Ecological Ramifications of Phosphate Extraction and Use: An In-Depth Analysis of the Environmental Impacts and Systemic Consequences

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Abstract :

Phosphorus (P) is a finite resource located within certain geologic reserves around the world. Morocco and the Western Sahara together account for roughly 75% of reserves, raising questions of how to more sustainably use this precious resource. Phosphorus is mined from rock and eventually converted into usable fertilizer, which is applied to croplands. This study aims, by adopting a global lens to explore the environmental consequences stemming from phosphate extraction and transportation, emphasizing the systemic impacts of these processes.

Author's Note :

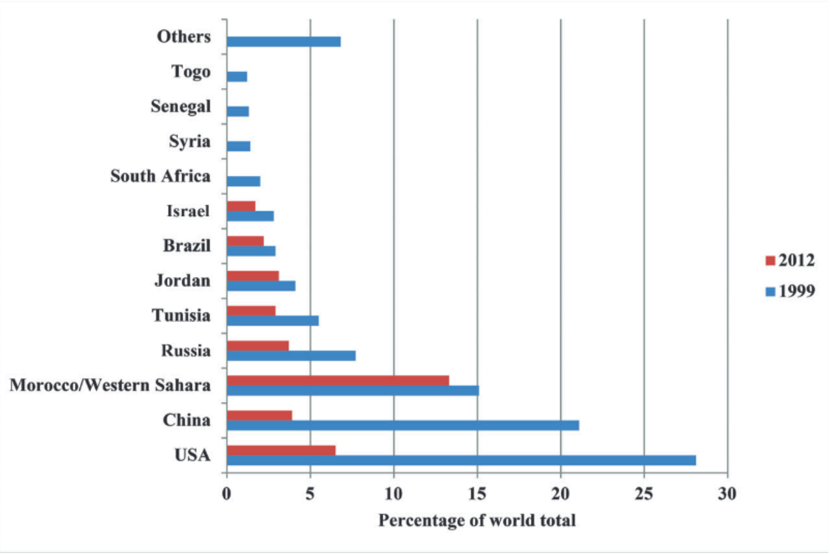
My personal interest in this stemmed from a discussion with one of the members of my nonprofit. She had mentioned that despite living in Morocco, we never thought of phosphorus as a danger for our environment, and that sparked an interest in this subject. I am particularly interested in anything in the sustainability realm that deals with the environment or climate change.

Keywords : Phosphorus, Environment, Mining, Transportation.

1. Introduction

Phosphate rock (PR) is a naturally occurring phosphorus- (P) rich rock with a P content of about 5%–13% (Jasinski 2009; Cordell And White 2011). Global food production is dependent on PR because P is a limiting factor in crop production. PR is mainly used in agriculture as phosphate (PO43–) fertilizer and animal feed, but is also used in the manufacture of detergents, food additives, andmetal stabilization (Ibrahim et al. 2010). Increasing population growth and the need to increase food production may also be responsible for the increasing demand for PO43– fertilizers. Based on estimates of current PR reserves, studies indicate that a depletion of global reserves is not likely to occur within this century (Heckenmüller et al. 2014). The International Fertilizer Development Center (IFDC) has also estimated that world PR reserves will be able to supply needed PR far into the future (VanKauwenbergh 2010). However, to prolong the life of this limited resource and prevent environmental pollution, the efficient use of P in crop production is important (Selles et al. 2011).

Fig. 1. World phosphate rock production, 1999. (Source: FAO 2004; Mew 2000). World phosphate rock production, 2012 (Source: Hecken Müller et al. 2014; Dennis 2013; ICL 2013).



Although very important in food production, water-soluble PO43– fertilizers manufactured from PR are susceptible to leaching and can contribute to P loading of water bodies, leading to eutrophication of surface waters and pollution of groundwater(Leone et al. 2008). Direct application of PR reduces leaching losses of P and is cost effective. However, direct application of PR has limitations such as low solubility and low reactivity, which reduces its agronomic efficiency (Husnain et al. 2014). This has discouraged its adoption by many farmers despite efforts to improve its effectiveness.The application of PO43– fertilizers is also an environmental concern because of the presence of toxic metals/metalloids and radionuclides in PR. The use of PO43– fertilizers with toxic metals/metalloids such as arsenic (As), cadmium (Cd), and lead (Pb) can contaminate the food chain and greatly affect public health. Toxic Metals/metalloids are considered grave pollutants due to their persistence, toxicity, and non-degradability in the environment.Cd can cause demineralization of bone and can harm the kidneys (Bernard 2008). It has been classified as carcinogenic because it can cause cancer (Ferreccio et al. 2013). Pb can cause damage to the central nervous system and trigger learning problems in children (Hou et al. 2013). Radionuclides like uranium (U)may cause lung cancer and tumors of the lymphatic and hemato-poietic tissues (USEPA 2000; Murakami and Oki 2015). It is impor-tant to know the potential of PR to increase the levels of these hazardous elements in the environment. The debate on the future availability of PR and controversy regarding its contamination potential has raised several questions through the years.

2. Environmental impacts of the uses and mining of PR

2.1. Water pollution

Leaching losses of applied P from fertilized farmlands can lead to pollution of groundwater, while runoff could pollute surface waters and lead to eutrophication. Eutrophication is the excessive loading of nutrients in surface waters resulting in excessive growth and accumulation of green and blue–green algae (Hodgkin and Hamilton 1993). This can lead to reduced oxygen levels in the water which causes declines in population of aquatic organisms, reduced biodiversity, and imbalanced trophic food webs (Kennish and de Jonge 2011; Scavia et al. 2014). P is generally the limiting nutrient for algal growth, and leach- ing of P from application of PO43– fertilizers to sandy soils is the main source of P (Hodgkin and Hamilton 1993). Although both N and P are major plant nutrients that can affect water quality, whole-lake experiments have shown that regulation of P alone can effectively mitigate eutrophication (Wang and Wang 2009). PR can increase P loading in surface waters through leaching of P from waste accumulated from mining operations, leaching and runoff from PO43– -fertilized soils, leaching of P from farmlands receiving animal manure, and use of P as detergents. Vandenhove et al. (2015) determined the effect of PO43– mining on aquatic ecosystems in five countries (Belgium, Spain, Syria, Egypt, Brazil). They predicted that the aquatic ecosystems around the PO43– fertilizer plants in Belgium, Spain, and Brazil are potentially most at risk. Bulut and Aksoy (2008) investigated the role of fertilizer application rate on P transport and loading to Lake Uluabat in Turkey.

Their results showed that, when the amount of fertilizer applied to agricultural lands was doubled, the P load to Lake Uluabat increased by 32%. P transported to Lake Uluabat declined by about 6%, 10%, and 16% when the fertilizer usage on the agricultural fields decreased by 20%, 30%, and 50%, respectively. Animal manure is a source of P because the animals are given feed containing P from PR.

PO43– fertilizers may also increase the mobility of As in As-contaminated soils, leading to As contamination of groundwater. P and As are both Group V elements with similar chemical properties and they both compete for exchange sites in the soil. Castlehouse et al. (2010) studied As mobilization using a natural As-contaminated soil and suggested that P may increase As mobility by increasing the concentration of non-specifically sorbed As. In another study, addition of PO43– fertilizers significantly in- creased the amount of As leached from lead arsenate–contaminated soils (Davenport and Peryea 1991). Because P addition leads to As mobilization in the soil, PO43– fertilizers have been used to increase As availability to As hyperaccumulating plants used in phytoremediation of As-contaminated soils (X. Cao et al. 2003; Fayiga and Ma 2006; Lessl et al. 2014). In the absence of As hyperaccumulators, compost and PO43– amendments increased As leaching in chromated copper arsenate- (CCA) contaminated soils (X. Cao et al.2003).
Another important use of PO43– compounds is in making detergents. The main P compound in detergents is sodium tripolyphosphate (Na5 P3 O10 ; STPP) which is prepared from H3 PO4 by neutralization with soda ash (sodium oxide) to form sodium hydrogen phosphates (Glennie et al. 2002). PO43– in the form of STPP is the most commonly used builder which forms complexes with Ca2+ and Mg2+ ions, creating favorable conditions for detergent action by reducing water hardness (Kundu et al. 2015). It has been reported that where STPP is used as builder in house- hold detergents, it contributes up to 50% of soluble P in municipal wastewater; therefore a reduction in the use of PO43– -based deter- gents is expected to reduce P loading of surface water bodies (European Commission 2015). Many suggested alternatives such as sodium citrates, ethylenediamine-tetraacetic acid (EDTA), and nitrilotriacetic acid (NTA) have been found to be less effective and less cost-efficient than PO43– in detergents (Kundu et al. 2015). The only alternative that may be effective is Zeolite A, which is com- paratively inert and derived from aluminium oxide (Landbank 1994). Measures to reduce the use of STPP-based detergents in the European Union (EU) include the introduction of laws or voluntary agreements to change to Zeolite A as the builder for household laundry detergents. STPP consumption has decreased substantially since the early 1980s due to bans or restrictions on its use in many developed countries (European Commission 2015).

In summary, waste from PR industries and PO 43– fertilizers has contributed to water pollution which could lead to eutrophication. It has been shown that reducing the amount of PO43– fertilizer applied to soils leads to a reduction of P loading in surface waters. Even though the use of PR products like PO43– fertilizers and detergents has led to the pollution of surface and groundwater bodies, regulation of these products has reduced the extent of environmental contamination.

2.2 The case study region: Eutrophication in Nigeria

Eutrophication is a threat to the water quality of rivers, lakes and reservoirs, hence their classification into oligotrophic, mesotrophic and eutrophic based on level of eutrophication. Recently in Nigeria eutrophication rates in water bodies have increased dramatically as a result of alterations in nutrient cycles related to land use. The increasing demand for food and food insecurity which has the increased use of fertilizers on farmland has been pointed out as contributing over 80% of eutrophication of water bodies worldwide. Adeyemo et al observes that land use around riverine areas in Nigeria is predominantly for farmland and this could be explanation for the high level of phosphate from run- off during the rainy season in Ibadan River. Nweze and Onyishi indicated that indiscriminate use of fertilizers around Nike Lake in Enugu, Nigeria is the major source of pollution causing Cyanophycean blooms and ecological disaster. Since the population boom in Nigeria in the 80's the use of N.P.K fertilizer has increased and led to the treat observed in water bodies located close to these farmland. When washed as a result of erosion, flooding increased the nutrient load of these water bodies. Other anthropogenic activities that can cause eutrophication in water bodies include increased silt, deforestation, lumbering activities and other land use perturbation.

2.3. Deforestation

A new WWF report, "Extracted Forests: Unearthing the role of mining-related deforestation as a driver of global deforestation", sheds light on how the impacts of mining, currently the fourth largest driver of deforestation, increases significantly, affecting up to 1/3 of the world's forest ecosystems, when indirect impacts are taken into account.

These indirect impacts, which include mining related infrastructure, settlements, agriculture through settlement, water and soil contamination and illegal logging, explain why demand by just six countries (often located far from the mines) are responsible for 51% of mining-related deforestation. 85% of the deforestation footprint of the EU, for instance, is located outside of the region.

More than 80% of direct mining-related deforestation takes place in just 10 countries, with tropical rainforests suffering the most damage – this most affected biome contains 29% of mining sites but 62% of mining-related deforestation.

Negative consequences for wildlife and ecosystems have already been recorded: the numbers of Indochinese tigers in the Greater Mekong region have decreased drastically due to habitat fragmentation from infrastructure development, and gold mining in the Amazon Basin has led to increased mercury levels in endangered species such as the Tucuxi river dolphin.

Mining activities have seen an alarming acceleration – more than 1/3 of the mining-related deforestation seen in the last 20 years occurred in just the last five years – and are tipped to increase in coming years.

Bad mining practices do not only lead to negative environmental impacts, they also result in negative social impacts and human rights violations that can only worsen if not addressed.

The report highlights how the rights of Indigenous communities are at risk in certain regions where mining expansion or processing of ores destroy ancestral territories, affecting and violating community interests.
By highlighting at-risk regions and both direct and indirect impacts that mining can have on forest ecosystems, the report provides governments and companies with an in-depth understanding of the challenges that need to be tackled.

“Metals are important for the development of human civilization and the life we live today. But the footprint left by the extraction of these commodities has a heavy toll on ecosystems,” said Tobias Kind-Rieper, Global Lead Mining & Metals, WWF Germany.

2.5. Greenhouse Gas Emissions

It is also important to consider the impact of land use change in the context of greenhouse gas emissions. The destruction of vegetation and soils when land is cleared for mining results in the release of carbon dioxide and other greenhouse gases. Another important consideration relates to the quantity of greenhouse gases released per unit mass of mined material, as some less concentrated mineral deposits require proportionally higher energy usage. For example, mining a kilogram of diamond produces around 800,000 kg CO2e compared to a kilogram of a highly abundant mineral such as iron which produces only about 2 kg CO2e.

The creation of products from mined materials uses high amounts of energy throughout the different stages of the production chain and most of this energy is currently sourced from the burning of fossil fuels.

Reducing reliance on fossil fuels in the mining process by electrifying the technology and running it off a green energy grid is a key aim to allow mining to continue along a more sustainable path. Automation of many of the stages of mining is also another vital change that will not only improve safety but also increase efficiency and cut energy costs. However, it will remain difficult to swiftly transition the mining industry into becoming a net zero emitter, and with the short supply of many rare earth metals, it is crucial to reuse and recycle mined materials wherever possible.

2.6. Soil pollution and Land occupation

2.6.1. Toxic metals/metalloid

The presence of hazardous elements such as toxic metals or metalloids in PR makes it a potential source of contamination, especially on agricultural soils receiving PO43– fertilizers. There are conflicting reports about the effect of PO43– fertilizers on the metal content of the soil. Some scientists suggest that application of PO 43– fertilizer does not increase metal content of soils, while others have reported otherwise. Ogunleye et al. (2002) reported that the average concentrations of toxic elements (As, antimony (Sb), Cr, Zn) in PR are not appreciably different from those in agricultural soils, and da Conceicão and Bonotto (2006) reported that the toxic metals in PO43– fertilizers applied to Brazilian crops did not raise their concentration in soil to harmful levels.

This was not the case in the UK, according to a report on the impact of long-term PO43– fertilizer applications on As concentrations in soil and herbage (Hartley et al. 2013). PO43– fertilizer used in the Park Grass Experiment between 1888 and 1947 added a substantial amount of As to the soil, resulting in a near doubling of the total As concentration in the topsoil. It has also been reported that PO43– fertilizer is a main source of As in areas of Sri Lanka where the population is affected by chronic kidney disease (Jayasumana et al. 2015). Analysis of fertilizers for their As content revealed that the highest amount was in TSP with a mean value of 31 mg·kg–1 (Jayasumana et al. 2015), while PR had the next highest concentration (8.56 mg·kg–1).
To investigate the effects of long-term applications of PO43–fertilizers on the solubility of Cd and Zn, three PO43– fertilizers were applied to soils in a laboratory experiment using a single fertilizer addition equivalent to 15 years of application (Lambert et al. 2007). Three MAP fertilizers containing various amounts of metals were also applied on cultivated fields for three years at three different rates. PO43– fertilizer treatments increased the Zn solution concentration in 83% and 53% of treatments in the field and laboratory, respectively, while it increased the concentration of Cd in soil extracts by 87% and 80% of the treatments in field and laboratory experiments, respectively (Lambert et al. 2007).

These hazardous elements in PR and PO43– fertilizers may enter the food chain through contaminated food crops and cause severe health problems for the unsuspecting public. It is therefore necessary to protect the public from consumption of food grown with contaminated PO43– fertilizers. Regulation of PR and PO43– fertilizers based on their composition is necessary to reduce health risks caused by potential contamination of the food chain. Regulatory bodies have established tolerable limits specifying concentrations of metals allowable in PR or PO43– fertilizers.

Gonçalves et al. (2014) reported that some countries like the USA, Canada, Australia, Japan, China, Germany, Sweden, and Finland do have legislation to enforce tolerable limits and standards for PO43– fertilizers. According to the report, the tolerable limit can vary between regions within one country. For example, in the USA the limit for Cd concentration in PO43– fertilizers is 4 mg·kg–1 in California but up to 165 mg·kg–1 in Washington. In other countries, it is about 50 mg·kg–1 in Switzerland and Finland, 300 mg·kg–1 in Australia, 8 mg·kg–1 in China, and as high as 343 mg·kg–1 in Japan.

Among the hazardous elements in PO43– fertilizers, Cd is the most widely studied because of its relatively high frequency of occurrence and its toxicity to human health (FAO 2004). Cd is toxic at very low concentrations and its uptake and accumulation in the food chain makes it a public health concern. Presently, there is no cost effective way of removing Cd from PR ores, but it is possible to produce PO43– fertilizers with very low Cd concentrations by using PR with a low Cd content (Van Kauwenbergh 2006). Regulatory limits on the Cd content of PO43– fertilizers are necessary because fertilization increases the risk of transferring the heavy metal into the food chain. The limits established by the European Commission were based on the reports of an impact assessment study which showed that fertilizers containing 20 mg Cd·kg–1 P2O5 or less are not expected to result in long-term accumulation in the soil, while fertilizers containing 60 mg Cd·kg–1P 2 O 5 could result in long-term accumulation of Cd in the soil (Roberts 2014).

Even though model simulation outcomes indicate that some of the existing fertilizer regulations are not strict enough to prevent significant accumulation of Cd in cropland soils (Chen et al. 2007), scientific risk assessments in the USA have shown that PO43– fertilizers containing relatively small amounts of Cd are safe and do not pose any risk to human health (Roberts 2014).

2.6.2. Radionuclides

There are conflicting reports on the effect of PO43– fertilizers on the radioactivity of receiving soils. It has been reported that the application of PR or soluble PO43– fertilizers to unfertile fields during farming could raise radioactivity levels in soils (Akhtar et al.2005; Mlwilo et al. 2007). However, a systematic study of the radionuclide content of various Yugoslavian soils reported no statistical difference between soils unfertilized since 1948 and normal agricultural soils (Baetsle 1991). This did not agree with a study in Pakistan, where fertilized farmlands had higher activity concentrations of Ra-226 (65%–85%) and K-40 (34%–43%) than barren land (Akhtar et al. 2012).

The extent of pollution and health risk associated with PR depends on factors such as the geochemical properties of the PR, method of mining and processing, soil characteristics, and environmental conditions (FAO 2004). Sometimes the composition of PR is different from that of fertilizers produced from it. For example, though high Ra-226 concentrations have been reported in Egyptian PR, the radionuclide content of PO43– fertilizers produced from Egyptian PR was found to be low (Hassan et al. 2015). The radionuclide concentration has also been found to vary with fertilizer type. Radiological analysis of PO43– fertilizers produced from PR showed that the activity concentration of U-238 was much higher in SSP (284 Bq·kg–1) and TSP (396 Bq·kg–1) than in DAP (<2.03 Bq·kg–1) and NPK fertilizer (NPK < 2.03 Bq·kg–1) (Hameed et al. 2014). Another study also measured the radionuclide content of different fertilizers in Egypt; results showed that SSP had the highest Ra-226 while NK fertilizer had the highest Th-232 and K-40 (Uosif et al. 2014).

Alpha track density can be used to determine the activity of radionuclides because they emit alpha particles. Kumar and Chauhan (2014) measured the alpha track density of plants grown with different fertilizer types. Results showed that the alpha track density of plants grown with PO43– fertilizers were higher than with organic and urea fertilizers. Studies evaluating the radiological impact of radionuclides in PO43– fertilizers have reported that the radium equivalent activity is below the permissible limit and does not pose any radiological risk (Saueia and Mazilli 2006; Khater and Al-Sewaidan 2008; Bituh et al. 2009; Cevik et al. 2010; Hameed et al. 2014).

Though many studies have reported the adverse effects of PO43– fertilizers on the environment, there is limited data on the effect of direct application of PR on the metal and radionuclide content of the soil, likely due to the low percentage of people involved in direct application.

In summary, although there are hazardous elements in PR, the application of PO43– fertilizers in farmlands may or may not cause soil pollution depending on several factors. Tolerable limits of toxic metals/metalloids for PO43– fertilizers have been established in different countries. The radionuclide content of different PO43–fertilizers varies widely, though PO43– fertilizers consistently have more radionuclides than organic and urea fertilizers. Risk assessments have shown that PO43– fertilizers containing small amounts of Cd in PR are safe, while radionuclides in PR do not pose any radiological risk.

3. Conclusion

All in all, the implications of phosphate extraction and utilization are of ecological significance with severe after-effects and far-reaching effects that should be closely watched. Our comprehensive analysis has revealed that processes of phosphate mining, extraction, and transport today represent acute ecosystems, water resources and human health threats.

The key environmental challenges brought about by phosphate production include habitat destruction, water pollution, soil erosion, and air pollution. In addition to this, the irreversible adverse effects of these activities include habitat loss, biodiversity extinction, and erosion that should be addressed through altered ground-up approaches and regulatory mechanisms. Addressing these challenges necessitates a multidisciplinary approach involving technological advances, better waste disposal systems, and the implementation of environmentally sound practices throughout the phosphate value chain. In addition, maintenance of relationships and transparent collaboration between stakeholders such as governments, industries, local communities should be forested for a meaningful fight against environmental impacts of phosphate extraction and use.

In facing the ensuing challenges fostered by the phosphate extraction and utilization, we need to strengthen sustainability, resilience, and our natural resource stewardship. Through an investment in research, innovation, and wholesome management strategies, we can endeavor to reduce environmental damage, protect biodiversity, and protect the welfare of the current and future generations. The only way we can manage to find solutions to the ecological impacts of phosphate extraction is through joint efforts and organized action that shall usher the world to a more consonant and balanced habitat with Mother Earth.

4. References

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