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Phosphorus – a “political” element for transdisciplinary chemistry education

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Abstract:

The paper describes a curriculum innovation project for integrating the sustainability-oriented socio-scientific issue of phosphate recovery into undergraduate chemistry education. Justification for the topic is derived from the importance of responsible use of phosphates as fertilizers for achieving some of the sustainable development goals issued by the United Nations in 2015, but also by the consideration of the phosphorus biochemical flow into the environment in the concept of the world's planetary boundaries. Integration of the topic into undergraduate general chemistry was operated by a digital learning environment providing the base for a transdisciplinary approach towards the topic. Findings are reported from an implementation case in a research university in the USA.

Keywords: chemistry curriculum development, education for sustainable development, phosphate, phosphate recovery, transdisciplinary learning

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Introduction

A mere glimpse at current headlines provides a whole spectrum of risks for life on Earth. Many of these, including climate change and biodiversity loss, are triggered or intensified by mankind. Several of these issues are highlighted in the concept of planetary boundaries; among them, the biochemical flow of phosphorus/phosphates into the environment has critical importance (Rockström et al., 2009). The concept of planetary boundaries identifies a safe corridor for mankind's future. In 2015, the United Nations issued a report with the 17 Sustainable Development Goals (SDGs), which require our world to stay within these boundaries through sustainable development.

Chemistry is central in achieving sustainability and in fulfilling many of the SDGs, such as those concerning clean water and sanitation or limiting climate change (Matlin, Mehta, Hopf, & Krief, 2015). The crucial role of chemistry in creating a more sustainable future is not limited to transforming production lines in the industry to be more environmentally friendly. As part of education for sustainable development (ESD), chemistry has also unique responsibility in preparing the minds of future global citizens, so they can develop plans and take actions to achieve the SDGs (Burmeister, Rauch, & Eilks, 2012). Chemistry education for sustainability should allow learners to gain insights into the interrelatedness of chemistry, society, technology and the environment (Hofstein, Eilks, & Bybee, 2011; Sjöström, 2013). This is a challenge but also a chance to increase students' motivation, as it provides a way to incorporate the SDGs and the concept of planetary boundaries into the chemistry curriculum to create relevant and meaningful content and contexts.

Phosphorus, or more accurately, phosphate, is important for several of the SDGs and is a part of the planetary boundaries concept. Learning the role of phosphorus or phosphates in local and global issues is, however, still not a desired outcome in many secondary and undergraduate chemistry curricula. The curriculum seems unlikely to extend beyond the chemical and physical properties and molecular structures of phosphorus or phosphates. There are many issues and challenges in today's world that can be easily connected to phosphates. For example, SDG 2, “Zero hunger”, will be unachievable without having sufficient phosphates for the production of fertilizers. At the same time, the discharge of too much phosphate into an aquatic system, however, can lead to eutrophication (extreme enrichment of nutrients leading to extensive growth of algae and/or plants with potential damages to the ecosystem; here due to phosphate and nitrate) a threat for clean water supply

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and a risk to life below water and on land (SDGs 6, 14 and 15). The associated risks with the biochemical flow of phosphate into the environment led to the inclusion of phosphate in the concept of the planetary boundaries.

In this paper, we present an overview of the discussion on the use of phosphates in connection to current ideas of the European Commission, the United Nations and the concept of the planetary boundaries in this regard. A specific example, recovering phosphate from wastewater, is also introduced to contribute to the development of a more sustainable future. The discussion provoked a curriculum design project that aims to find ways to incorporate this topic into chemistry teaching at the secondary and undergraduate level, providing an opportunity to take a transdisciplinary teaching approach, forming a synthesis of chemistry learning with different aspects of biology, economy, geography and history.

Phosphorus – a “political” element

The European Commission added phosphate rock to their list of critical raw materials in 2014 (EC (European Commission), 2014, 2017). Critical raw materials are defined by their high economic importance and certain supply risk. The high economic importance of phosphorous lies in its use in fertilizers because of its essential macronutrient role in any plant growth and thus food production. Fertilizers are needed to secure the agricultural production of food and animal feed whose demands are increasing as the world's population grows (FAO (Food and Agriculture Organization of the United Nations), 2017). The supply risk arises from the unequal geographical distribution of world reserves (USGS (United States Geological Survey), 2017). Seventy-five percent of the world's phosphate reserves are located in only one country, Morocco (Killiches, 2013). Some of Morocco's reserves are, however, located in the former Western Sahara, a region with an unresolved political conflict until today (UN (United Nations), 2018). Without considering this frozen conflict, Northern Africa in recent years appeared to be a region with a risk of political instability that has fortunately not involved Morocco so far, but there is no guarantee that it will not be influenced by the winds of painful changes happening in that region for the last few years.

The consumption of phosphates is as unequally distributed as its reserves around the world. China, India, Brazil and the USA consume about 70 % phosphate fertilizer per year but represent only about 40 % of the world's population. Africa, with more than 75 % of the natural phosphate resources and with a growing population accounting for 20 % of the world population, consumes only 2–3 % of phosphate fertilizer per year. Running out of phosphate resources worldwide is unlikely in the near future. Although from the current perspective, the natural phosphate resources will serve for about 300 years and running out of phosphate resources worldwide is unlikely to happen in the near future, there is no way to guarantee that the rate of consumption will not change depending on potentially increasing demand (Killiches, 2013). Nevertheless, certain deposits will expire, and quality will decrease over time.

Even though overall phosphate resources are unlikely to be depleted, resources in a single country can be shut down, and just this can have devastating consequences. What runout of phosphate could mean for a country can be seen through the example of Nauru. After becoming independent in 1968, Nauru sold large amounts of guano, which is bird excrement with a high phosphate content. By exporting guano, Nauru became one of the richest countries worldwide. However, after the final exploitation of guano, it is now one of the poorest. In order to prevent such tragedies to happen and make the world a more sustainable place, it is vital to generate sustainable policies and a lifestyle shaped by a *“development that meets the needs of the present without compromising the ability of future generations to meet their own needs”* as described in the Brundtland-Report (WCED (World Commission on Environment and Development), 1987, p. 11).

Sustainable lifestyles and developments were suggested already in the Agenda 21 (UNCED (United Nations Conference on Environment and Development), 1992). There are many different agendas and ideas concerning sustainable development. One of the latest and maybe the most important one is the Agenda 2030, which was issued by the United Nations in 2015 and is also known as the *“Transforming our world”* report (United Nations, 2015). The Agenda 2030 announced 17 Sustainable Development Goals (SDGs). With those SDGs, the UN agreed on a balanced view of the common sense of sustainability, e.g. to end poverty, reduce inequalities, and fight for gender equality.

A responsible use of phosphates considers at least the following SDGs: #2 (Zero Hunger), #6 (Clean Water and Sanitation), #12 (Responsible Consumption and Production), #14 (Life below Water), and #15 (Life on Land).

The aim of zero hunger is especially important in developing and emerging countries. Phosphate fertilizers play a crucial role in achieving food security (Cordell & White, 2011). The role of phosphate in fertilizers is irreplaceable, and thus Zero Hunger is highly connected to the availability and distribution of phosphate. With the high use of fertilizers in certain countries, eutrophication is a risk for clean water in the future, affecting both life below water and on land. Finally, food should be subject to responsible consumption and production as all

consumer products should be. Responsible consumption entails effectively producing food without harming the environment with irresponsible fertilizer use. This is also a question of equity and global justice, when Africa with its fast-growing population, which comprises about 20 % of the world's population, has access to only 2–3 % of the world's used phosphate fertilizers.

Actually, the worldwide consumption of fertilizers for food production is not considered to be sustainable in terms of biochemical phosphorus flow into the environment. This fact is highlighted within the concept of planetary boundaries (Rockström et al., 2009) (Figure 1) that suggest a corridor within mankind can act without irreversibly harming the environment. Exceeding planetary boundaries raises uncertainty and the risk of damage, and after crossing further parameters, the risk of irreversible damage increases. This does not mean that the earth is irreversibly damaged immediately after crossing any parameter, but the risks increase (Steffen et al., 2015). As one of the planetary boundaries, phosphorus flow into the environment has two control values, the phosphorus flow from freshwater to oceans as well as the one from fertilizers to erodible soil. In 2015, both controls have doubled the value defined within the planetary boundaries and thus are far in the high-risk area (Steffen et al., 2015).

Figure 1: Planetary Boundaries (Steffen et al., 2015).

An effective and long-lasting solution suggested to avoid potential problems regarding phosphate such as run out, eutrophication, the release of heavy metals-especially cadmium and uranium- due to the exploitation of natural phosphate rock, or a supply bottleneck is recycling. Several recycling methods are currently under research and development. Most processes focus recycling of phosphate from wastewater, sewage sludge, or sewage sludge ash. One example of a recycling process is the ExtraPhos process by the Chemische Fabrik Budenheim KG (2016). Here, the pH value is lowered by using gaseous carbon dioxide to free phosphate out of its sewage sludge matrix. The solution is filtered, and lime milk is added. The phosphate precipitates as calcium phosphate, which can be used directly as fertilizer. Redefining the phosphate cycle might solve some environmental problems but could also help achieve SDG 2 “Zero Hunger” through producing quality fertilizers from wastewater.

Transdisciplinary learning on phosphates in undergraduate chemistry education

Undergraduate general chemistry courses often suffer from a structure of the discipline approach by focusing almost exclusively on abstract facts, theories and content (Cooper, 2010; Cooper & Klymkowsky, 2013). There are many valid reasons for integrating topics from the sustainability debate (Vilches & Gil-Pérez, 2013) or social perspectives (Hofstein et al. 2011) into chemistry education; however, their integration remains scarce. When the central role of chemistry in sustainable development is considered, this sounds surprising (Matlin et al., 2015). Furthermore, topics from such debates have a high degree of relevance with inherent value for education (Eilks & Hofstein, 2014).

The connection between chemistry education and sustainability has long been suggested (Burmeister et al., 2012; Colucci-Gray, Perazzone, Dodman, & Camino, 2012; Jegstadt & Sinnes, 2015; Vilches & Gil-Pérez, 2013). Integrating sustainable development into teaching, particularly chemistry teaching, is a chance to strengthen the societal relevance of learning science (Hofstein et al. 2011). In addition, Vilches and Gil-Pérez (2013) suggest introducing planetary emergencies as part of the chemistry curriculum, which can also be related to the

planetary boundaries. They name topics such as ecosystem degradation, ozone depletion and desertification. Hodson (2003), on the other hand, recommends the incorporation of topics relating to food security and agriculture including starvation and use of water and mineral resources. Today, these topics can be discussed in light of the SDGs more effectively and linked directly or indirectly to planetary boundaries. Some can also be linked to the use of phosphate.

Chemistry is essential for solving many of the sustainability challenges of today. Therefore, chemistry education should be concerned with all these developments. A sole chemistry perspective is, however, not sufficient. Vilches and Gil-Pérez (2013) highlight this fact by saying “None of them [the sustainability issues] can be understood or addressed without taking into account the whole ensemble” (p. 1860). For adding such transdisciplinary perspectives into teaching chemistry, a socio-scientific issue (SSI) framework is suggested (Sadler, 2004; Simonneaux, 2014). Simonneaux and Simonneaux (2012) name sustainable development itself as an SSI.

To show the multifaceted nature of SSIs, digital learning environments proved to be feasible (Zowada, Gulacar, & Eilks, 2018). In order to introduce the phosphate recovery and its uses as a popular SSI, a learning environment was developed first for German non-formal secondary chemistry education before being translated into English and adopted for utilization in secondary and undergraduate chemistry education in English-speaking countries or those where the language of undergraduate education is English. The learning environment (Figure 2) was designed with PREZI. It is based on four questions: “What is phosphate?”, “How can we recycle phosphate?”, “Why is phosphate a limited resource?”, and “How is phosphate used?” It provides basic chemistry with explanations and examples from biology, geography, economy and history to allow students to obtain a holistic picture about phosphates and its recovery as a chemistry related socio-scientific issue.

Figure 2: Overview learning environment.

The project was implemented in three phases: (1) Preparation, which included completing pre-discussion assignments and exploration of the digital learning environment, (2) Discussion of the topic with peers during a weekly 50-min discussion session where students assumed one of the four roles (economist, industrial representative, environmental activist, or farmer) to help students look at the phenomena from different angles and consider current and potential issues related to phosphate recovery, and (3) Reflection, which encouraged students to summarize the key points from group and whole course discussions and to complete the post-assignments. Students were offered extra credit to increase the motivation and active participation in all these stages. For the material see the supplementary information.

Findings and discussion

The sample of this study consists of general chemistry undergraduate students from a research university in California. Seven hundred and nine students participated voluntarily in the study (female = 466; male = 236; other = 3; I'd rather not say = 4). In order to document students' perception of the interventions, a questionnaire with 13 Likert-scaled items (4-level) and four open questions were developed and administered.

The results from the Likert items are presented in Figure 3. Most students indicated that they learned a lot about phosphate (91 % agreed or agreed mostly), and 46 % of the students agreed or agreed mostly that they would look for information on phosphate after the course. The topic was liked by 74 % of students and perceived as interesting by 85 % who chose agreed or agreed mostly. The topic was new to most of the students; 92 % (agreed or agreed mostly) stated that they learned a lot of information that they did not know before. Ninety-two percent of the students also agreed or agreed mostly that the topic is important, and 89 % agreed or agreed mostly that it shows an important application of chemistry in everyday life. Furthermore, 60 % agreed or agreed mostly that such topics should be part of their training. Seventy-two percent agreed or agreed mostly that the topic is so important that it should be covered in school or university. Sixty-two percent (agreed or agreed mostly) had fun while learning about phosphate. Seventy-three percent disagreed or agreed partially that they will not be more sensible on this topic in the future. Overall, the topic was perceived as relevant for the chemistry curriculum by 62 % (agreed or agreed mostly), and 63 % became motivated to deal with chemistry more in depth through such topics, indicated by their selection of agreed or agreed mostly option on the questionnaire. The students seem to have connected the topic to societal issues like hunger or questions of equity and seen the connection between chemistry and potential solutions for their future. Seeing the positive responses to items 1, 3, 4, 5 and 9 indicate the strong positive perception of the teaching approach. The high agreement to items 8, 10, 12 could be explained by the high societal relevance of this topic for the future (Stuckey, Hofstein, Mamlok-Naaman, & Eilks, 2013). Positive perception of items 8, 10, 12 support the social relevance and should motivate chemistry instructors to integrate this topic more thoroughly into the chemistry curricula.

Figure 3: Perception of 709 students on 13 Likert-items towards the topic of phosphate and its recovery.

Four open-ended questions asked them to (1) name new learned aspects, (2) share the ideas that arose while discussing the topic, (3) comment if the curriculum is enriched with this activity, and (4) reveal their position regarding this activity that is not part of the exam. The open-questions were analyzed using qualitative content analysis (Mayring, 2000). Fifty questionnaires were analyzed and categorized for each question. To prove the categories, the categorical system was applied to randomly selected items for each question. The random selection was done using a random number generator to get a number from 51 to 709. Five random numbers were generated, and from each, the next ten answers were analyzed leading to a sample of 100 answers on each of the questions.

Regarding question 1, most students commented on the recycling and mining processes. Some students connected mining processes to and listed socially or environmentally relevant aspects of the topic. For example, they mentioned that they did not know “*mining phosphate is dangerous for the environment and the people*”. Another group of comments emphasized phosphate’s finiteness and its importance in agriculture. Other important facts were also mentioned several times in students’ responses, such as pollution problems due to heavy metals release, the story of the island of Nauru, and the location of phosphate mines.

In question two, the students referred to the lack of awareness of issues around phosphate in general. They focused on phosphate’s economic, social, environmental aspects and the fact that it is a limited resource. Recycling was also a frequently mentioned topic. Other named topics were connections to the future and general

problems - heavy metals release - and general concerns. One student was *“deeply concerned about the future of humanity without phosphate.”*

About the enrichment of the curriculum, which was the focus of question 3, 27 out 100 students wrote that they do not see this activity as curriculum enrichment although eleven of them stated that it is an interesting and an important topic to the society. One student made it clear in his comment: *“I don’t think that recycling and mining of phosphates particularly enrich my studies as I plan on becoming a doctor, but I’m sure there must be an indirect impact on my field of interest.”* Remaining students mostly agreed that the whole activity improved their learning experience due to personal interest, the importance of the topic, potential applications of chemistry, or a broader/deeper view provided in the activity. The following quote highlights students’ perceptions on the activity in this group: *“I did not know phosphate was critical to sustaining agriculture and everyday life to this extent as well as how quickly it is being depleted. Learning recycling of phosphate through urine or biomass was very interesting.”*

Regarding the fourth question, 19 students out of 100 indicated that they had a lack of motivation since the topic was not tested in an exam. One of them told that *“I just do not see how knowing about phosphate recycling is going to help me get a good grade on my final; can’t make the connection.”* Meanwhile, majority of the students appreciated the importance of this topic when they considered the connection of the discussions to the real world and possible consequences of the phosphate issue in future. In this regard, one student said: *“This issue is far more important than my grade, as it impacts human survival.”*

The topic of phosphate and its recovery appeared to be interesting for many students. Answers to the open-ended questions made it obvious that the topic was new to most students, and that most of them felt that the topic has high importance. Seven students referred to the fact that the topic was new to them and about 90 % agreed or mostly agreed with Likert-item 5. Thirty-eight students justified the importance by the fact that phosphate is a limited resource or due to its relevance in agriculture (27 students). The topic shows an application of chemistry related to a potential important issue that will be faced in future. Most secondary school and college students think that the discussion around phosphate sustainability is relevant for chemistry curriculum and find it provoking and motivating to learn chemistry more in depth. The concerns raised in some students’ answers for the open-ended questions can be understood as a personal connection between the topic itself and the student. According to Sadler, (2004, p. 623) *“The most fruitful interventions would be those which encourage personal connections between students and the issues discussed.”* Our case indicates that phosphate sustainability is such a topic, which might lose its importance and become a less-worried issue in future, e.g. through broad recycling. However, this study shows the potential outcomes and benefits of including current and relevant sustainability topics into chemistry curricula. Nevertheless, only one third of the students stated that they would look for further information on phosphate recovery. There might be two reasons behind their choice: either the learning environment was perceived to inform students well about most aspects so that they felt they did not need more information or the topic was not in realm of their interests because many of the students were majoring in non-chemistry and environmental technology-related science and engineering fields.

Conclusions

“New” concepts and ideas like the SDGs or planetary boundaries provide rich new content, contexts, and issues for chemistry curricula and teaching. In this study, we implemented the topic of phosphate sustainability into a general chemistry course in the USA with positive effects. This study suggests that more topics from the sustainability debate should be identified and integrated into teaching chemistry to reflect their relevance and the relevance of chemistry for our future. The curricula along with the associated assessment have to change in order to include such topics and encourage students in the discussion of topics under inclusion of their transdisciplinary and socio-scientific nature. Chemistry educators should not worry about taking risks because some of them are worth trying as Hodson (2013) encourages all educators and tells: *“Don’t be nervous about the curriculum implications of adopting an SSIs-oriented approach [...]; don’t be flustered by having to deal with controversy and the cut and thrust of debate that inevitably occurs in small group discussions; don’t be scared about the prospect of stepping into the unknown. Above all be prepared.”* (p. 328f).

Supplementary information

The PREZI learning environment and a laboratory guide for experiments on phosphate recovery are available at www.chemiedidaktik.uni-bremen.de/materialien.php (See for Teaching Materials in English Language at the bottom of the page.)

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