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REVIEW

Innovations of phosphorus sustainability: implications for the whole chain

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Abstract Phosphorus (P) is a non-renewable resource, therefore ensuring global food and environmental security depends upon sustainable P management. To achieve this goal, sustainable P management in the upstream and downstream sectors of agriculture from mineral extraction to food consumption must be addressed systematically. The innovation and feasibility of P sustainability are highlighted from the perspective of the whole P-based chain, including the mining and processing of P rock, production of P fertilizers, soil and rhizosphere processes involving P, absorption and utilization of P by plants, P in livestock production, as well as flow and management of P at the catchment scale. The paper also emphasizes the importance of recycling P and the current challenges of P recovery. Finally, sustainable solutions of holistic P management are proposed from the perspective of technology improvement with policy support.

Keywords P-use efficiency, recycling, sustainable management, the whole P chain

1 Problems and challenges of phosphorus in the whole chain

Phosphorus (P) is a finite, non-substitutable, non-renewable and geographically restricted resource. Because the demand of agricultural production is increasing and the peak in global production could occur in the next decades, although this view remains controversial, P is receiving more and more attention as a disappearing nutrient[1–4]. The world is caught in the global P paradox. Access to P is becoming increasingly limiting, leading to food insecurity. Meanwhile excessive use of P in many agricultural and urban settings is causing environmental degradation[5].

Due to its unique characteristics (slow diffusion and high fixation in soils due to its physical and chemical properties), P has low availability in soil, and is a major limiting factor for crop production in various soils of the world[6]. There is no denying that the applications of chemical P fertilizers and animal manures to agricultural land have improved soil P fertility and crop production in past decades. However, the low P-use efficiency directly determines the accumulation of P in the soil, forming a huge P reservoir in the fertilized soils and causing potential environmental risks. As to animal production, P is also an essential nutrient for livestock growth, while losses of P from animal manures through direct discharge or runoff and leaching from manure-applied fields contribute considerably to water pollution in many countries[7,8].

In addition, due to the uneven distribution of phosphate deposits, future P shortages may have national security implications. Some projections predict that the available phosphate resources on earth will be depleted in the next few decades. Although the timetable (ranging from a few hundred to a thousand years) of P depletion is controversial, there is agreement on the need for improving use efficiency and recovery of P. Geopolitical constraints on phosphate reserves are already evident and may become more severe in the future. Moreover, there is evidence that various systems at different geographic scales have significant P wastage and loss as well as high discharge to water bodies. Continued high discharge of P to water bodies will accelerate harmful processes such as algal blooms, hypoxia and eutrophication, which are already

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apparent and may cause irreparable damage to aquatic ecosystems[1].

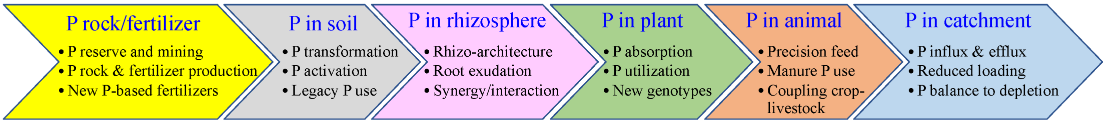
In summary, increasing concerns about long-term availability and accessibility of major sources of phosphate rocks in the world, highly efficient use of P in agriculture, and recycling P from waste highlight the need to investigate sustainable measures to cushion the world food system from the short- and long-term impacts of global P shortages. A holistic solution for sustainable P management in sectors upstream and downstream of agriculture from mine to fork is becoming increasingly urgent. This review highlights innovations of P sustainability for the whole P supply chain (Fig. 1).

2 Phosphorus reserve and production

With the development of seismic exploration technology and the released available official data, the known recoverable reserves in the world were updated to 67 Gt in 2015, in some 60 countries and regions in Africa, Asia, North and South America, and the Middle East, among which more than 85% of the reserves are concentrated in Morocco, China, the USA, South Africa and Jordan. Morocco has the world's largest phosphate reserves, accounting for 75% of the global P reserves[9]. Although China's phosphate rock reserves rank the second in the world, it only accounts for 4.7% of the world's phosphate resources. In addition, China is mainly dominated by low-grade phosphates with less than 10% high-grade phosphates rocks. China, however, shared more than 50% of global phosphate rock production in recent years, causing an unsustainable use of P.

China also has made a great contribution to the global P fertilizer production. Since 1980, China's fertilizer industry has developed rapidly, especially for P fertilizer production, increasing from 2.6 Mt P_2O_5 in 1980 to 17.3 Mt P_2O_5 in 2016, which was mainly driven by governmental subsidies[10,11]. Although the P fertilizer industry has experienced rapid growth in China during 1980–2005, the production of mineral P fertilizers still cannot satisfy the increasing fertilizer demands over this period due to restrictions in the limited industrial production capacity and the strong demands from agriculture. Millions of tons of P fertilizers have been imported to fill the gap. With the continuous introduction of advanced processing and production technologies from abroad early this century, an annual growth rate of 10.7%

(a) P flow chain



(b) Sustainable P use and recycling

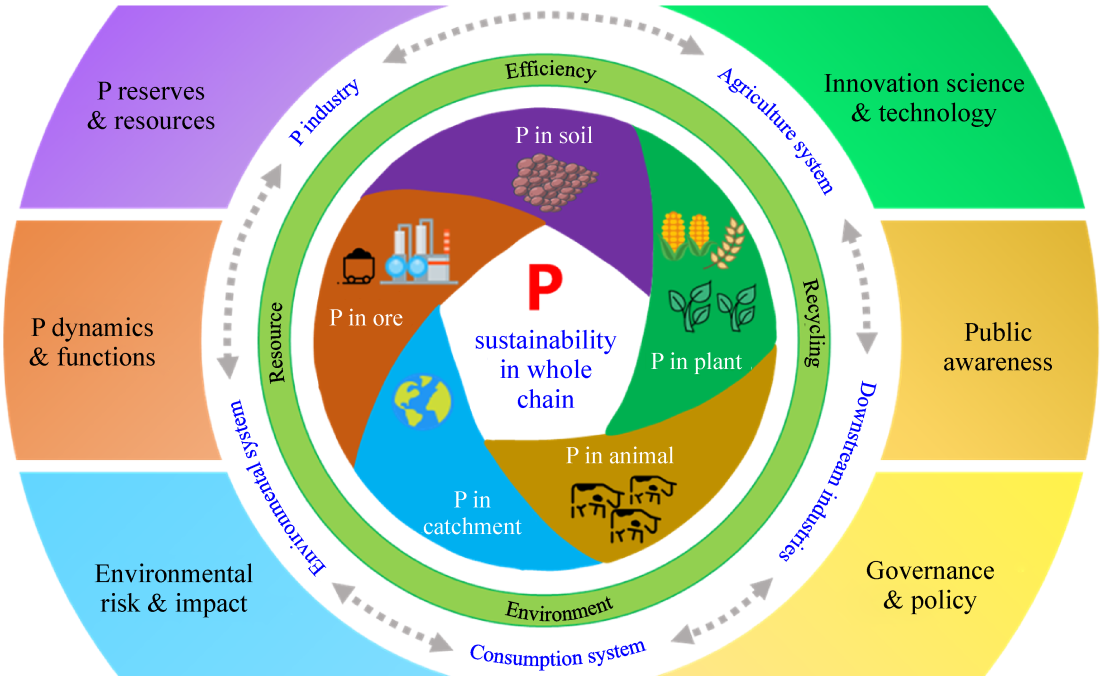


Fig. 1 Conceptual model for a P flow chain, and sustainable use and recycling at different scales. (a) P flow chain; (b) sustainable P use and recycling.

for China’s P fertilizer production was achieved from 2000 to 2005. Consequently, China became the world’s largest producer and consumer of P fertilizers and has been a net exporting country since 2006.

Overuse of mineral fertilizers has resulted in serious negative impacts on the quality of arable land and the rural environment in China[12,13]. Therefore, in 2015, the Ministry of Agriculture of China issued the *action plan for zero growth of fertilizer use by 2020*[14]. This policy has directly resulted in the gradual decline in P fertilizer production and consumption since 2015.

3 Phosphorus in soil

The forms of P in soil include inorganic P and organic P. P mainly exists in inorganic form in most soils, and these inorganic forms are mainly orthophosphate, which can be generally divided into mineral-P, adsorbed-P and water-soluble P[15,16]. The main form of P in soil solution is orthophosphate. Three different forms ($H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}) of phosphate are formed by the gradual dissociation of hydrogen ions. Plants can only take up P dissolved in the soil solution, and since most of the soil P exists in stable chemical compounds, only a small amount of P is available to the plant[17]. The types of P compounds that exist in the soil are mostly determined by soil pH and by the type and amount of minerals in the soil[18]. Mineral compounds of P usually contain Al, Fe, Mn and Ca[19]. In acidic soils, P tends to react with Al, Fe, Mn, while in alkaline soils the dominant fixation is with Ca[20]. The optimal pH range for maximum P availability is 6.0–7.0. Maintaining a soil pH in this range also favors the presence of $H_2PO_4^-$ ions, which are more readily absorbed by the plant than HPO_4^{2-} ions (present in soil solutions with a pH > 7.0)[21].

Once P fertilizer is applied to soil, P transformation and its subsequent fixation by the soil matrix start to occur due to various soil physical, chemical and biological processes. From an historical analysis, P management in major cropping areas has faced great challenges in China. Soil legacy P and P deficiency coexisted in the past decades. Although an average concentration of Olsen-P in topsoil of China’s major croplands was as high as 20.4 $mg \cdot kg^{-1}$ in the 2010s, which is above the critical level of P for environmental risks[22], there are still large areas of Chinese arable land with Olsen-P below 10 $mg \cdot kg^{-1}$, the critical level for staple crops. These low-P soils are expected to require large amounts of P fertilizers in the future in order to improve soil fertility. Concurrently, excessive P inputs and other inappropriate P management practices in both crop and animal production systems have resulted in severe eutrophication of lakes, rivers and estuaries[23]. Agricultural non-point P sources are becoming the major source of P contamination in water[24]. Therefore, sustainable P management should be site-specific to improve the fertility of low-P soils, increase P-use efficiency in animal production systems, and minimize the environmental risk of P losses especially from soils (even low P soil due to erosion) and poorly-managed animal production sectors.

In the soil-animal-water system, soil P management is of fundamental importance because the soil serves as a sink of manures from animal production and is the major source of P losses to water bodies in China. Over the decades, Chinese farmers and agricultural scientists have developed several soil P management strategies, including soil-based and root/rhizosphere-based P management strategies, greatly contributing to the sustainable P use.

4 Phosphorus in the rhizosphere and mycorrhizosphere

4.1 Phosphorus in the rhizosphere

The rhizosphere is a critical zone around the root and is affected by various soil physical, chemical, and biological processes[25,26]. The interactions between plant, soil and microorganisms are the most intense in the rhizosphere. The rhizosphere in turn is the key hub to control nutrient transformation (particularly for P due to its high fixation, low mobility and low bioavailability in soil) and plant uptake[27]. Plant roots can greatly modify the rhizosphere environment by secreting organic compounds such as carboxylates, mucilage, phosphatases and signaling substances, which are the key drivers of the rhizosphere process and play a decisive role in the activation and absorption of P and other insoluble nutrients[6,28]. There is a steep P concentration gradient in the radial direction away from the root surface. Given its low solubility and mobility in the soil, P removed from the rhizosphere through plant root absorption cannot be quickly replenished. Although the total P content of soil often exceeds the plant requirements, the high chemical fixation of P results in low availability to plants[29]. The availability of P is highly correlated with soil physical and chemical properties, and affected by plant root growth and function. Two key processes determine the availability of P to plants[6,30]. The first one is the spatial availability. Root growth and mycorrhizal association affect the spatial availability and acquisition of P[31]. Plants are able to respond to P deficiency by changing their root architecture. Increases in root/shoot ratio, root elongation and root branching are a common phenomenon under P deficiency. These changes in root morphology eventually lead to the expansion of the root-soil contact area and expand the spatial availability of P. In theory, P mainly exists in the topsoil, but recent studies have shown that the contribution of P resources in subsoil cannot be ignored[32,33]. Moreover, Bauke et al.[33] have shown that an efficient use of subsoil P was achieved only when nutrient supply in arable topsoil was sufficient.

To some extent, this suggests that only a well-developed, deep-rooted root system can expand the space in the subsoil to efficiently obtain soil nutrients. Mycorrhizae can also expand the soil volume available for nutrient absorption in the whole soil profile (see Section 4.2). The second process is associated with P bioavailability. Root-induced chemical and biological changes are vital for improving P bioavailability[19,34]. These processes mainly include proton release to reduce rhizosphere pH, carboxylate secretion to increase the availability of sparingly-available P through chelation or ligand exchange, and release of various enzymes (such as phosphatases and phytases) to mobilize organic phosphates[35,36]. Hence, the rhizosphere, as a critical interface for plant-soil-microorganism interactions and is an important zone to control and regulate P transformation and flow from soil to plant, which ultimately affects the soil P release and use efficiency by plant, as well as biogeochemical cycling of P. A better understanding of the root-soil-microorganism interaction and regulation mechanism is crucial for improving P use efficiency and sustainability in the future.

4.2 Phosphorus in the mycorrhizosphere

Mycorrhizosphere interactions are also important for improving soil P use. Arbuscular mycorrhizal fungi (AMF) hyphae extend the P uptake volume beyond the rhizosphere depletion zone up to 12 cm[37]. When the extraradical hyphae of AMF absorb nitrogen in the form of $NH_4{}^+$-N, they can release protons to the soil to solubilize a proportion of the fixed inorganic P[38]. In addition, the interaction between AMF and their associated bacteria enhances soil organic P utilization because AMF cannot use organic P directly[39,40]. Microscopic observations and molecular analyses showing bacterial colonization on the surface of AMF hyphae and spores demonstrate that a close relationship between AMF and bacteria exists[41,42]. The extraradical hyphae of AMF release carbon-rich compounds, such as low-molecular sugars, carboxylates and amino acids, to the bacteria, which have two functions. First, hyphal exudates serve as C source to enhance the bacterial population. Secondly, hyphal exudates serve as signals to stimulate the bacterial phosphatase activity. For example, fructose released by AMF induces the expression of the phosphatase gene in the bacterial cell[43]. Importantly, the relationship between AMF and bacteria in P utilization can be regulated by the C:P ratio in soil[44]; reducing soil C:P ratio by adding starter P fertilizer to P-deficient soils can stimulate the P-solubilizing capacity of bacteria and improve plant P uptake[45]. AMF hyphae recruit bacteria that produce alkaline phosphatase and perform the functions, which are absent in fungal hyphae, to enhance soil organic P mineralization in situ in the field[44,46]. Also, a recent study showed that the stimulating effect of AMF on hyphosphere bacteria can be influenced by various abiotic and biotic factors. Both host plant species and soil phosphate forms influence the hyphosphere interaction significantly by changing the microbiome structure[47]. These processes in the mycorrhizosphere modify the P transformation and availability, thus changing P-use efficiency of the plant.

4.3 Phosphorus in plant-soil feedback

Plant roots interact closely with soil microorganisms that enhance nutrient acquisition (e.g., AMF) and with pathogens that cause root necrosis or plant death[31,48,49]. Root and rhizosphere microbiomes, as part of the extended plant genome, are key determinants of plant health and productivity[50–52]. In both agricultural and natural ecosystems, a preceding plant often leaves a microbial legacy for subsequent-plant growth[53]. Negative plant-soil feedback (PSF) is often observed in continuous monoculture, driven by the accumulation of host-specific pathogens and allelopathy compounds as well, while the accumulation of mutualists can result in positive PSF[53,54]. In addition, microorganisms are important decomposers[55] and integral to the soil P cycle, and as such are important in mediating the availability of P to plants[56]. A research challenge is to maximize positive PSF to mobilize and utilize soil P by optimizing the associations between above- and below-ground processes through appropriate cropping systems and managements. Both environmental filtering and plant traits may co-determine the differentiation of root microbiota and P utilization. Sufficient supply of P nutrient decreases P-solubilizing bacteria in the rhizosphere[57], but plants may preferentially select root microbiota to assist host P acquisition under P-deficient conditions, leading to positive PSF[58]. As such, the effects of soil biota on plant survival, growth and nutrient uptake also critically depend on plant traits and nutrient acquisition strategies[59–61]. Hence, using PSF to elucidate how, and to what extent, the root and rhizosphere microbiomes respond to P gradients is crucial for deciphering the nature of plant-microbial interactions and designing optimal cropping systems.

5 Phosphorus in the plant

The enhanced ability of crop plants to use P and to produce biomass and yield under given available-P conditions, can be achieved by improved P uptake efficiency (PupE) and P utilization efficiency (PutE). Root functions at morphological and physiologic levels are crucial to improve PupE. Given that soil P has low mobility and is often concentrated in the upper zones, a root system architecture with shallow root angles, dense lateral root branching and long root hairs advantages P uptake by enhancing topsoil exploration[62,63]. This effect of root distribution in the soil profile could be different under dryland conditions. In addition, increases in capacity of roots to secret protons, acid phosphatases, ribonuclease and carboxylates to contribute to mobilization of inorganic phosphate allows this mobilized P to be subsequently taken up by the root epidermically-expressed phosphate transporters[6]. In many crop species, PupE has been improved by modifying root functions through genetic approaches, for example, use of *OsPSTOL1* (phosphorus starvation tolerance 1) and *Pup1* (phosphorus uptake 1) gene/allele in rice[64,65].

For PutE, it is essential to reduce the P demand of plants without negatively impacting on growth and yield. This may be achieved in two ways. First, plants can efficiently optimize the internal P use by reduction of superfluous rRNA, degradation of organelle DNA, replacement of phospholipids by non-P lipids (i.e., sulfolipids and galactolipids)[66,67]. Secondly, suitable distributions of P within the plants can enhance the remobilization from organelles such as vacuoles and senescing tissues to the new growth, or reduce the partitioning to developing seeds for nutritional and environmental benefits[68,69]. Importantly, plants have developed a sophisticated regulatory network to precisely control P uptake and utilization processes through either local or systemic signal, as well as interactions between P and other nutrients, e.g., N and Fe[70–72].

6 Phosphorus in livestock

Plant production provides an important basis for animal production, highly influencing livestock development, along with the flow of P throughout the industry chain. China’s livestock industry has experienced a vast transition during the last three decades, which profoundly effects on domestic and global food provision, resource use and P losses. The number of livestock units have tripled in China in less than 30 years, mainly through the growth of highly-intensive industrial livestock production systems, and the increase in monogastric livestock (from 62% to 74% of total livestock units)[73]. Total production of animal-source protein has increased nearly 5-fold. The increase in animal production from the 1980s onwards has greatly contributed to the increased P losses to the environment, particularly surface waters and to a decrease in the P-use efficiency in the food chain. Estimated total P losses from animal production were as large as about 50% of the total fertilizer P input in 2010. The P-use efficiency in animal production at the animal level has slightly but steadily increased, mainly due to a shift from grazing-draft animals to monogastric animals in confinement[74].

This new transition is targeted to increased production efficiency and environmental performance at the system level by coupling of crop-livestock production systems, whole supply chain manure management and increased grassland productivity as major components[75]. Two options have been analyzed for a drastic increase in P-use efficiency by linking crop and animal sectors by 2030, i.e., precision P animal feeding and improved manure management. Integration of these two options will more than double P use efficiency in animal production. The management of the new transition should focus equally on the spatial planning of livestock farms, and the improvement of livestock production efficiency, animal feed production (including forage and grasslands) and manure management[75].

7 Phosphorus in the catchment

Agricultural intensification is one way to meet increasing global food demand in the coming decades. Although this strategy can potentially spare land from conversion to agriculture, it relies on large material inputs. However, in recent decades, P has significantly increased the load on freshwater ecosystems, and continuous nutrient influx has caused serious environmental problems. Worldwide, these problems have led to deterioration of water quality and loss of aquatic biodiversity. Agricultural sources (excluding rural living sources in typical areas, the same hereinafter) discharge main pollutants including 284700 tons of P to waters[76]. From 2006 to 2014, after the control of point sources, such as treatment of rural urban sewage, the P content in lakes decreased, but the non-point source of P pollution load changed little, and the cause of legacy P made it impossible to restore lakes to a good ecological condition within several decades[77].

The eutrophication of surface waters has become an endemic problem. Nutrient loadings from agriculture are a major driver. Consumption of chemical fertilizer P has increased about 100-fold, from 0.05 Mt in 1960, when it was first used, to over 5 Mt in 2010, with an abrupt increase since 1978. Manure P input to Chinese arable land has also increased steadily since 1949, to reach 3.4 Mt in 2010[74]. It is estimated that less than 20% of fertilizer P can be used by crops during the growing season in China[78], resulting in a large P surplus in the soil over the long-term. Previous studies have demonstrated that excessive Olsen-P values above the critical P leaching level greatly increase the risk of P losses to water bodies through runoff and erosion, which may lead to serious environment problems[79–81].

A framework needs to be developed for an integrated approach to alleviate nutrient surplus in waters. More consideration needs to be given to the nutrient efficiency of the whole supply chain and the interactions between different subsystems. Effective nutrient management strategies should highlight the following aspects. First, the leading role of wastewater sources in the P cycle of river catchments may be much larger than previously recognized, and in densely populated areas the contribution of agriculture to eutrophication of rivers and lakes needs to be re-evaluated in this regard. Secondly, direct discharge of manure is likely to be the most important source of unexpected and serious nutrient pollution in surface waters of China, and there is a need for better manure management by coupling crop and livestock production. Thirdly, involvement of all sectors in the whole supply chains from fertilizer suppliers, farmers to sewage treatment plants and integration with water policy is needed in the future nutrient management in the catchment.

8 Phosphorus recycling in the whole chain

Of the global phosphate rocks exploited, over 86% of the total is used as mineral fertilizers for agricultural production[82]. While only about 16% of fertilizer-applied P flows to food with the crop harvest, a greater proportion flows to animal manure[2,83]. It is estimated that the annual production of livestock and poultry manure contain 2.46 Mt of P[84]. Therefore, the recovery of P would not only alleviate the environmental pollution[85], but also capture the value of this secondary P resource. At present, several problems exist for P recovery. First, without a better understanding of P recycling, the peak point for P supply cannot be accurately estimated[86]. Secondly, the lack of effective P recovery technology makes it hard to adopt targeted recovery methods[87]. Moreover, the suboptimal reference standards to guide the P recovery lead to a poor adoption in the actual production activities[88,89]. Finally, it is impossible to solve the problem in a targeted way with few scenario analyses for P recovery technology and utilization. All these problems create a gap between scientific theory and field practice.

Closing the P circle is a key aspect of the sustainable use of P resources[90]. It is necessary and urgent to establish the metabolic P flow, analyze the pathway of P loss and explore measures to control P loss. Based on the analysis of the specific P loss pathways in various industries, including the form and the environmental factors affecting P loss, the recovery technology model of P in different industries should be studied[91]. Based on the previous research results, combined with the current experimental analysis, systematic studies should be conducted in terms of the form of phosphate recovery, the subsequent mode of use and the efficiency of the recovered products, so as to formulate a set of scientific guidelines. These are needed to scientifically and effectively analyze the actual P recycling process and utilization, collect relevant information to establish a specific P recycling model and modify P recycling standards based on the policy advantages, which will be conducive to the sustainable P usage (Fig. 1).

9 Solutions for phosphorus management

9.1 Technologies

9.1.1 New phosphorus fertilizers

To improve the P-use efficiency of fertilizers and reduce losses, many studies focus on the innovation of fertilizer products as well as making full use of low-grade phosphate rock. In terms of physical form, nano-P fertilizers have become a current focus of attention, as these can effectively increase the contact area with soil and increase P mobility[92]. In addition to environmental risk zones, controlled-release P fertilizers offer the potential to reduce runoff losses [93]. In terms of chemical form, many studies have focused on organic P fertilizers[94], chelates and polymers. One study has also shown that based on temperature and pH controlled-release rates, targeted P fertilizers are a promising new direction[95].

9.1.2 Precision phosphorus input and management

The root/rhizosphere-based nutrient management has been demonstrated to be an effective way to improve nutrient-use efficiency[26,96]. It has three components. Firstly, optimizing total nutrient input to a critical level to maximize root/rhizosphere efficiency. Secondly, improving localized nutrient supply to induce root proliferation and strengthen rhizosphere effects through changing nutrient composition and supply intensity. Thirdly, exploring biological interactions to change nutrient-use efficiency. For livestock production, precision feed P use is also important to increase the efficiency of use of P contained in feedstuffs, for example by adding phytase[97].

9.1.3 Recycling and reuse of phosphorus

To reduce the reliance of agriculture on the use of inorganic fertilizers and the geopolitical uncertainties associated with global phosphate reserves, recycling and reuse technologies have been evaluated. This is first achieved by using all sources of agricultural waste (such as livestock manure and crop residues) to produce organic fertilizer by composting and thermal processing[98]. Also, struvite can be used to recover P from wastewater to produce controlled-release P fertilizer[99].

9.2 Policy supporting for sustainable phosphorus use

The consumption of phosphate rock (P_2O_5) in China increased from 0.25 Mt in 1960 to nearly 32 Mt in 2010. If no measures are taken, the demand for phosphate rock is estimated to reach about 36 Mt by 2030. If industrial efficiency, agricultural demand and recycling efficiency are improved, the demand for phosphate rock could be reduced to 6.6 Mt. Increasing the P-recycling rates for animal manure from 60% to 90% and the P recycling rate of wastewater from 0% to 75% could reduce the demand for phosphate ore by some 3.6 Mt. Controlling the application of P fertilizer to 8 Mt and banning the export of P could reduce the demand for phosphate rock by up to 13 Mt. For industrial processing, if the recovery rate of phosphate rock mining increases from 60% to 80%, the recovery rate of phosphate rock processing will be increased from 94% to 98%, and the proportion of medium and low concentration P fertilizer will be increased to 40%, which will reduce the demand for phosphate rock by over 11 Mt annually. To achieve these goals, strong environmental protection and P resources management policies are needed, as well as strong agricultural science and technology innovation and service policies (Fig. 1).

10 Actions and changes

To address the challenges facing the capacity to achieve P sustainability, the key actions and changes required need concerted effort. A holistic solution is needed to integrate P use from mining, processing, fertilizer production, application, recycling to policy (Fig. 1). First, it is necessary to make better use of the existing known phosphate mineral resources, and to also increase the investment in geological surveys, and improve the reserves and quality of phosphate rock resources. There is a need to integrate existing P rock resources, improve use efficiency of medium and low-grade P rock, innovate P rock mining technology and methods, and reduce tailings waste. Governments should strengthen management to ensure the rational exploitation and utilization of P resources, and dynamically supervise the P production capacity. Policy makers should develop effective policy frameworks to stimulate and support such sustainable P management. Countries need to introduce legislation that provides incentives and policies to support sustainable approaches to meeting the world's demand for P[100]. The most important thing is to strengthen cooperation among countries around the world to solve the problem of uneven access to of phosphate minerals[1]. Optimization of P fertilizer production is also urgently needed. P fertilizer production enterprises should increase technological research and development, change the characteristics of P fertilizer and develop the next generation of new efficient P fertilizers. Moreover, breeders should select genotypes with high P efficiency to improve the ability of crops to explore and take up P from the soil, which can be combined with innovative nutrient management techniques and better education for farmers to improve the P-use efficiency and maximize sustainable P use. There is an urgent need for a more comprehensive and systematic approach to improved exploitation of soil legacy P, nutrient management based on technological advances in precision agriculture, plant breeding and microbial engineering together with a greater reliance on the recovery of P[101]. Government and society need to strongly support sustainability-related, innovative P research, development, knowledge transfer and education. Finally, the most important thing to remember is P recovery and recycling. It is inevitable that P recovery and recycling will be essential to global food security. The existing heterogeneity of P waste flow, the demand for agricultural P, the availability of resources and the spatial pattern of land use require that multiple P recovery strategies must be addressed[102]. P recycling strategies should aim to address multiple elements (e.g., C, N and P) and multiple resources (e.g., food, energy and water), and ultimately to close the P loop. The link between research and policy needs to be strengthened to ensure that industrial and supply chain realities are recognized. There is a need to increase awareness of and advocacy on P issues, with emphases on policymakers and key stakeholder groups[100]. It is imperative to adopt a comprehensive, interdisciplinary, multi-element, multi-resource approach to maximize knowledge transfer and communication between stakeholders and sectors, promote good data availability including accurate information on P stocks and flows across to all sectors, to rebuild the broken P cycle (Fig. 1). Moreover, the P value chain and corresponding policy issues should also be addressed in the near future, and the recommendations and management strategies suggested in the study should be shaped and adapted to variable environmental and social conditions.

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