Phosphorus Recovery and Recycling

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Editors

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Foreword: Phosphorus Recycling — Mending a Broken Biogeochemical Cycle by Roland W. Scholz

Understanding the Dissipative Nature of Phosphorus

The book *Phosphorus Recovery and Recycling* is a milestone in the course of taking global action to sustainably mend an *anthropogenically broken natural-phosphorus cycle*. Phosphorus is a *bioessential* and *unsubstitutable element of life* and a necessity for food production. In most ecosystems of the world in its pre-agricultural age, weathered phosphorus atoms cycled many times on a small scale before erosion and runoff transported particulate and soluble phosphorus to the ocean or it became unavailable as a result of lithification or leaching processes. For atoms that end up on the seafloor, it takes 10–100 million years before they become re-exposed by tectonic uplift. This has been fundamentally changed by agricultural activity, particularly the arable land covering approximately 10% of Earth's terrestrial area (Smil 2000; Scholz et al. 2014). On agricultural land, a larger number of phosphorus atoms do not cycle a single time.

Today, 50% of worldwide food production is estimated to be based on mineral fertilizers (Galloway et al. 2008). There are no reliable estimates of global runoffs and erosion, but phosphorus flows have a dissipative nature. According to the literature, global estimations suggest that about one third of mineral fertilizers are lost by runoff and erosion (from weathered and mineral fertilizers) annually (Scholz et al. 2014). An assessment of hidden or virtual phosphorus flows is needed, e.g., for food production, and thus is an important factor for sustainable food management.

If we look at the supply side of the mineral phosphorus supply, there is no technology on the horizon or an alternative compartment (such as aquatic systems) to higher concentrated but finite phosphate rock deposits that could substitute for phosphate mining from ores. If we were to consider covering the current annual mineral phosphorus production from (average) seawater, this would require us to extract phosphorus from seawater at an average volume of the magnitude of 100 times the Amazonas effluent (Scholz and Wellmer 2013a). Alternatively, seabed mining could provide access to additional phosphate rock deposits. However, from an environmental perspective, this is an ambiguous and highly uncertain option.

Thus, the long-term supply security of phosphorus of mineral origin for humankind is questionable. For example, the 2017 USGS Mineral Commodity Summaries on *Phosphate Rock* (Jasinski 2017) states "**Recycling:** None."[1] Let me explain why this is a critical issue and why the present book is an overly timely, important, and – in my opinion – key contribution to sustainable resource management.

Phosphorus Recycling, a Key Feature of Sustainable Agriculture

As described by Franklin Hiram King (1848–1911) in his book *Farmers of Forty Centuries* (King 1911/2004), the Asian agricultural system has developed technologies for recycling almost everything in order to enable "permanent agriculture." This has included the use of night soil or mud from rivers where dissipated phosphorus from agriculture, sewage, etc., have accumulated. King notes: "Manure of all kinds, human and animal, is religiously saved and applied to the fields in a manner which secures an efficiency far above our own practice" (p. 9). Asian farmers were "scrupulous in their care to make everything that can possibly serve as fertilizer for the soil" (p. 23). This phrasing may also be applied to desperate farmers' raiding of Napoleonic battlefields such as Waterloo (1815) to access potential fertilizers from the bodies of the dead (Hillel 1991). The recycling of organic fertilizers has become a fundamental characteristic of the stable, viable Asian model of agriculture. Furthermore, historically, we find similar patterns in other parts of the world.

Reshaping the Derailed Phosphorus Cycle of the Industrial Age

Since the start of the Industrial Age, humankind has faced strong growth of national and, thus, global GDP is linked to – in many domains – an almost exponential increase in the consumption of energy carriers, construction aggregates, industrial minerals, and metal ores. Technological innovation has been a key driver of this increase. The foundation for the increase of mineral phosphorus use is based on Sir John Bennet Lawes' (1803–1873) patent for producing superphosphate by treating phosphate rock with sulfuric acid. We can see this as a cornerstone of increasing the world's carrying capacity of population size. Industrialization was accompanied by a rapid increase in urbanization. The small-scale, largely closed nutrient-recycling scheme on the scale of farms, villages, and small towns (including the night-soil industry) was broken. Today, most of the phosphorus in sewage, for instance, is not

[1] There are certainly some recycling streams in agriculture and other fields. However, no statistically relevant phosphorus recycling of phosphorus which can be used in idustrial processes takes place from sewage, manure, food waste, industrial slags, or other streams from a mineral economics perspective.

recycled. Globally, only a small share of households and industries are connected to sewerage systems. Estimates suggest that "it is likely that over 80% of wastewater is released" (Connor et al. 2017) without adequate centralized or decentralized treatment. In Croatia, a member state of the European Union, approximately 70% of wastewater is released without treatment (International Bank for Reconstruction and Development / The World Bank). This situation leads to severe environmental impacts, primarily for the world's *poor*, i.e., lower-income countries. But in addition, the situation in developed, high-income countries has become critical, for instance, as the direct recycling of phosphorus via centralized sewage plants has become uneconomic (due to the costs of long-distance transportation) and therefore has been discontinued. In other developed countries, direct recycling has been halted for environmental (heavy metals) and health (pathogens) reasons. Germany, however, has recently continued allowing the direct application of sewage from small-scale – mostly rural – wastewater sewage plants (Bundesregierung Deutschland 2017). Manure flows from animal factory production are another significant stream whose recycling potential is not fully used, and it is much larger than sewage flows (globally of factor 2–3).

From Recovery to Recycling

Phosphorus is a Janus-faced element and has been called the devil's element (Emsley 2000). Phosphate minerals are the source of a key nutrient, but in its elemental form, white phosphorus (P_4) is highly toxic and was banned from use in matches (then called Lucifers) by the Berne Convention in 1906. Phosphorus is an essential raw material of high value adding industrial products, including EV, electronics, pharmaceuticals, and high-functional plastics. Furthermore, although phosphorus is an excellent additive for effective detergents, wastewater from laundry, like phosphorus loads in human urine and feces, causes environmental damage and dead zones in aquatic systems. This situation calls for phosphorus recycling of wastewater in highly populated areas such as urban systems. In order to attain this ambitious goal on a global level, humankind has a long road ahead. Increasing the current low percentage of centralized and decentralized sewage treatment is a major goal and must precede recovery and recycling. Besides sewage, phosphorus inherent to slaughter and food waste, manure from various animal species and types of farming, industrial slag, and industrial wastes including phosphorus must be identified and, ultimately, recovered. The benefit of recovery is the reduction of environmental damage – and thereby costs – to lakes, rivers, coastal zones, etc. Estimates for the United States suggest that nutrient pollution costs about $2.2 billion annually in diminished property values (Dodds et al. 2008).

Recovery from within the supply chain as well as at the end of the pipe frame is feasible. However, as the world of tomorrow may see 80% of the world's population living in cities, proper technologies and policy instruments are needed to promote, foster, and establish economic phosphorus-recycling schemes today for the sewage and human biowaste.

Moving Toward a Circular Economy

Japan, countries of the European Union, and several other highly developed nations are on the cusp of advancing from recovery to recycling. The European Union demonstrated its strong commitment to phosphorus in 2014 when it put phosphate rock on a list of critical raw materials and referred to recycling as a potential option in terms of economic importance and supply risk. This significant step was taken although, at the present time, there is no physical scarcity of phosphate rock supply in the short term, i.e., in this century and most likely not in this millennium (Scholz and Wellmer 2013b). In a recent paper (Scholz and Wellmer 2018), we analyzed the reasons this route was taken and identified three. *First*, recycling would increase supply security. This relates to the 2007/2008 price peak of fertilizers and agro-goods, as well as the fact that a large share of the globally traded phosphorus is sourced from countries with political stability rated as low. As such, recycling can foster increasing diversity among phosphorus producers and thereby reduce supply risk. A *second* reason is linked to the principle of intergenerational justice, a basic regulative concept that was agreed upon at the 1992 United Nations Rio Convention. In order to reduce opportunity costs for future generations and provide long-term access to high-grade deposits, the broken phosphorus cycle has to be closed. *Third*, the key ideas of a *circular economy* (Pearce and Turner 1990; Ghisellini et al. 2016), or *cradle to cradle* (Braungart and McDonough 2002), which are less than 30 years old, increasingly acknowledge that recycling and closing loops in the supply–demand chain are at the competitive edge of economic development.

Toward Technology Development for Sustainable Resource Use

The book *Phosphorus Recovery and Recycling* focuses on the perspective of highly developed European and Asian countries (in particular, Japan). Many chapters strongly emphasize high-quality phosphorus recovery from sewage plants (in which phosphorus precipitation by chemical or biological means has been achieved) or slags from steelmaking. This is certainly one important line of sustainable technology development that may contribute to a responsible use of phosphorus through its recovery from different types of wastes. However, we should not forget that much phosphorus could be recovered from mining wastes. If we take a view of the entire supply-chain perspective (this view has been taken in Scholz et al. 2014), about 30–50% of the phosphorus in mines does not enter the value chain (Scholz and Wellmer 2015). Here, secondary mining, i.e., extracting the phosphorus from (lower-grade) mining waste by floatation, would be beneficial from a number of perspectives. We suggest that mineraI flow analysis and mineral flow management could help identify the most efficient recycling potential in globalized, highly technologically developed countries and in the potentially digitally monitored world of the twenty-first century. If we take this perspective, we can argue that the recovery of phosphorus from sewage is not the most important issue from a mass-flow perspective. Sewage includes only about 5% of the anthropogenic flows (Scholz and Wellmer 2015), and only a small amount of this small percentage is accessible via wastewater treatment.

However, the recycling of phosphorus from sewage is undoubtedly at the cutting edge of technology development and may pave an important section of the road toward phosphorus recycling. There are a couple of thermal, chemical, and presumably biological technologies that are on the cusp of becoming economically competitive by substituting other – obviously unsustainable – pathways, such as disposing (phosphorus of) dried sewage in the incineration processes of cement production or coal-fired power plants. Finally, urban sewage and biowaste (e.g., food waste) can be economically recycled, as they are available in a highly geographically concentrated form. These phosphorus-recycling technologies should be supported by proper political or legislative actions. The 2017 amendment of the German sewage sludge ordinance serves as a good example. This amendment demands that – after a transition phase of 12–15 years – any larger German sewage treatment plant (i.e., 500 of 9300 existing plants treating two thirds of Germany's sewage) will be required to recover 50% of the phosphorus in sewage water (if P concentrations in sewage sludge are not below 20 g P per kg of dry matter) (Scholz and Wellmer 2018). This promotes what I like to call the *sustainability competition of technologies*, in this case, for phosphorus recycling. I am confident that the present book, like this German law, should be considered significant "catalysts" or steps forward on the journey toward a sustainable future of resource management.

Several main challenges of sustainable phosphorus recycling were identified at the end of the Global TraPs project (2010–2014), a transdisciplinary process that included key actors of all nodes of the supply chain. At that time, two of seven "hot spot" areas identified for gaining better insight into sustainable phosphorus management were related to recycling. One was the "economic extraction of heavy metals/radionuclides," particularly from phosphate fertilizers. The other was "phosphorus recycling technologies for integrated soil fertilization" (Scholz et al. 2014). The latter includes nutrient utilization from sewage ash and slags in the recycling stream as well as the melioration and processing of sewage, e.g., by contamination-free mineral fertilizers. The present book elucidates, deepens, and broadens these issues in a comprehensive and substantiated manner.

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Preface

Phosphorus (P) is an essential element for all living organisms. Since P cannot be replaced by any other element in biochemical processes, humans ultimately rely on P availability. Today, P is mostly obtained from mined phosphate (P_i) rock. However, global P_i rock reserves are concentrated in a limited number of countries such as Morocco, Iraq, China, and Algeria (USGS 2017). More than 90% of countries in the world have no significant reserve of P_i rock and are most entirely dependent on imported P. Nevertheless, P_i rock is a nonrenewable resource on a human time scale, and high-grade P_i rock is being depleted by ongoing mining worldwide.

The current use of P is inefficient and leaky, particularly in the agricultural sector, thereby causing eutrophication problems in natural bodies of water. Moreover, since P_i rock is generally contaminated with toxic heavy metals and radioactive elements, there is some concern that they may cause health and environmental issues through the long-term application of chemical fertilizers to farmland. In this sense, the sustainable management of P is becoming an increasing global concern on food and environmental securities. International and national platforms to address issues surrounding the sustainable management of P have been founded in Europe, North America, and Japan.

P recovery and recycling can play a critical role in closing the anthropogenic cycle of P, thereby contributing to the sustainable management of P. This book presents the latest research advances, innovations, and applications of P recovery and recycling which is becoming a rapidly evolving and challenging field of engineering. Full-scale applications are highlighted to illustrate the performance and effectiveness of the new technologies. This book provides advanced engineering knowledge, information, and new ideas in the field of P recovery and recycling practices. The intended audience for this book includes engineers, planners, consultants, municipal staff, and resource managers, among others.

This book is structured in seven main parts. Part I first reviews the enabling/disabling legal and social framework on P recovery and recycling. The individual six chapters of Part I deal with a different aspect of the framework, including P flow, circular economy, life cycle assessment, P reserves, production and applications, and success factors for full-scale implementation. In particular, Chap. 1 gives a comparative overview of the full-scale applications and their importance in relation to the potential in Europe and Japan which are front-runners in P recovery and recycling practices in the world. Both Europe and Japan have a multitude of reasons for proactively seeking strategies for sustainable P management: high P import dependency, soil nutrient imbalance, eutrophication, and agricultural sustainability. Chapter 1 also introduces the innovative P value chain concept that maximizes the synergies of P recycling across the biosphere and the technosphere. The technology and business innovation based on P recycling, called P innovation, is expected to make a great contribution not only to the sustainable agricultural production but also to the secured supply of high-purity P to the manufacturing industry.

The twenty three chapters of Parts II to V cover recent research advances and applications of P recovery and recycling from secondary resources such as incinerated sludge ash (Part II), sewage sludge and night soil (Part III), steelmaking slag (Part IV), and animal manure (Part V). Each chapter covers a different technology option for P recovery and recycling from secondary resources. In particular, Chaps. 8, 9, 17, 18, and 25 highlight the performance and effectiveness of the full-scale applications. Chapters 7 and 14 also introduce full-scale processes for manufacturing phosphoric acid from sewage sludge ash, while Chap. 16 sheds light of the full-scale production of fertilizers from secondary resources. Finally, Parts VI and VII cover emerging technologies for P recovery and recycling using solid adsorbents and biotechnology.

We hope that this book provides a cutting-edge resource of information in this rapidly evolving field for a variety of readers, including students, researchers, and professionals interested in and responsible for sustainable use of P. This book can also be considered, in a way, the follow-up of the previous book entitled *Sustainable Phosphorus Management*, published by Springer in 2014. We would like to encourage readers to go through this previous book for a better understanding of the sustainable management of P. We also hope that this publication will promote further progress in the research and development of P recovery and recycling. Finally, we would like to thank all the contributors for their willingness to share their knowledge, know-how, and experiences in this book. We must appreciate the time and efforts of all the contributors for committing their time to the publication of this book.

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