Phosphorus Recovery -a need for an Integrated Approach

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Abstract

Increasing cost of phosphate fertilizer, a scarcity of high quality phosphate rock (PR)and increasing surface water pollution are driving aneed to accelerate the recovery and re-use ofphosphorus (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 towards P sustainability and future food, bio energy and water security is in its infancy because of a number of technological, socio-economic and institutional constraints. There is no single solution and resolving these constraints requires concerted collaboration betweenrelevant stakeholders and an integrated approach combiningsuccessful business models withsocio-economic and institutional change. We suggest that an operational framework is developed for fast tracking cost-effective recovery options.

Keywords: Phosphorus, Recovery and Reuse, Phosphatic fertilizers, depletion, Eutrophication

1. 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. 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 thebioavailability 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 et al., 2016). Phosphate rock (PR) as a non-renewable 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 (Cordell et al., 2011). For example, Withers et al. (2015) proposed a global 5R stewardship strategy (Re-align P inputs, Reduce P losses, Recycle P in bio-resources, 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 re-use P from secondary resources as part of the drive towards a P circular economy with zero waste (Withers et al., 2015b). In practice, P recovery in both developed and developing countries is still in itsinfancy and requires more awareness raising,research efforts and business opportunities amongstgovernment, agricultural organisations, industries andthe 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.

2. Drivers for phosphorus recovery and reuse

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

2.1 Scarcity of exploitable phosphate rock

World consumption of Phosphorus fertilizers and industrial use are projected to increase gradually from 43.7 million tonnes in 2015 to 48.2 million tonnes 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 towards the improved recovery rates and the mining of lower grade PR (Heffer et al., 2006; IFDC, 2010; Jasinski, 1998-2013; Ulrich, et al., 2013;Goradzda 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,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 2100that could be a serious threat to the security of the P supply (Van Vuuren et al., 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 phosphours security is directly linked to food security and environmental protection (Cordell et al., 2011; Mayer et al., 2016).

Phosphaterocks often contaminated with heavy metals such as fluoride and cadmium, are usually very high. The extraction / removal of these heavy metals are a costly process and demands more energy. The reduced availability of high quality PR and disposal of by-products further makes 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.

2.2 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 (Jaisinski, 2012). The price in US dollars in 2008 was increased about 800% than 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 to 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, 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).

2.3 Rising levels of water pollution

Increasing population, intensive agricultural production and rapid urbanizationhave 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 non point pollution sources have major impact on the water environment with the increaseofPhosphorus concentration in wastewater and sewage systems. This yields to either fertility erosion or adverse environmental effects like loss of biodiversity, eutrophication etc.

Large amount of Phosphorusare discharged as wastes 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, 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 et al.,1999; Mayer et al., 2016).

The Phosphorus present inthe 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.

2.4 Renewable solution

Phosphorus has no substitute in food production (Cordell 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 et al., 2011). Phosphorus is a non-renewable resource, but fortunately it is possible to recover and recycle. Recovery can occur at all stages of the P cycle (Fig.1).There are also different strategies that be used to recover phosphorus from different sources.

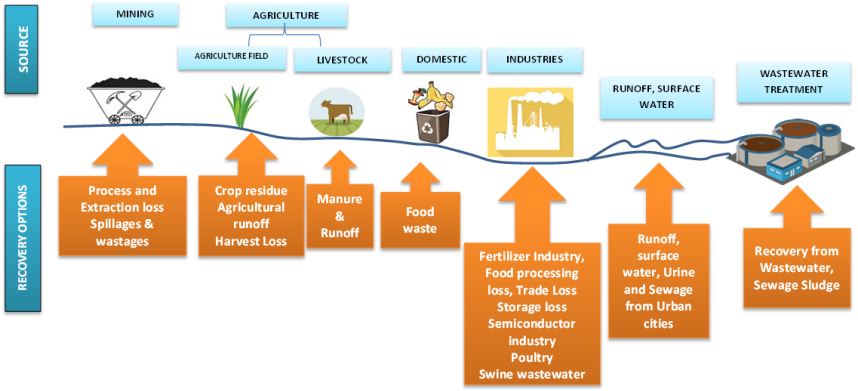

Fig. 1. Phosphorus Recovery Options

In general, Phosphorus is recovered by separation and crystallization process as struvite or hydroxyapatite, and the separated minerals can be used by the fertiliser 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 playa pivotal role in recycling of phosphorus resources.

3.0 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, acidification

have been in common practice. Dry thermal process and thermo mechanical 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 et al., 1999;de-Bashan and Bashan, 2004; Rittman 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 treating 60 m3.hr−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 are much more limited (Balmer, 2004;Desmidt et al.,2015).

4.0 Influence of different variables and strategies

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

Table 1**. Sector wise potential constraints on P Recovery**

Waste sector	**Constraints on P Recovery**		
	Technological	Socio-economic	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 Precovery 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 bio-solid management	• The transportability of P-containing materials other than synthetic fertilizers remains a key technological and economic challenge to closing the P cycle • Feasibility of the recovered phosphorus, odour 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 fertiliser 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 aluminium, lead and cadmium	• Lack of enhancing chemical engineering techniques • Chemical consumption cost for pH adjustment etc.(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 etc.	• 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 decentralised 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 WWT and lack of stringent environmental standards • Lack of incentives

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The recovered products might have some impurities and contaminants such as heavy metals. Occurrence of heavy metals, precipitation contents, nitrogen, potassium, sulphur,have also to be taken care of, during the process of phosphorus recovery. The separation of heavy metals and impuritiesrequires 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 bio-solids or manure for farm land 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 oflow-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, sludge, etc..

Depending upon the wastewater treatment facilities, the recovery unit could be introduced in such a way that it easily fitswith 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 phosphorusfertilizer replacement should be encouraged and be adopted for arable farming. Dynamics of Phosphorus vary depending on the regional and industrial structure (Wyant,*et al.,* 2013). Nationwide statutory requirement to remove Phosphorus is to be taken into 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, policy makers 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 (36), sooner or later we have to develop new technologies to re-capture the lost P from natural waters. Algae cells can effectively concentrate P from water into cells, which is much faster than geological processes. There is already cheap and cost-effective ways to flocculate harmful algal blooms (HAB) at very large scale (37-41), 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 socio economic 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.

5.0 Need for an Integrated Approach

With world population growth and increase per capitaproductionof bio-energy and bio-fuel 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 significanttime for developing social, economic and environmental analyses (Fig.2) to evaluate the costs and benefits of scaling-upphosphorus recovery from available sources throughout the developing world. This can be achieved through the joint research and development programmes between water, fertilizer and phosphorus industries.

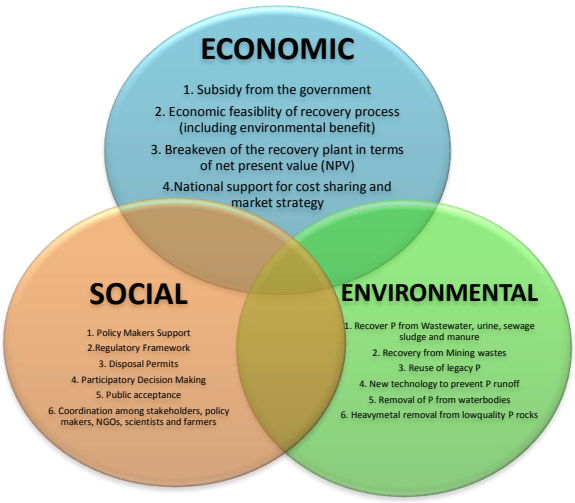

Fig. 2 Integrated approach for Sustainable uses of Phosphorus

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 plays a major role in the selection process. Nationwide monitoring of Phosphorus fertilizer application and local and regional nutrient balance is therefore highly warranted. Hence, acomprehensive review has to be taken on the basis of the influent concentration of Phosphorus, recognition of that regional soil types and physic chemical 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 andincreasedfield applications of recovered phosphorus are highly needed.Legislative and economic incentives and marketing strategy should also be discussed at regional and global level.

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 co-ordination of nongovernmental organisations, stakeholders and scientists is essential for realising 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.

6.0 Conclusion

Phosphorus recovery is considered a key P sustainability option to help reducethedependency on mined-Pand the resulting environmental pollution, and thereby improveand 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 priceincreases, recovery could become more economically and socially viable providedthat national/regional bodies support the commercial exploitation of recovered P. Hence, revenue generation can be considered as appreciable opportunity to drive the recovery process. In summary,it is observed thatfor extensive and efficient P recovery, thereexists an on-going and under development 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 socio-economic, technical and institutional strategies is neededto ensure food, bioenergyand water security in the future. To facilitate the P recovery as sustainable option,an integrated approach among scientists, industrialists, stakeholders and policy makers should beestablished.

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 emphases the need for an integrated approach on Phosphorus recycling and reuse to ensure the sustained availability of phosphorus.

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