Global phosphorus and the case for phosphorus recovery

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The need to manage the demand and supply of this important resource has become crucial.

Introduction

Phosphorus is obtained primarily through surface mining (about 75%) of phosphate rock. The vast majority (more than 80%) is mined from sedimentary formations, in which the phosphate content ranges from 5% to 40% as the P_2O_5 apatite form. As more and more of these formations are mined, the quantity of phosphate recovered is in decline, and because sedimentary rock contains heavy metals (such as cadmium), the quality of the phosphates being recovered is also in decline. Today, for every tonne of phosphate rock processed, 5 tonnes of a waste product, known as phosphogypsum, is created. This waste product is not easily disposed of because it is a radioactive hazardous waste due to its high levels of radium. As a result, large stockpiles of waste phosphogypsum are accumulating worldwide.

Phosphorus is the 11th-most abundant mineral in the earth's lithosphere. The estimated global presence of the phosphate resource is in the range of 4000 billion metric tonnes. But much of the resource is currently inaccessible. In fact, the estimated accessible reserves range from 30 billion metric tonnes to 40 billion metric tonnes. These are currently being extracted at rates estimated at 167 million metric tonnes per year, though current global production capacity exceeds 6,300 million metric tonnes. Reserves are estimated based on the economics of accessibility. A reserve is considered countable if it can be profitably extracted. In the case of phosphates, this has historically been about US$ 40/tonne. Obviously, as economic trends change, they affect profitability and therefore reserve estimates also change.

Despite the apparently large phosphorus resource base, there are indications that the known accessible reserves could be depleted by the end of the 21st century. The reason lies in the phosphorus cycle. Once phosphorus is mined, it enters the human use cycle (for example, in supporting food production). That phosphorus eventually (that is, over decades) returns to the soil or water environments as a component of the waste products from human activity. Once in these environments, though some can be reused (through re-uptakes in new terrestrial and aquatic biotic growth), much remains 'bound' and re-enters the geologic cycle (through sedimentation) which spans millions of years before it can be mined and used again. Once phosphorus re-enters the geologic cycle, it is, for all intents and purposes, forever lost for further beneficial use. This is illustrated in Figure 1.

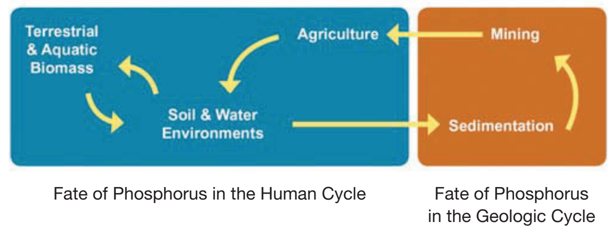

Figure 1: Fate of phosphorus.

Estimates show that since just 1950, the phosphorus lost to the geologic cycle exceeds 25% of all the phosphorus mined to-date. Unless phosphorus is prevented from re-entering the geologic cycle, there is a point in the future when the extractable reserves will be depleted, as mentioned above. This is expected to carry dire consequences for human existence as one knows it today. Therefore, whether or not phosphorus depletion becomes a global reality depends much on managing global demand for phosphorus with remaining available supply.

Global demand

Though the phosphorus mineral was first discovered in the late 1600s, it was not until more than 200 years later that its highly beneficial use as a fertiliser (for enhancing food production) was first realised. Today, fertiliser is by far the dominant use for phosphorus (more than 90% of mined phosphates are used in producing agricultural fertilisers for food production). Due to its large agricultural sector, the US accounts for nearly one-quarter of the world's total demand for phosphorus, while China/Asia accounts for about one-fifth, due to both agricultural and industrial expansion.

The global demand for phosphate-based fertilisers continually grows, and without doubt, it remains the fundamental pillar in the world's capacity to support its expanding population. Not surprisingly, because of its direct link to food production, demand for phosphate-based fertilisers (and hence its price) is heavily influenced by the agricultural sector's capacity to produce enough food to support continued population expansion. It has been estimated that food production must increase between 50% to 70% in order to meet the food needs for the estimated 9.2 billion population in 2050. The greatest influence on the demand for phosphorus for fertiliser production is the energy input required for producing phosphate-based fertilisers, and historically the energy source has been fossil fuels. As energy prices rise, fertiliser prices rise concomitantly.

Global population growth is not the only thing driving demand for phosphorus. Rapidly advancing economies in developing countries in Asia, Africa and South America are demanding higher protein-enriched diets (particularly meat) which in turn require significant increases in food chain production. Furthermore, the increasing demand for biofuels to supplement fossil fuels in the world's expanding transportation sector also places new demands on phosphate-based fertilisers.

Can the globe's supply of phosphorus meet these growing demands? The remaining reserves of phosphate-based rock are known to be located predominantly in China, Morocco, South Africa and the US. Together, China and Morocco hold 75% of these reserves. Some believe that additional reserves will be located as extraction and recovery technologies advance (for example, from off-shore deposits), but this remains highly speculative. Many argue, therefore, that demand will continue to outpace supply until reserves are depleted, unless major shifts occur in the way phosphorus demand is currently managed. And some believe these shifts must be accomplished within the next two decades.

Closing the supply-demand gap

Closing the gap between the expanding demand for phosphorus and its shrinking reserves can be addressed on several fronts. Clearly, a major change in the manner in which the world's food production chain is managed is crucial. Research has shown that from the point of phosphate extraction from a mine, to the point of human consumption of food, more than 80% of that source phosphorus is lost, and much of that to the geologic cycle. This is depicted in Figure 2. It is estimated that about 20% is lost in the extraction and fertiliser production processes and about 60% is lost in the food production (40%) and consumption (20%) chains.

By applying basic best management practices in food production supported by governmental policy interventions, it is believed that global phosphorus demand can be reduced by more than 25% by the end of this century. Coupling this with shifts away from meat-based protein diets, the overall demand can be reduced by half.

Figure 2: Phosphorus losses.

Human waste has, for millennia, been used as fertiliser in supporting food production. This is due to the concentration of nutrients present in human excreta material. It is estimated that based on the current global population, if all human excreta wastes were collected and used as fertiliser, this could replace nearly one-third of today's global phosphorus-based fertiliser demand. Though this may seem impractical today, it is clear that the recovery of phosphorus from human waste must be, and indeed eventually will be, a significant part of the total solution for balancing phosphorus demand with its supply. The opportunity to do so exists in both developed and developing countries.

In the developing world, the most significant opportunity lies in source separation of urine and faecal wastes. As these countries develop, and new, 'first-in' infrastructure for wastewater collection and treatment systems is considered, it is appropriate for the sewerage collection infrastructure to allow for the separate collection of urine and faecal matter. Waste separation is most cost-effectively accomplished at the source point (that is, using special toilets installed in homes, businesses and institutions, that are designed with the means to separate urine and faeces).

Urine contains more than 50% of the phosphorus that enters a treatment facility. By separating the urine, the phosphorus can be readily recovered by simple precipitation chemistry (either at the source or at a central collection and storage facility) and readily reused as a slow-release fertiliser. Furthermore, wastewaters that have urine removed are more stoichiometrically balanced in terms of their carbon, nitrogen and phosphorus content, and therefore more efficiently treated in conventional biological treatment systems. This has the ancillary benefit of reducing energy inputs in the treatment process.

In developed countries, the opportunity, though present, is much more complicated. In many of these countries, sewage collection infrastructure has been in place for decades and it does not have the means for separating waste streams. The massive investments societies have made in these fixed assets make it impractical, and politically next to impossible, to abandon them in favour of creating new (or even retrofit them with) infrastructure designed to accommodate source separation on a large scale. Instead, the opportunity for developed countries currently lies in the removal and recovery of phosphorus from the liquid and solids ractions of the full sewage flow at 'end-of-line', or central treatment facilities.

In many developed regions and countries (particularly Europe and the US), regulatory frameworks are in place to reduce nutrient loads being discharged into the environment via the effluents from municipal and industrial wastewater treatment works. As a result, schemes for the removal of phosphorus to meet these regulations have historically focused on chemical precipitation using metal salts. Unfortunately, this transfers phosphorus to the geologic cycle leaving it unavailable for recovery. More recently, however, technologies have been developed whereby phosphorus is recovered from the treated waste streams again using precipitation chemistry, but resulting in a precipitate form that is immediately available as a slow-release fertiliser for agricultural use. This precipitate is essentially struvite, a phosphate mineral compound consisting of magnesium, ammonium, and phosphate ($NH_4MgPO_4 \cdot 6H_2O$ and occasionally referred to as 'MAP') whose solubility is extremely low in natural waters.

Though the recovery of phosphorus using struvite precipitation chemistry is feasible from most municipal (and some industrial) wastewater streams, it has been found to be most efficient and cost-effective when applied to treatment facilities that employ biological phosphorus removal technology coupled with anaerobic digestion of the excess solids.

Up to 90% of the phosphorus present in a raw wastewater stream can be recovered from the solids treatment train (Figure 3). In the biological phosphorus removal process, phosphorus is concentrated in special bacterial species capable of storing phosphorus in quantities far exceeding those amounts needed for growth and reproduction. During exposure to anaerobic environments in the treatment plant (such as anaerobic digestion), this stored phosphorus is released from these bacteria back into solution where it remains with the digestion reject streams (such as solids dewatering centrates or filtrates) where it can be readily precipitated as struvite at reasonably high recovery efficiency rates. In fact, systems are now commercially available that are designed to provide this recovery function, and can be easily integrated into the treatment train. The resulting struvite product is then directly marketed as a fertiliser.

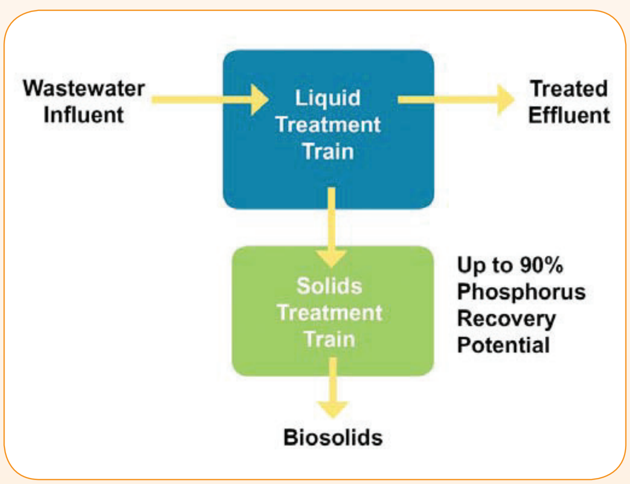

Figure 3: Phosphorus recovery from solids train.

The recovery function is not limited to the reject streams from anaerobic digestion. Processes exist where phosphorus is removed and recovered ahead of the digestion process, again as a struvite byproduct. The advantage of these types of systems is that they significantly reduce the potential for undesirable struvite formation within the digester unit, which results in extensive maintenance challenges.

It is noteworthy that the predominant application of these commercial phosphorus recovery systems has been at facilities that employ biological phosphorus removal technology. However, numerous conventional facilities, which have integrated anaerobic selector zones into their conventional activated sludge treatment train for purposes of improving settleability of the activated sludge, find that some degree of biological phosphorus removal often develops inadvertently, paving the way for phosphorus recovery from these as well. However, much research remains to be done, to develop efficient and cost-effective methods for recovering phosphorus (via the struvite or other mechanisms) from conventional treatment systems.

Conclusion

Phosphorus is a finite resource. Because it has no known substitute, when it is depleted, the world would have no way to sustain life as is currently known and understood. Debating whether phosphorus will deplete in 50 years or 300 years is meaningless. What matters is that the world cannot continue in a 'business-as-usual' mindset with respect to how the phosphorus resource is utilised. The solution to the global phosphorus problem lies not in exploring for new sources of supply, but in managing and reducing the current demand for phosphorus. Reducing demand requires improving the efficiency by which existing phosphorus supplies are utilised, that is, reducing losses in i) fertiliser production ii) the 'farm-to-fork' food production chain and iii) the food consumption chain, and by recovering phosphorus from all known waste streams.

The recovery of phosphorus from municipal (and some industrial) wastewaters is the opportunity that must not be overlooked and it exists in both the developing and developed societies. In the developing countries, it lies in installing new sewage collection infrastructure that separates waste streams at their sources such that phosphorus can be efficiently and cost-effectively recovered. In the developed world, it lies in outfitting existing treatment infrastructure to achieve phosphorus recovery. This is being done within treatment systems already designed to remove phosphorus for regulatory compliance, but it needs to expand into all levels of treatment, including conventional levels. In all cases, the goal is to capture the phosphorus from the waste stream and recycle it directly to the human cycle rather than losing it forever to the geologic cycle.