



Sustainable Use of Phosphorus: Capturing the Philosopher's Stone
M.A. de Boer

Summary

Phosphorus (P) is essential for all forms of life. It cannot be substituted and it is indestructible as it is a chemical element. Each year, 263 million tons of phosphate rock is mined, but only a fraction makes it back into the soil. Crops are consumed and end up in the sewage system as waste. Even though phosphorus is a scarce element, most phosphorus is lost in water bodies after consumption, leading to extreme algae growth and water pollution. Humanity could only produce half of the food that it does today when phosphorus-containing fertilizers could not be added to the soil. Therefore, phosphates should be recovered and recycled to close the cycle.

In this PhD thesis entitled “Sustainable use of phosphorus: capturing the philosopher’s stone” several essential aspects for converting our current linear P economy to a circular P economy have been discussed. Growing cities entail challenges, but opportunities too. Nowadays, waste is controlled at centralized wastewater treatment plants (WWTPs), which enables urban mining. A particular solution is the recovery of P at these urban mines as struvite or sewage sludge ash, which is progressively more implemented.

In **Chapter 1**, the current status quo of the phosphorus market has been described. Phosphate reserves are not equally spread around the world, with three-quarters located in Morocco and The Western Sahara. Moreover, studies regarding the estimated time until depletion of phosphate rock deviate significantly with respect to each other. The main intermediary compounds for phosphorus products are

phosphoric acid, mainly used for fertilizers, and white phosphorus, which is the key building block for the chemical P industry. About 95% of phosphoric acid is made via the wet-process by acidulation of phosphate rock to create wet phosphoric acid as well as phosphogypsum and hydrogen fluoride. An important aspect for the processing of phosphate rock is the quality of the rock, which is dependent on the ore type (sedimentary or igneous), level of radioactivity and hazardous metal contents. Wet phosphoric acid can be further purified via extraction and precipitation processes to obtain phosphoric acid comparable to that produced by the thermal process.

Currently, phosphate rock is used as the starting material, but with the focus on a circular P economy it is interesting to investigate secondary phosphates harvested from urban mines, such as struvite, too (**Chapter 2**). Recent work, published by Chen et al., has been considered by the European Commission for guidance concerning the revised fertilizer regulation. Chen et al. states that application of struvite alters the antibiotic resistome in soil. They did, however, not describe their struvite recovery method and found that various antibiotics were detected in struvite, while other studies have shown that organic contaminants are typically not present in struvite after precipitation. To date, most struvite is recovered from municipal sources with significantly lower levels of antibiotics than what is found in the piggery wastewater that the authors investigated. Therefore, the use of the research of Chen et al. to guide policy for recovered phosphate products is inappropriate.

To analyse the health risks of the use of struvite, we have studied the uptake of pharmaceuticals into the crops fertilized with contaminated struvite in

combination with the NH_4^+ adsorbent materials biochar and zeolite, described in **chapter 3**. Five fertilizers were prepared by nutrient recovery from urine spiked with six pharmaceuticals using: struvite crystallisation (1), struvite crystallisation combined with N adsorption on zeolite (2) or biochar (3), N adsorption on zeolite (4) or biochar (5) without struvite crystallisation. The fertilizer with the highest purity product and the lowest uptake of pharmaceuticals was struvite combined with zeolite (2).

The bioaccumulation of pharmaceuticals in tomato fruit biomass from each of the contaminated fertilizers in the crop trial was found to be lower than 0.0003% in all cases, which is far below the acceptable daily intake (ADI) levels (750 kg of dry tomatoes should be consumed per day to reach the ADI limit). Consequently, the subsequent risk to human health from tomato fruit grown using urine derived struvite-sorbent fertilizers is found to be insignificant.

In order to reach a circular phosphorus economy, it is essential to define the specific flows and recovery potential of the greatest P losses in the cycle. We have developed for the first time such a complete, quantitative overview, which highlights the potential of urban mines for P recovery in the Netherlands (**chapter 4**). Appropriate P recovery technologies are already available to prevent phosphorus losses at wastewater treatment plants or via sewage sludge ash treatment, yet these are not widespread implemented. Furthermore, we formulated several P recovery scenarios to illustrate the recovery potential for The Netherlands and its relation to the current national phosphorus demand.

Our results show that The Netherlands can be self-sufficient for its own fertilizer production, if P from the prospective urban mines is recovered and recycled efficiently. 100% of the Dutch sewage sludge is already mono-incinerated into sewage sludge ash. In weight, the P in the Dutch sewage sludge ashes can cover up to 275% of the Dutch fertilizer demand, from which 121% is the high quality Bio-P ashes.

We have also calculated the recovery potential by implementing struvite precipitators at the larger WWTPs (>50.000 population equivalent), of which thus far about two-third have implemented Bio-P removal. If all WWTPs that currently use Bio-P removal will implement the most effective struvite precipitator, 79.7% of the P of our fertilizer demand can be covered. 539–3.187 ton of P/yr can be recovered in the form of struvite, which corresponds to 4.401–26.027 ton of struvite/yr. If all WWTP will use Bio-P removal and implement a struvite precipitator, this will afford 1.144–4.579 ton of P/yr, which corresponds to 114.5% of the Dutch fertilizer demand. The next step after recovery is recycling. Therefore, it is vital for the creation of a circular phosphorus economy that the end-products have a market demand and can be applied as high-grade fertilizer.

We have addressed the current status quo of phosphate production, the quality of the recovered products and the potential to cover the national demand; other essential aspects for a P recovery transition are the drivers and barriers of the actual implementation of the technologies (**chapter 5**). Several key stakeholders involved in this transition in The Netherlands were interviewed, which enabled us to address the current barriers and drivers of phosphate recovery transition from urban mines from a political, economic, social, technical, legal and environmental

viewpoint. The main barriers found for fertilizer companies were the different and unclear characteristics of struvite compared to common fertilizers and the end-of-waste status of struvite that hinders free market trade. Many water boards indicate that the main barrier is the high investment cost with an uncertain return on investment for on-site struvite recovery processes. The main driver for struvite is the reduction of maintenance costs of the wastewater treatment plants and for phosphorus recovery from sewage sludge ash the low organic pollutants in the P recovery product.

The Netherlands is a front-runner on phosphate recovery and therefore an interesting case for understanding sustainable transitions, which is analysed in **chapter 6**. Several frameworks exist to understand socio-technical transitions. In this study, a framework will be discussed which combines the multi-level perspective, explaining the pressures from the niche and landscape level, with institutional entrepreneurship to clarify the entrepreneurial activities within the regime based on happenings and entrepreneurial activities explored within the Dutch phosphate transition.

