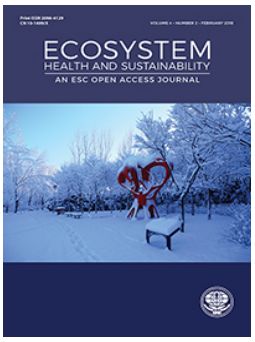

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Phosphorus recovery: a need for an integrated approach

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REVIEW

Phosphorus recovery: a need for an integrated approach

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ABSTRACT

Introduction: Phosphorus (P) is an essential element in food production. P consumption is increasing over the years due to increasing population and increasing demand for agricultural yields. Managing the agricultural P through the understanding of bioavailability, transport, and runoff will maximize the soil productivity and minimize the environmental effects. Efficient management in agriculture, governance, and lack of integrated international governance need to be addressed to overcome the P scarcity issue.

Results and Discussions: This article is focusing one such efficient management of P resource addressing the major portion of phosphorus which is unnoticed in agricultural residues, manures, and other sources. Increasing cost of phosphate fertilizer, a scarcity of high-quality phosphate rock (PR), and increasing surface water pollution are driving a need to accelerate the recovery and reuse of phosphorus (P) from various waste sectors. Options to recover P occur all along the open P cycle from mining to households to oceans. However, P recovery as a regional and global strategy toward P sustainability and future food, bio energy, and water security are in its infancy because of a number of technological, socioeconomic, and institutional constraints. Resolving these constraints requires concerted collaboration between relevant stakeholders and an integrated approach combining successful business models with socioeconomic and institutional changes.

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Phosphorus; recovery and reuse; phosphatic fertilizers; depletion; eutrophication

Introduction

Phosphorus (P) is a finite and valuable resource and an essential nutrient for optimal biological functioning of microbes, plants, and animals. In natural ecosystems, soluble P salts that are slowly released from rocks through weathering are taken up by plants, and in turn by animals, and returned to the soil through decaying organic matter derived from plant residues and animal excreta (Figure 1). Due to solid nature of P-based compounds, unlike other nutrient cycle, the P movement is slower from living organisms into soil, water, and sediment.

Phosphorus deposited in the oceans via natural runoff will eventually be transformed into sediments and rock formations over millions of years, to be eventually, released again through weathering, and the cycle starts over. Societal need to produce food for a continually growing population has interrupted this natural P cycle by converting mined and relatively inactive phosphorus rock (PR) into a range of more soluble and reactive P compounds that have increased the bioavailability of P to crops, animals, and humans, and for use in industry. This increased availability of highly reactive P has not only enabled successive green revolutions in different regions of the world but also led to a number of undesirable consequences for ecosystem services, including reduced soil and aquatic biodiversity and increasing risks to human health due to eutrophication (MacDonald et al. 2016). Eutrophication occurs because the use of P in the food chain is highly inefficient leading to widespread leakage in runoff from soils and farming systems and wastage to landfill sites (Van Dijk, Lesschen, and Oenema 2016). Phosphate rock as a nonrenewable resource is also consumed at an alarming rate and a future P scarcity or increased cost could potentially threaten future food and bioenergy security (Cordell and Neset 2014).

Large fraction of phosphorus accumulates in soils due to excessive fertilizer, animal manure, or municipal waste application and become susceptible to transport via surface runoff and results to eutrophication in surface waters. Hence, the phosphorus is a serious concern for most aquatic ecosystems. Solutions to all these issues rely on developing strategies for more sustainable P use

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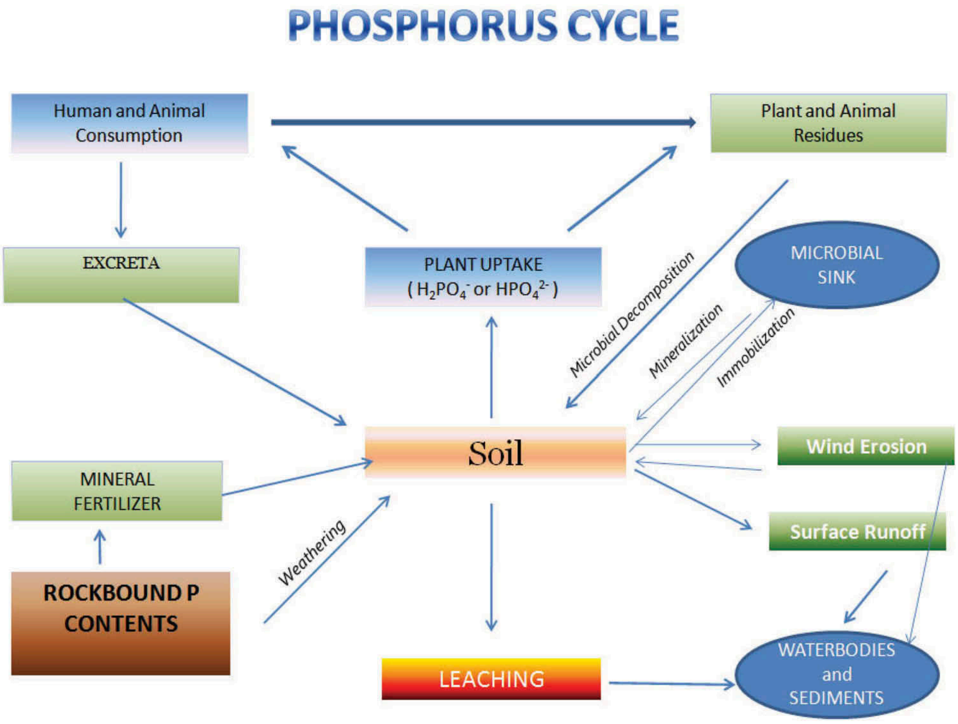

Figure 1. Phosphorus cycle.

(Cordell, Rosemarin et al. 2011). For example, Withers et al. (2015) proposed a global 5R stewardship strategy (Realign P inputs, Reduce P losses, Recycle P in bioresources, Recover P in wastes, and Redefine P in food production systems) and concluded that adoption of the 5R strategy would result in a more resource-efficient, resilient, competitive, sustainable, and healthier society. A central "green chemistry" concept for reducing reliance on PR-derived, reactive P is to recover and reuse P from secondary resources as part of the drive toward a P circular economy with zero waste (Withers et al. 2015b). In practice, P recovery in both developed and developing countries is still in its infancy and requires more awareness raising, research efforts, and business opportunities amongst government, agricultural organizations, industries, and the public as key stakeholders. Here, we consider the rationale for the development of a stakeholder collaboration and operational framework to deliver a range of sustainable P-recovery solutions.

Drivers for phosphorus recovery and reuse

Scarcity, over-abundance, and increasing cost are the three major factors that drive the need of a more efficient management of the P cycle.

Scarcity of exploitable phosphate rock

World consumption of phosphorus fertilizers and industrial use are projected to increase gradually from 43.7 million tons in 2015 to 48.2 million tons in 2019 (USGS, 2016). It was estimated that, the current phosphorite and apatite reserves will become exhausted during the next 64–400 years, depending on a potential trend in the phosphorus industry, and forces to move increasingly toward the improved recovery rates and the mining of lower grade PR (Heffer et al. 2006; IFDC 2010; Jasinski, 1998–2013; Ulrich et al. 2013; Gorazda et al. 2013). In 2008, about 175 Mt of phosphate concentrates, averaging 30.7% P_2O_5 content was mined (IFA 2009), whereas about 198 Mt of PR were mined in 2011 (Jasinski, 1998–2013). An estimate shows that the depletion of P resource would be around 20–35%. By 2100, about 40–60% of the current resource base would be extracted. Continuing dependent trend of high rates of P application for agriculture will lead to a depletion of more than 50% of the total resource base by 2100 that could be a serious threat to the security of the P supply (Van Vuuren, Bouwman, and Beusen 2010). Several studies have been reported that the phosphorus reserves can be estimated to occur within a period of 100–400 years (Günther 1997; Cisse and Mrabet 2004; Dery and Anderson 2007;

Cordell, White, and Lindström 2011; Rosemarin, De Bruijne, and Caldwell 2009; Smit et al. 2009; Vaccari 2009; Cordell, Rosemarin et al. 2011; Van Vuuren, Bouwman, and Beusen 2010).

High grades of PR reserves are dwindling over the years and intensive production of crops requires the addition of phosphatic fertilizers. Increased use of fertilizers and manures has led to yield a significant change in the nutrient cycle. Hence, there is an imbalance in the nutrient cycle, causing major environmental and economic problems and ultimately now emerged as a major global challenge. Global phosphorus security is directly linked to food security and environmental protection (Cordell, Rosemarin et al. 2011; Mayer et al. 2016).

PRs are often contaminated with high proportion of heavy metals such as fluoride and cadmium. The extraction/removal of these heavy metals is a costly process and demands more energy. The reduced availability of high-quality PR and disposal of by-products further make the price of raw materials to increase. Therefore, phosphorus has been raised as a pressing concern for the affordability and the sustainable use of nutrients.

Increasing cost of phosphatic fertilizers

Depletion of resources and quality phosphatic reserves leads to increase in the price of phosphatic fertilizers. Fertilizer production was insufficient during the year 2007–2008 due to increase of world agriculture, which led to a big rise in demand for phosphate-derived fertilizers (Jasinski 2012). The price in US dollars in 2008 was increased about 800% than in 2007 (Schroder et al. 2010). This is partly due to the growing demand in energy crops for biofuels to replace oil, and growing market for biofuels leads to increase of growing plants for fuel which will further add to the demand for phosphate (Ridder et al. 2012). Increase in price causes adverse effects on farmers and consumers in both developed and developing countries, hence many developing countries cannot afford conventional chemical fertilizers. Therefore, to afford and overcome the demand issues, the time has come to think of alternative efforts for efficient management of phosphorus resources. According to Elser et al. (2014), the sudden shift and decline in price is a warning sign that similar large disruptions in fertilizer markets could occur in the future. Research findings confirm that volatility of fertilizer price has moved into a new, high-price regime. Improved nutrient efficiency on crops and introducing new technology for enhanced nutrient recycling from different sources can set up the solution to the high-price issues (Elser et al. 2014; Mew 2016).

Rising levels of water pollution

Increasing population, intensive agricultural production, and rapid urbanization have led to widespread pollution of inland and coastal waters with P causing impaired water quality, reduced biodiversity, and risks to human health. Examples of the pollution effects are increased biomass benthic and phytoplankton communities, composition change in macropytes and zooplakntons, death of coral reefs and loss of coral reef communities, decreasing water transparency, problems in taste, odor, and water treatments, effects on fish population and algal and bacterial blooms, which can kill livestock and may pose a serious health hazard to humans (Carpenter et al. 1998). When compared to point-source pollution, the nonpoint pollution sources have major impact on the water environment with the increase of phosphorus concentration in wastewater and sewage systems. This yields to either fertility erosion or adverse environmental effects like loss of biodiversity and eutrophication.

Many countries are addressing the eutrophication through best agricultural practice and operating within recommended ranges, greater attention toward the reducing nonpoint sources, and the "4R" approach (i.e., Right rate, Right time, Right source, and Right placement of P) to fertilizer management (Jeppesen et al. 2007; Chambers et al. 2012; Howden et al. 2013; Jarvie et al. 2013; Withers et al. 2014; Sharpley 2016).

Large amount of phosphorus is discharged as waste into the water bodies. Erosion and runoff of mined phosphorus have been identified as major causes of phosphorus loss. Nearly all consumed phosphorus is transported as sewage to municipal wastewater plants (Gorazda et al. 2013). Withers et al. (2014) suggested the need of more science to clarify the eutrophication contribution in catchment-specific assessment for the accurate assessment of recovery rate.

Majority of the developing countries have no effective collection system of these wastes. Presence of excess nutrients in aquatic ecosystems promotes eutrophication that causes increased cost of water treatment, loss of recreational value, and reduced value of commercial fisheries. In addition, the lack of infrastructure and lack of legislative framework for the treatment process further intensifies the problem. Poor incentives and cost of payments for treatment and disposal of these wastes are also one of the major reasons for the poor phosphorus recovery. Hence, to overcome the economic hurdles, policy measures such as regulations and incentives are needed to protect the water bodies and sustainable use of phosphorus (Driver, Lijmbach, and Steen 1999; Mayer et al. 2016).

The phosphorus present in the night soil (human excreta) organic wastes, and agricultural wastes, has to be explored for the effective recycling of phosphorus. Since the balance between human and animal contribution may vary from region to region, research on livestock production and agriculture and urban runoff waters needs to focus regionally on the sustainable availability of phosphorus-recycling resources.

Renewable solution

Phosphorus has no substitute in food production (Cordell, Rosemarin et al. 2011); therefore, emerging issues on its increased availability and phosphorus recovery from wastes have been raised (Scholz and Wellmer 2013). To ensure the global food security, there is a critical need to re-examine the current use pattern of phosphorus and thereby overcoming the scarcity issues and conserving this finite resource. There is no single solution to resolve the problem for ensuring the continuous availability of phosphatic fertilizers (Cordell, Rosemarin et al. 2011). Phosphorus is a nonrenewable resource, but fortunately it is possible to recover and recycle. Recovery can occur at all stages of the P cycle (Figure 2). There are also different strategies that can be used to recover phosphorus from different sources.

In general, phosphorus is recovered by separation and crystallization process as struvite or hydroxyapatite, and the separated minerals can be used by the fertilizer and feed industries. The recovered phosphorus is commonly free from heavy metals and other impurities, and valuable for industries such as production of chemicals, food and beverages, iron and steel, etching agents, flame retardants, and electric vehicle batteries (Mayer et al. 2016).

Phosphorus-containing wastes can be a source of renewable energy like methane or hydrogen (Mayer et al. 2016). Need for innovative solutions in nutrient management, water processing and recycling, strict environmental regulations, restrictions on application of sludge in farm lands, and increasing social pressure will also play a pivotal role in recycling of phosphorus resources.

Available methods and processes

Phosphorus can be recovered from liquid phase, sludge phase, and sludge ash. Various technologies have been introduced to recover the phosphorus from liquid wastes such as chemical precipitation, biological phosphorus removal, and crystallization. Regarding the solid waste recovery, the processes like sludge digestion, precipitation of struvite, and acidification have been in common practice. Dry thermal process and thermomechanical process have been used to recover phosphorus from sludge ash (Morse et al. 1998; Desmidt et al. 2015). Phosphorus can be recovered from innovative physical, chemical, and biological methods from a diverse range of sources (Morse et al. 1998; Cornel and Schaum 2009; Driver, Lijmbach, and Steen 1999; de-Bashan and Bashan 2004; Rittmann et al. 2011; Mayer et al. 2013; Batstone et al. 2014; Zhou et al. 2016). There are many full-scale implementation processes that are in infancy state for phosphorus-recovery technologies in Europe, North America, and in Asia (especially in Japan). The available information shows that the OPEX (Operating Expenditures) for the NuReSys process

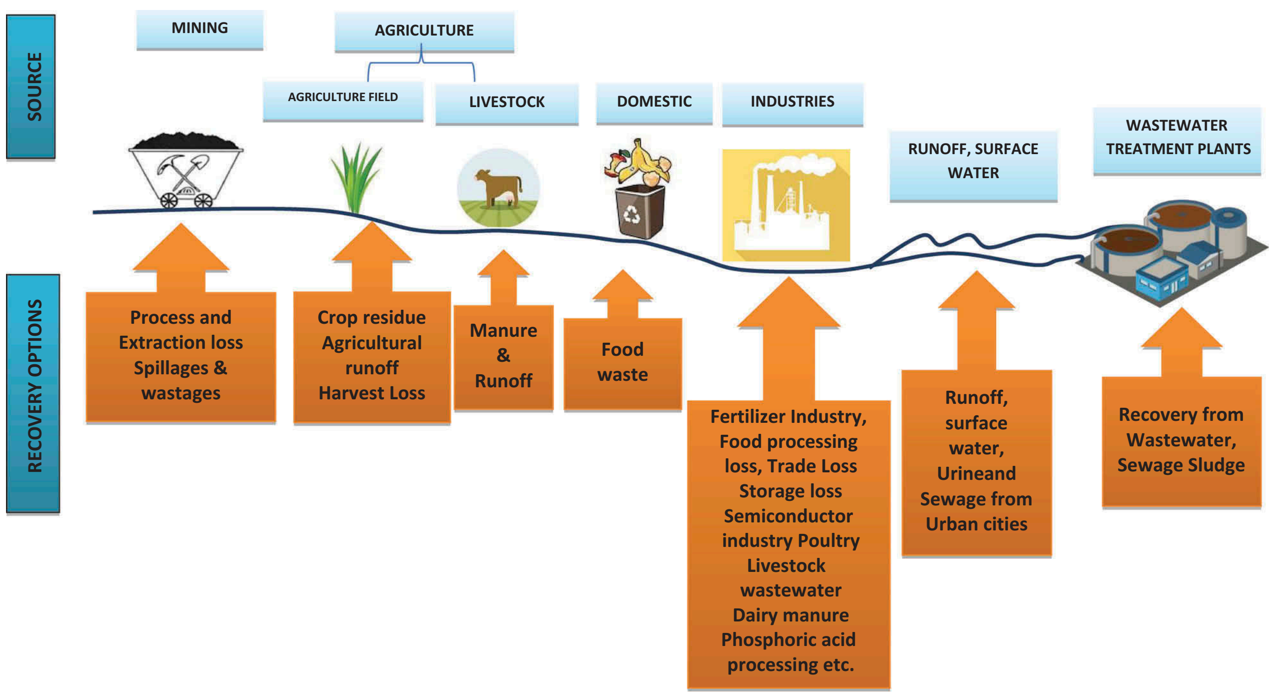

Figure 2. Phosphorus-recovery options.

treating 60 m^3 h^{-1} wastewater, containing 120 mg L^{-1} PO4-P is 1.6 EUR kg^{-1} P. The CAPEX (capital expenditures) of the process is 4.4 EUR kg^{-1} P. This clearly shows that phosphorus recovery is considered to be viable, environmentally safe, and technically feasible. However, the economic feasibility is much more limited (Balmer 2004; Desmidt et al. 2015).

Influence of different variables and strategies

Low phosphorus availability in many of the world's agricultural soils has been reported and globally massive variation in P imbalances was observed particularly in Europe and South America (Graham et al. 2011). But predicting the P imbalance at regional level is complicated due to different complex factors such as individual practices by farmers, Degree of weathering and erosion, environmental conditions, crop-dependent removal, and socioeconomic factors. However, requirement of P nutrition for crops depends on the ability of soil to replenish the soil solution with the different forms of phosphate existing in the soil. Hence, more efficient use of P fertilizers is warranted to overcome the global nutrient imbalances.

Phosphorus could be potentially reused from dissipated P (Withers et al. 2015), and this recovery of P subjects to various constraints. A table summarizing different actual or potential constraints for each sector is presented in Table 1.

The recovered products might have some impurities and contaminants such as heavy metals. Occurrence of heavy metals, precipitation contents, nitrogen, potassium, and sulfur have also to be taken care of, during the process of phosphorus recovery. The separation of heavy metals and impurities requires higher chemical consumption and this ultimately results in the deleterious impact on wastewater treatment plant and the environment. It further increases the cost of phosphorus recovery. Therefore, the operational cost, energy cost, and cost for chemical usage should be maintained as minimum as possible, so that the actual benefit of recovery process will be realized.

Phosphorus-rich influent and high-sludge disposal areas should be identified for implementing the P-recovery technology so that P recovery becomes viable. Recycling technologies require a minimum payback period so that the net savings of operation cost can be estimated.

Recovery of phosphorus from small sewage plants in rural and semi-urban areas may not be economically feasible due to the low percentage of recovery and increased cost of technology. Technically, the transportation cost will not compensate for the recovered cost. In such case, the farm-land application of sludge may be the viable option for recovered phosphorus. Recoveries from food wastes have some limitations due to diverse sources of origination and complex mixture. This may be overcome by source separation (Mayer et al. 2016). Steps should be taken to encourage the application of biosolids or manure for farmland application. This will be a simple and cost-effective method of recycling.

The developing and low-income countries may not be in position to adopt the high-cost technologies. To skip over such economic hurdles, the low-income countries need the alternate low-cost technologies. Maria et al., (2011) states that as far as the environmental benefits are considered, the phosphorus recovery becomes economically feasible. A high level of performance of low-cost recovery technologies should be identified to create a value chain from the wastes. Local governments and the agricultural departments should take necessary steps to adopt the low-cost technologies and agricultural practices, and to create awareness among farmers and gardeners for the application of such phosphatic fertilizer/material produced from the phosphorus-rich resources like sewage and sludge.

Adoption of conservation practices, improved agricultural practices, legislations, and directives are resolving the eutrophication issues and improving the water quality. These directives are controlling the amount, methods, and timing of nutrient application to land for containing the runoff and nutrient delivery to the ecosystem. For example, in Northern Ireland, a national P surplus target of 10 kg P ha^{-1} applies to a small number of derogated farms under the EU Nitrates Directive regulations. Many legislative measures have evidences in reducing the farming intensity or improved water quality (Bechmann et al. 2007; Dobbs and Pretty 2008; Worrall, Spencer, and Burt 2009; Maguire et al. 2009; Meals, Dressing, and Davenport 2010; Jarvie et al. 2013; Withers et al. 2014).

Depending upon the wastewater treatment facilities, the recovery unit could be introduced in such a way that it easily fits with the existing treatment system. Phosphorus can be technically recovered from the liquid phase through sludge fractionation and biological removal processes in the same treatment system to save the cost and energy coupled with increased phosphorus-recovery efficiency. Phosphorus-recovery technologies have already been put into applications in developed countries, but most of the technologies are still in its infant stage.

The phosphorus recovery from sewage-treatment system should be made mandatory, so that the P recovery will become a compulsory option in practice. Usage of sewage sludge as phosphorus fertilizer replacement should be encouraged and be adopted for arable farming. Dynamics of phosphorus vary depending on the regional and industrial structures (Wyant, et al. 2013). Nationwide statutory requirement to remove phosphorus is to be taken into

Table 1. Sector-wise potential constraints on P recovery.

Waste sector	Constraints on P recovery		
	Technological	Socioeconomic	Institutional
Mining	• Large investments in technology • Iron problem in both wet-acid and thermophos process • Should have a reasonable P content and a limited water	• Impurities should not reach threshold level • The space availability for recovery phosphate • Sustainability for P-recovery reactor operation	• Lack of contact with recovery experts and research institutions • Limited efforts on increasing the effectiveness of recovery process • Lack of efforts on region-specific applicability of the various strategies for enhancing P recovery and reuse
Agriculture	• Transport cost – due to distance between source and productive agricultural land or other end uses • Large amount of organic material • Manure has high ash content • Implications of biosolid management	• The transportability of P-containing materials other than synthetic fertilizers remains a key technological and economic challenge to close the P cycle • Feasibility of the recovered phosphorus, odor, and safety • Lack of market demand	• Management and maintenance responsibilities • Lack of recommendations for the increased use of secondary P • Lack of monitoring and policies to reduce the use of P • Lack of co-operation with other stakeholders e.g., farmers • Lack of testing methods for determining their bioavailability and fertilizer-use efficiency • Lack of information about recovery fertilizer value • Lack of awareness • Public misperceptions
Industry	• Reactor and process control differs in industries and their wastes • Contaminants e.g., iron or aluminum, lead, and cadmium	• Lack of enhancing chemical engineering techniques • Chemical consumption cost for pH adjustment (if struvite recovery can be achieved without chemical) • pH adjustment or at lower pH, then the process would become economic) • High capital costs and the high energy consumption • Quality control • Economic feasibility	• Lack of recommendations for industries to reduce P inputs in products where possible • Secondary phosphates from other countries usually not permitted to transport waste across the border • Legal provisions on phosphorus recovery are needed, such as those envisaged as part of the currently planned amendment of the Sewage Sludge Ordinance • Lack of regulatory mechanisms • P should be regarded as a priority raw material • Lack of policies to reduce the use of P in food production
Household	• Sewage sludge incineration ash contains considerable amounts of Iron, Zinc, and Copper which are difficult to avoid	• Land space availability in high-population areas • Increases in need for chemicals like iron-precipitate chemicals	• No pressure on cities having large number of population to install P-recovery systems • Permission for sludge incineration is problem in many countries • Lack of awareness in general public, so that P waste from food can be minimized
Wastewater	• Available phosphorus from different waste streams • In centralized treatment systems with large sunk costs, energy and resource costs of pipe networks • Increased risk of losses • High water content in wet sludge • Precipitation in the pipes	• Trace of heavy metals • Lack of small-scale and decentralized sanitation systems in small-population areas • Possibility of transmissible diseases • Drying would involve high-energy consumption • Transporting high water content is not economically feasible. • Energy use vs. nutrient recovery	• Lack of integrated approach (of social, institutional, and technical strategies/measures • Legislative framework to ensure the adequate level of treatment and general acceptance • Dissimilarities between the processes
Water	• Variation in recovery rate • Most common method used for P removal in water is enhanced biological phosphorus removal (EBPR) or chemical phosphorus removal (CPR). Both methods require high capital costs and high energy consumption, especially high capital investment in mono-incinerators • Major challenge is the separation of remobilized heavy metals from phosphorus and the disposal of the waste contaminated acid. • Geo-engineering for lake restoration	• Issues of locally available land to accommodate the risk of transfer to surface waters • In elution and precipitation processes, the consumption of chemicals needed and thus, the costs can be reduced • Energy use versus nutrient recovery • Phosphorus control versus water quality	• Lack of recommendations and regulations for Waste Water Treatment (WWT) and lack of stringent environmental standards • Lack of incentives

consideration. As some countries have already implemented the above, it is highly essential to revamp our ideas to adopt the regulations on the basis of the regional industrial structure throughout the world. National and regional bodies, industrialists, policymakers, and the public should work globally to develop and popularize the most feasible technologies.

To recover the lost P in natural water is particularly challenging because this is hardly, economically feasible without technical breakthrough. However, our existing society has created a one-way pathway for P from rocks to farms to lakes and oceans (Elser and Bennet, 2011); sooner or later we have to develop new technologies to recapture the lost P from natural waters. Algae cells can effectively concentrate P from water into cells, which is much faster than geological processes. There are already cheap and cost-effective ways to flocculate harmful algal blooms at very large scale (Spears et al. 2014; Shi et al. 2016; Li and Pan 2013; Pan et al., 2011; Zou et al. 2006) which makes it possible to harvest P and take them back to land resource by floating technologies.

Hence, it is suggested to have an integrated approach with biogeochemical, environmental engineering, and socioeconomic views to identify the feasible P-recovery options starting from the material-flow analysis to economically sustainable and environmental-safe technologies for the benefit of human society as well as the environmental security.

Need for an integrated approach

With world population growth and increased per capita production of bioenergy and biofuel crops, the recapturing and reuse will be the potential solution to meet the ever-growing future demand for fertilizer phosphorus. Recycling may be an economic option, only in the case of large and geographically concentrated waste streams because of the accumulation of large amount of sewage and manures from livestock.

The recovery of phosphorus through recycling may definitely become an economically attractive and ecologically viable option and the time has come to invest significant time for developing social, economic, and environmental analyses (Figure 3) to evaluate the costs and benefits of scaling-up phosphorus recovery from available sources throughout the developing world. This can be achieved through the joint research and development programs between water, fertilizer, and phosphorus industries.

The choice of a method is complicated as it is highly site-specific. The regional water quality (influent quantity), size of the treatment plant, and economic considerations play a major role in the selection process. Nationwide monitoring of phosphorus fertilizer application and local and regional nutrient balance is therefore highly warranted. Hence, a comprehensive review has to be taken on the basis of the influent concentration of phosphorus, recognition of that regional soil

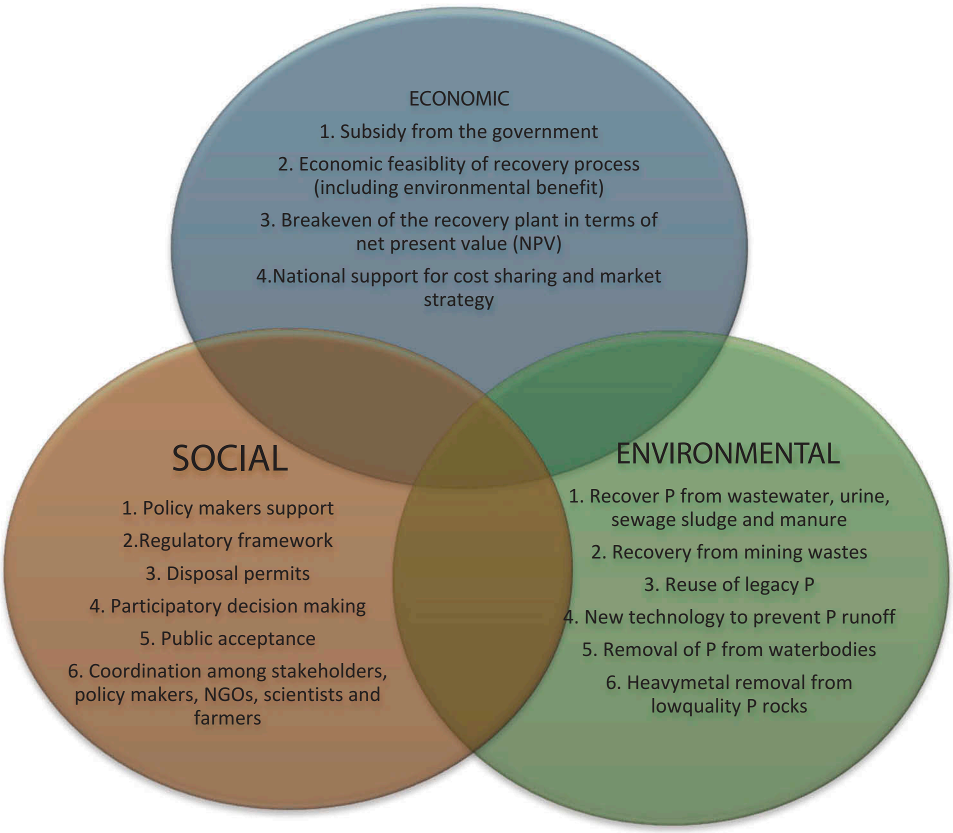

Figure 3. Integrated approach for sustainable uses of phosphorus.

types and physicochemical properties, and potential to use the recycled phosphorus.

Initiatives are necessary for each local government to encourage the use of recovered phosphorus, which will accelerate the process of implementation. Nationwide speed-up for regulatory approvals and increased field applications of recovered phosphorus are highly needed. Legislative and economic incentives and marketing strategy should also be discussed at regional and global levels.

Depending on the quantity and quality (heavy metals) of wastewater and the solid wastes, a global-level feasibility option should be illustrated for the estimation of cost of materials for the recovery plant. It will be useful to the stakeholders and wastewater industry to estimate the level and value of recovered phosphorus. At the same time, awareness and public acceptance about recovery from waste materials and the coordination of nongovernmental organizations, stakeholders, and scientists is essential for realizing the value of phosphorus recovery. Therefore, it is also important that the economic, environmental, and social benefits of the recovery and reuse of P are to be explained to various stakeholder groups such as mineral fertilizer industries, other associated industries, water industry, public members, decision-makers, and regulators.

Conclusion

Phosphorus recovery is considered a key P sustainability option to help reduce the dependency on mined-P and the resulting environmental pollution, and thereby improve and preserve societal well-being and delivery of ecosystem services for future generations. We have defined recovery as a sustainable nutrient management strategy for improving nutrient efficiency and to ensure the food, resource, and environmental security. As P-fertilizer market price increases, recovery could become more economically and socially viable provided that national/regional bodies support the commercial exploitation of recovered P. Hence, revenue generation can be considered as an appreciable opportunity to drive the recovery process. In summary, it is observed that for extensive and efficient P recovery, there exists an on-going and underdevelopment process, some unsolved practical problems, and a large knowledge gap, especially considering the legacy P in the soil. There is no single solution for tackling the P issue; therefore, an integrated approach with socioeconomic, technical, and institutional strategies is needed to ensure food, bioenergy, and water security in the future. To facilitate the P recovery as sustainable option, an integrated approach among scientists, industrialists, stakeholders, and policymakers should be established. For improving food security and water quality, phosphorus recovery provides a valuable solution. An integrated approach provides support for understanding the regional-level agricultural practices, environmental conditions to address the nutrient imbalances at global level, and also to compare the different recovery methods to identify the more economically feasible method.

Keeping in view of ensuring the availability of phosphorus to meet the growing demands of plants, sincere efforts are to be taken globally through many platforms. However, there exists a knowledge gap on integrated assessment of potential solutions and lack of coordination among the global-level researchers, scientists, industrialists, and end-users. Therefore, this article emphasizes the need for an integrated approach on phosphorus recycling and reuse to ensure the sustained availability of phosphorus.

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