative strategies—such as the use of phytase as a feed additive or biofortification programs—instead of *lpa* mutants has been carried out without considering the long-term money saving to be derived from low-phytate crops. In the early 1990s, environmental issues or sustainable P management were of secondary importance, and no predictions of possible changes in feed costs were included. Nowadays, the situation is completely different, since rock phosphate prices increased significantly, and the vulnerability of the entire food system puts global food security at risk. Considering this scenario and the benefits of low-phytate crops, are we willing to grow a plant that perhaps yields 5–10% less, but is overall more nutritious [76]? Our answer is yes, but with the proper support from institutions and long-term efforts in classical breeding or genetic engineering.

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