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Phosphorus reserves depletion, concentration in a single geolocation, and the likelihood of weaponization for geopolitics: a scenario analysis

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Abstract

One of the most serious issues that humanity will confront in the future is the depletion and concentration of phosphorus in a single geographical location. It is the most limiting and critical element for food production, with no natural alternatives. Because most soils are phosphorus deficient, intensive application of phosphate-based fertilizers is mandatory to boost agricultural productivity on limited farmland. More phosphorus in the form of fertilizers is needed to produce enough food to feed the booming global population; yet, much of it is lost to streams, causing eutrophication. Besides, phosphorus for fertilizer production is sourced from reserves that were predicted to deplete in less than thirty decades, with resources first concentrated in North Africa. The study aimed to examine and forecast the future reserve depletion, distribution, and the likelihood of using phosphorus as a geo-political instrument, based on the assumption that the scarcer and more unevenly distributed the resource, the more desirable it is for political weaponization. Phosphorus depletion time was calculated using the static reserve-to-production (R/P) ratio, and future resource trends were projected under varied scenarios from 2023 to 2220 using time series analysis. The study found that on average, the global reserves will take 300-400 years to deplete, while that of China and the United States reserves will be depleted by 265 and 2073, respectively. By 2100, a substantial portion of the reserves will be in North Africa, accounting for around 95% of global phosphorus reserves. In this sense North Africa will dominate the phosphorus market, making it more oligopolistic. Given its importance to survival, North Africa, like any other resource-rich country, is likely to exploit phosphorous as a geopolitical weapon, especially during times of intense resource competition.

Keywords: *Concentration; Depletion; Distribution; Geopolitics; Geopolitical tool Phosphorus reserves; Single geolocation*

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Introduction

The most serious issue in future agro-world is the role of phosphorus in modern agriculture for high-quality, large-scale food production to feed the world's ever-growing population. Food production requires the usage of major plant nutrients such as nitrogen, phosphorus, and potassium, which are sourced from mineral fertilizers (Dawson and Hilton, 2011; Stewart et al., 2005). Of the three, phosphorus is finite, un substitutable, bio essential and the most critical nutrient for food production (Cordell, 2010; Heckenmüller *et al.*, 2014). It is thus the most essential mineral, playing an important role in modern life and human existential issues. Since most soils are phosphorus deficient (Wissuwa, 2003; Yan *et al.*, 2023), continuous application of phosphate-based fertilizers is required to supplement.

Inefficient phosphate mining and processing (Cordell *et al.,* 2012; Scholz and Wellmer, 2015), as well as wasteful fertilizer use (Sheriff, 2005), have resulted in an ever-increasing demand for the phosphorus. As a result, the closed natural phosphorus cycle has been replaced by anthropogenic open cycles, which permanently moves phosphorus from the biosphere to the hydrosphere (Filippelli, 2008; Yuan *et al.*, 2018). These practices, accelerate over-exploitation of phosphate resources and put reserves at risk of depletion that could have a substantial social and economic impact in the foreseeable future. The impact would include reserve depletion, decreased farm output, increased food costs, worsening food insecurity and escalating social and economic challenges.

Depletion and uneven distribution of phosphorus resources around the world is alarming, making it a concern and a possible future political instrument (Reijnders, 2014; Tiessen *et al.,* 2011; Udert, 2018). For example, Northern African alone currently accounts for more than 78% of the world's P reserves (S. M. Jasinski, 2024). Given that P rock is predicted to be depleted within the next 100-300 years (Elser and Bennett, 2011; Van Kauwenbergh, 2010), and before the depletion is realized, reserves will be concentrated first in a single geo-location (Van Vuuren *et al.,* 2010), in this case in North Africa. The political difficulties may arise if supply cannot match demand. In this scenario, North African is projected to dominate the phosphorus market much more oligopolistic than oil. Thus, it is likely to employ it as a geopolitical tool in the future to negotiate its political interests.

Phosphate demand, supply, production peak, depletion (Cordell, Drangert, *et al.,* 2009; Walan, 2013), and fertilizer consumption trends (Borkar, 2023; Kharbach and Chfadi, 2021; Motesharezadeh *et al.,* 2017) have all been studied and modelled extensively. However, the impact of uneven phosphate rock reserve distribution and concentration to a single geographical location has not received the attention it deserves, particularly during periods of severe resource rivalry or political instability. It is widely acknowledged that as resources become scarcer, producer countries tend to safeguard them through a number of means, including tariffs, supply restrictions (Geissler *et al.,* 2019; Mancheri, 2016), sanctions, and submission requirements (Biglaiser and Lektzian, 2011; Neuenkirch and Neumeier, 2016). Some governments have employed in the past similar measures in response to scarce resources such as currency (Caytas, 2016), technology (Sun, 2019), minerals (Mancheri, 2016), gas, and oil (Woehrel, 2008), and the same is expected for phosphorus in the future.

This study however, aimed at assessing the likelihood of phosphorus being used as a political tool, with the assumption that the scarcer and more unevenly distributed the resource, the more appealing it is for weaponization. In addition, the study did not however focus at when the reserve would be emptied, but rather at the potential consequences during periods of high resource competition as reserves declined and concentrated to one geographical location, notably around the end of the century. The static reserve-to-production (R/P) ratio was used to calculate the reserve duration and the likely reserve depletion year, and time series analysis was used to forecast future resource trends. Three scenarios were considered when using time series analysis to forecast reserve trends. The scenarios are: i) constant annual production or consumption; ii) a 1 to 2 percent increase in annual production or consumption; and iii) a 1 to 2 percent decrease in annual production. Aside from the three scenarios, the discussion also covered phosphorus depletion, depletion accelerators, an altered phosphorus cycle, and phosphorus concentration to a single region. As well, the discussion involved resources as a political tool, the history of using resources as political weapons, the reasons of resource competition, conflict, and weaponization, and offered ways and solutions to the problem.

The availability of phosphorus would affect fertilizer and food costs, as well as world economic growth. As fertilizer and food prices rise, the growing disparity in access between rich and poor countries may have serious geopolitical complications. In this regard, a better understanding of future P rock demand and supply, as well as necessary mitigation, is required, otherwise humanity may face geopolitical consequences for which the world is unprepared.

Materials and methods

The data used in this study came from the United States Geological Survey (USGS). It was then used to calculate the reserve-to-production ratio (R/P) (Walan, 2013) to determine the most likely period of phosphorus depletion, assuming the current production rate and with or without substantial resource discovery in the future. In fact, the 2023 USGS data on phosphorus reserve and production were used to calculate the reserve depletion time. Furthermore, time series analysis was used on historical phosphorus output data from 1932 to 2023 to anticipate future phosphorus resource patterns through 2200. Workability and accuracy of a model was first tested on historical data on phosphorus reserve and production from 1932 to 2023, before used to predict its future trends from 2023 to 2200. The forecast was subjected to three scenarios; i) constant annual production or consumption; ii) a 1 to 2 percent increase in annual production or consumption; and iii) a 1 to 2 percent decrease in annual production. Using these scenarios, reserve trends were projected from 2023 to 2200

Results

Forecasting phosphorus reserve depletion

Reserve depletion trend forecast based on reserve-to-production (R/P) ratio is shown in Table 1. The depletion timeframe is based on the assumption that no further discoveries will be made, and that consumption will continue as reported by USGS in 2023.

Table 1

Estimated depletion time of phosphate reserves using the 2023 reserve-to-production (R/P) ratio

Regions	Reserves	Production	R/P ratio	Depletion year
USA	1,000,000	20000	50	2073
China	3,800,000	90000	42	2065
Rusia	2,400,000	14000	171	2194
Middle East	2,710,000	23800	113	2136
North Africa	57,580,000	49200	1170	3193
Australia	1,100,000	2500	440	2463
Other Regions	5,410,000	20500	264	2287

Reserve trends projection

The global phosphorus reserve trend was projected from 2023 to 2200 using time series analysis under various scenarios as shown in Table 2 and Figure 1. The scenarios were i) phosphorus reserve steady consumption or production, ii) production increases of 1 and 2 percent per annum, and iii) production decreases of 1 and 2 percent per year (Figure 1).

Table 2

The forecast on regional reserves trends from 2023 to 2200, under different scenarios

Region	At Constant annual production	1% increase in annual production	2% increase in annual production	1% decrease in annual production	2% decrease in annual production
North Africa	87% remaining	64% remaining	2192, deplete	94% remaining	97% remaining
China	2065, depleted	2058, deplete	2053, deplete	2078, deplete	2120, depleted
Middle East	2136, depleted	2098, depleted	2082, depleted	28% remaining	58% remaining
USA	2072, depleted	2063, depleted	2057, depleted	2092, depleted	4% remaining
Rusia	2194, depleted	2122, depleted	2194, depleted	52% remaining	72% remaining
Australia	60% remaining	2191, depleted	2137, depleted	81% remaining	89% remaining
World	47% remaining	2170, depleted	2125, depleted	75% remaining	86 % remaining

Table 3

Results of previous studies on reserves depletion, and modelling (Illakwahhi et al., 2024)

Article	Depletion time (years)	Model type	Assumptions
Herring and Fantel (1993)	50-100	-	Linear growth or exponential production growth at a rate of 1- 1.7%
Smil (2000)	80	Static R/P	Continued constant production
Vaccari (2009)	90	Static R/P	Continued constant production
Smit et al. (2009)	69-100	Dynamic R/P	0.7-2% production growth rate until 2050 and a 0% increase after that
Van Kauwenbergh (2010)	300-400	Static R/P	Continued constant production
Cooper et al. (2011)	370	Static R/P	Continued constant production
Sverdrup and Ragnarsdottir (2011)	30-330	System dynamics	Demand-supply model, using price and recovery feedback to supply scarcity
Koppelaar and Weikard (2013)	100-200	System dynamics	Demand-supply model, using price feedback and global flow analysis. Recycling postpone depletion

*Year of depletion assumes lifetime estimated from date of publication

Discussion

Forecasting phosphorus reserve depletion

The R/P ratio predicts that the global phosphorus reserve will last for 336 years as of 2023. The reserves of the United States, China, Russia, Middle East, North Africa, Australia, and other regions would last for 50, 42, 171, 113, 1170, 440, and 264, respectively. The depletion timeframe is based on the assumption that no further discoveries will be made, no any intervention measures are implemented, and that consumption will continue as reported by USGS in 2023 (Table 1). In this sense, global phosphate rock reserves will be drained by the year 2287, while those of the United States, China, Russia, the Middle East, North Africa, Australia, and other regions will be depleted by 2073, 2065, 2194, 2136, 3193, 2463, and 2287, respectively. In 50 years, after the United States and China have depleted their supplies, they will outsource phosphorus from North Africa, the Middle East, and other regions, causing the resources of North Africa, the Middle East, and other regions to last shorter periods than presented in Table 1. Likewise, after 150 years, several countries and areas such as the United States, China, Russia, and the Middle East would have depleted their supplies, forcing them to rely on phosphorus import, primarily from North Africa, resulting in its reserve lasting fewer years than indicated in Table 1.

Reserve trends projection

Global phosphorus reserve trends have also been projected using time series analysis under several scenarios (Table 2), such as phosphorus reserve steady consumption or production, production increases of 1 and 2 percent per annum, and production decreases of 1 and 2 percent per year (Figure 1). The data for this research came from a Mineral Commodities Summary published by the United States Geological Survey. Moreover, the data in Table 2 indicates the depletion time frame and percentage of remaining resources by 2200. The scenarios used in this study are discussed hereunder.

The first scenario: phosphorus constant production/consumption

This scenario assumes that the 2023 reserves and production rate will remain unchanged over the projected period, implying that there will be no further discoveries, and less implementation of sustainability measures. According to the forecast, by 2200, the remaining global phosphate rock stocks will be 47%, North Africa will retain 87% of its reserves, Chinese stocks would have been drained by 2065, Middle Eastern reserves would have been depleted by 2136, the Unites States reserves would have been depleted by 2072, and Russia's reserves by 2194. Australia would still have 60% of its reserves.

The second scenario: an increase in annual production of 1 to 2 percent

The assumptions for this scenario are that future increases in phosphorus production and consumption will be driven by population growth and extensive fertilizer application in developing countries. As the world's population grows, so will the demand for phosphorus-based fertilizers to produce more food to feed it. The world population will increase from 8.1 billion in 2023 to 9.7 billion in 2050 and 10.4 to 11 billion by 2100 (Gruzieva *et al.* 2019; Zhao *et al.,* 2023). This suggests that between 2023 and 2100, the global population might expand by 2.3 to 2.9 billion people, representing a 28-36 percent increase in population. Increased population means more food and fertilizer consumption, and consequently more phosphorus mining. The farmers in developing countries particularly those in Africa and Asia with currently low fertilizers purchasing power and consumption will increase their power, hence driving up the demand for phosphorus. As farmers' purchasing power for fertilizers increases, their need to access more fertilizers will increase as well. Furthermore, increased fertilizer requirement for biofuel production will rise phosphorus production(Farias et al., 2020) and fasten reserves depletion. Similarly, rising per capita phosphate fertilizer demand as a result of dietary trends toward phosphorus-intensive meat and dairy products will push up the requirement to extract additional phosphorus (Cordell, Drangert, et al., 2009; Cordell and White, 2013).

The first case in this scenario is an increase of 1 percent annual production. According to the forecast under this circumstance, Table 2 predicts that by 2200, North Africa will still have 64% of its reserves, while the rest of the world would have been depleted. The global phosphorus reserve will be drained by the year 2170 with output increases of one percent. However, because other regions such as the United States, China, Russia, and the Middle East will consume their deposits much earlier, they will have outsourced phosphorus from North Africa, and hence North Africa's reserves will last shorter than stated in Table 2. With a 1% annual growth in phosphorus use, the United States, China, Russia, the Middle East, and Australia will deplete their reserves by 2063, 2058, 2122, 2098, and 2191, respectively. The 2nd case under this scenario is an increase in production by 2 percent. According to the forecast under this circumstance, reserves will be depleted before 2200. For example, North Africa, China, the Middle East, the United States, Russia, and Australia's reserves would have been spent by 2192, 2053, 2082, 2057, 2194, and 2137, respectively, while the world's reserves would have been drained by 2125.

The third scenario: decrease in 1 and 2 percent annual production

The assumptions in this scenario are that a drop in production might be caused by fresh discoveries of new reserves, innovation and used of improved technology in phosphorus mining, processing, recovery and recycling will decrease amount of phosphorus mined annually. Phosphorus reuse, recycling, or recovery throughout the production and consumption chains will also decrease phosphorus requirement for fertilizer production. The substitution of phosphorus with other minerals in the detergent, soft drinks, pyrotechnics, incendiary shells, and steel industries will reduce phosphorus consumption. Furthermore, increasing phosphorus usage efficiency and lowering losses will also improve reserve life. The adoption of precision agriculture technology, which uses fertilizer efficiently, and organic farming, which does not use mineral fertilizers at all, will cut demand and increase reserve life. All these will reduce the demand and decreases the annual production. Additionally, continued fertilizer application will result in soil saturation with phosphorus due to phosphate residue in the soil.

The first scenario envisions a 1% reduction in annual phosphorus production or consumption. According to this analysis, North Africa will retain 94% of its reserves by 2200. The Middle East, Russia, Australia, and the world will each have 28%, 52%, 81%, and 75% of their reserves, respectively. On the other hand, the Chinese and US reserves will be drained by 2053 and 2092, respectively.

The second scenario envisions a 2% reduction in annual phosphorus production or consumption. The analysis under this case indicates that North Africa would still have 97% of its reserves while that of Chinese would deplete by 2120. The analysis under this instance indicates that North Africa would still have 97% of its reserves, whereas China's stockpiles would be depleted by 2120. Similarly, the world would still have 86% of the phosphate reserves by 2200. Moreover, the Middle East, United States, Russia, and Australia would still have 58%, 4%, 72% and 89% of their reserves, respectively. It is critical to remember that in order for phosphate reserves to last long and sustainably, all practices that promote a reduction in phosphorus usage must be undertaken.

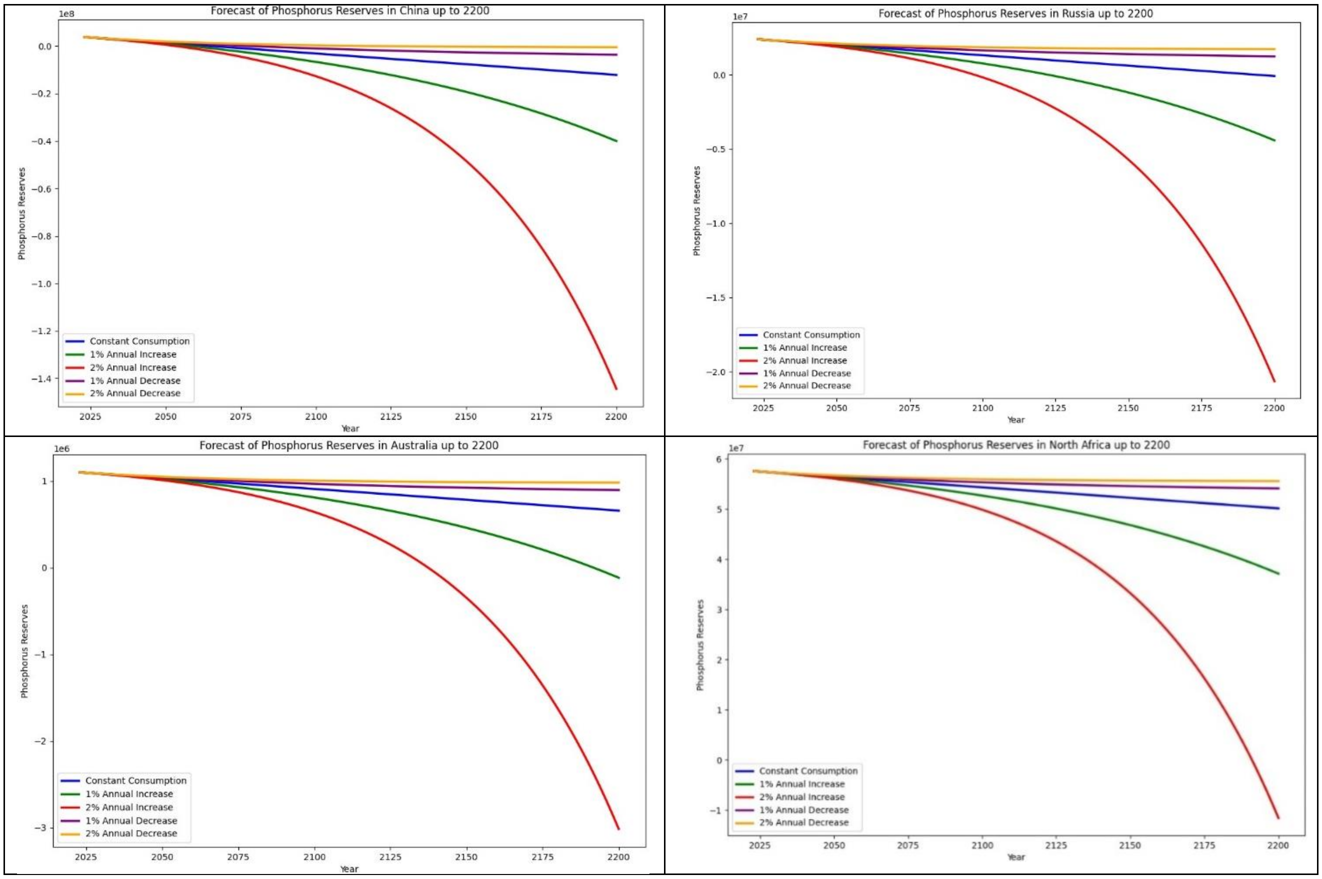
Basis for phosphorous depletion

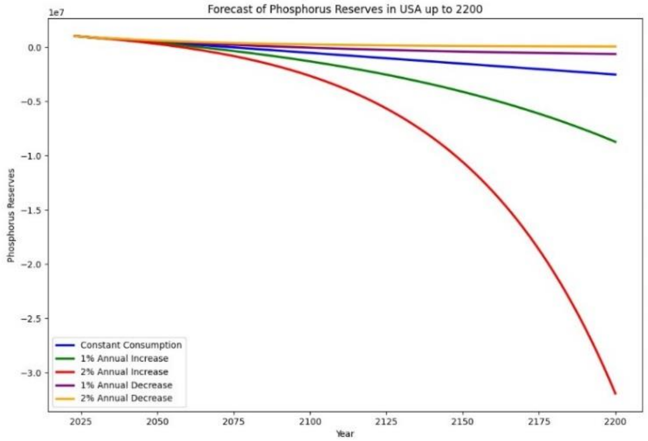
It is, however, very difficult to predict with certain when all phosphate stock would be depleted because natural resources are dynamic in nature. This argument is founded on the concept that what is a resource now can become a reserve tomorrow. Nonetheless, factors such as new discoveries, reserves quality, mining and processing technology, fertilizer prices, farming technology, phosphorus recovery, recycling, and reuse, phosphorus use efficiency, population boom, and the demand for food will influence when all phosphate rock reserve will be depleted (Cordell, Drangert, et al., 2009; Desmidt *et al.*, 2015; Scholz and Wellmer, 2015; Walan, 2013). Above all, the broken phosphorus cycle is siphoning the reserves by permanently moving phosphorus from lithosphere to hydrosphere.

The time range for phosphorus depletion is divided into two camps, with hopeful beliefs (optimistic) on one side and gloomy thoughts (pessimistic) on the other. The optimistic view is that there will be a lot of phosphate rock reserves left by the end of the century, and that reserves will be present far into the future as more resource discovery is forecast (Edixhoven *et al.*, 2014; S. Jasinski, 2023; Scholz and Wellmer, 2016). Long-term phosphorus adequacy is dominated by debates concerning resource abundance vs shortage; however, the primary concern is its future geopolitical and supply independence (Cordell, 2010; Cordell and White, 2011).

Figure 1

Depicts phosphate rock reserve trend projections from 2023 to 2200 for the world, Middle East, China, Russia, Australia, North Africa, and the United States





Some studies attempted to project the depletion time of the existing phosphate deposits (Table 3), predicting that phosphate reserves will run out by the end of the twenty-first century or the beginning of the twenty-second century (Smit *et al.,* 2009; Vaccari, 2009). However, there is significant variability in the timeline for phosphorus depletion. The large disparities between these research can be explained by the use of different resources and statistical models (Desmidt *et al.,* 2015). The differences in assessments of the lifetime of phosphate rock reserves was also acknowledged by (Chowdhury et al., 2017). Similarly, (Walan *et al.,* 2014) found that future phosphate rock output forecasts varied greatly depending on the models and assumptions used by researchers. These models predicted depletion times when phosphate rock stocks were around 16 billion tons, but they are now estimated at 74 billion tons. It is now obvious that the depletion timeline will differ from the one expected in the early 2010s. Although the time frame for depletion of phosphate rock supplies varies between research, they all agree on one important point: the resource will not survive much longer than two centuries. Indeed, it is widely acknowledged that, regardless of how much reserve exists, any nonrenewable resource will be depleted at some point in the future, whether in hundreds or thousands of years.

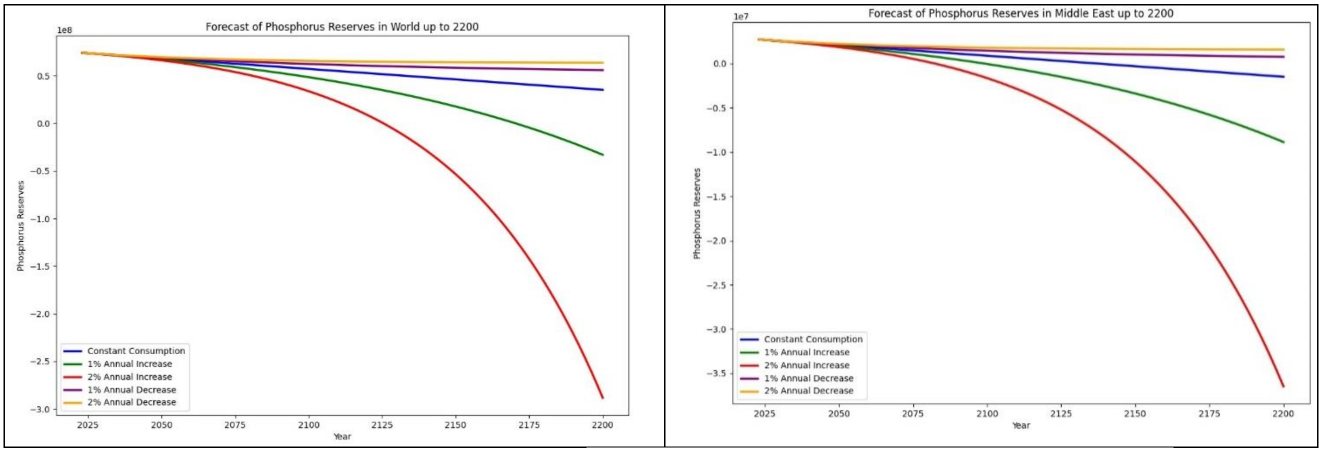
Estimates of remaining phosphate reserves duration are very variable and contentious, ranging from 200 to 300 years at current production rates, to millennia if more resources are discovered and better mining and processing technologies adoption, as well as recycling, recovery and reuse. However, the spatial concentration of phosphate rock reserves raises worries about food security in countries and regions that rely on imported phosphate rock and/or fertilizer.

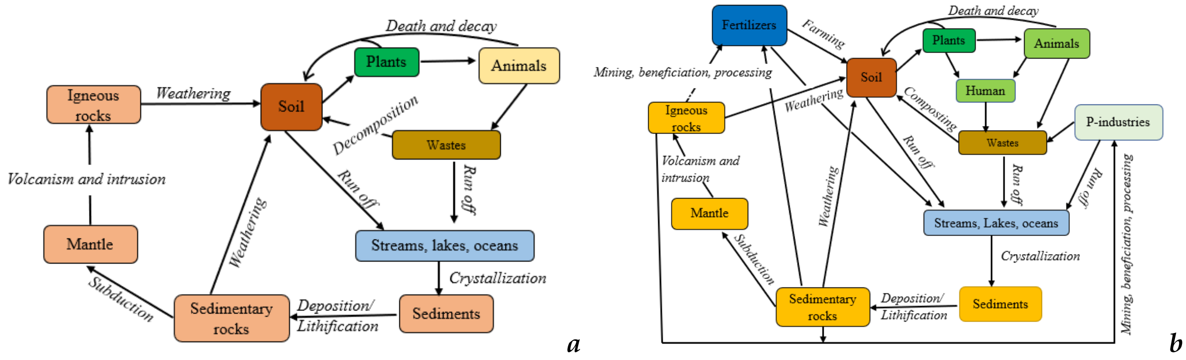
Accelerators of phosphorus depletion

Accelerated depletion has been attributed to several issues, such as disrupted phosphorus cycle, losses due to poor mining and processing technology as well as extensive and ineffective fertilizers use. The cycle is disrupted due to the continual flow of phosphorus from land to water bodies caused by phosphorus loss in the production and consumption chains.

Figure 2

*Phosphorus cycle (**a**-natural P cycle; **b-**anthropogenic P cycle)*





A broken phosphorus cycle

Natural phosphorus cycle involves the transfer of phosphorous through the lithosphere, biosphere, and hydrosphere refers to phosphorus cycle (Childers *et al.,* 2011; Gupta, 2021). Phosphorus naturally cycles between the lithosphere and hydrosphere, as well as between soil and living organism or between aquatic species and sediments. Figure 2 depicts a natural phosphorus cycle, with boxes representing reservoirs, arrows indicating the direction of flow, and the process by which phosphate is transported from one reservoir to another is stated in italics. Moreover, the main reservoirs of phosphorous on earth are living organisms and relatively insoluble calcium phosphate deposits in rock and sediments (Illakwahhi *et al.,* 2024). Because all phosphorus is practically solid at room temperature and pressure, with the exception of phosphine, which is a gas, its cycle does not involve the atmosphere.

Weathering releases soluble phosphates in soil from phosphate-containing rocks (Mendes *et al.,* 2021). Plants absorb soluble inorganic phosphate from the soil, and animals can receive it through plants or animals that eat plants. Once within living creatures, it is used to produce organic molecules such as phospholipids (a component of the cell membrane), nucleotides (DNA and RNA), ATP, and bones and teeth (Illakwahhi et al. 2024; Kesler, 2007; Oelkers *et al.,* 2008). Organic phosphates in plant and animal tissues return to the soil after death and decay (Dhawale *et al.,* 2013; Kesler, 2007). Through the mineralization process, bacteria in the soil break down organic phosphates, making them available to plants again.

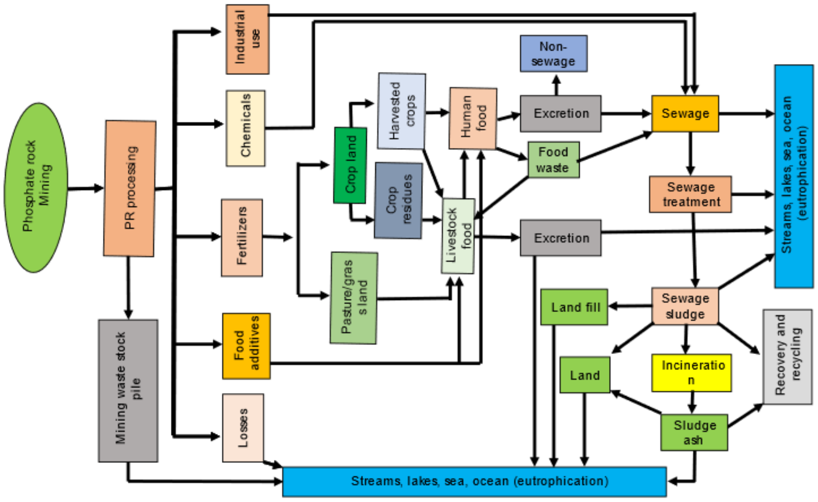
Phosphorus can even be washed away from the soil, wastes, vegetation, and animals and end up in the lakes, seas and oceans. Once in the sea or ocean, it can be buried in the seafloor and progressively integrated into sediments by crystallization or precipitation (Childers *et al.*, 2011; Illakwahhi *et al.*, 2024). Sedimentary phosphate rocks are generated under ideal conditions by lithification of sediments, which can then be returned to the mantle via the subduction process. Tectonic processes, earth quakes, volcanism, and geological uplifts gradually expose buried sedimentary and igneous phosphate rocks to the surface of the earth (Dhawale *et al*. 2013; Oelkers *et al.*, 2008). The cycle is restarted as rocks and sedimentary deposits weather, releasing inorganic phosphates into the soil and surface water, where plants can absorb and incorporate them into organic molecules. Animals can obtain it by feeding on plants or other animals. A complete phosphorus cycle between lithosphere and hydrosphere takes millions and millions of years and it is multidirectional (Illakwahhi et al., 2024). In fact, the phosphorus cycle is made up of a series of small processes that may or may not ever interact, process that can occur in time frames as short as days and as long as millennia (Figure 2). To conclude, it is appropriate to say "the phosphorus cycle, like all other cycles, has no beginning or conclusion and certainly there is no single direction of movement"

An altered phosphorus cycle

This refers to the transfer of phosphorus between lithosphere, hydrosphere and biosphere under human influence (Illakwahhi *et al.*, 2024). Human activities such as mining, fertilizers production and application, farming, and waste disposal and management all contribute to a broken natural phosphorus cycle (Figure 3). When plants are grown on land, they absorb soluble phosphates and assimilate them into their body tissues; when these plants die, the phosphorus in their tissues is recycled back into the soil (Lambers and Plaxton, 2015; Prasad *et al.*, 2016). The phosphorus that has been recycled into the soil will be available to the plants in the following season. However, when plants from agricultural land are harvested, the amount of phosphorus recycled back to the soil is reduced. Thus, farming reduces the amount of available phosphorus in the soil, necessitating the application of phosphatic fertilizers to replace the phosphorus lost in the soil through crop harvesting.

Figure 3

Broken phosphorus cycle



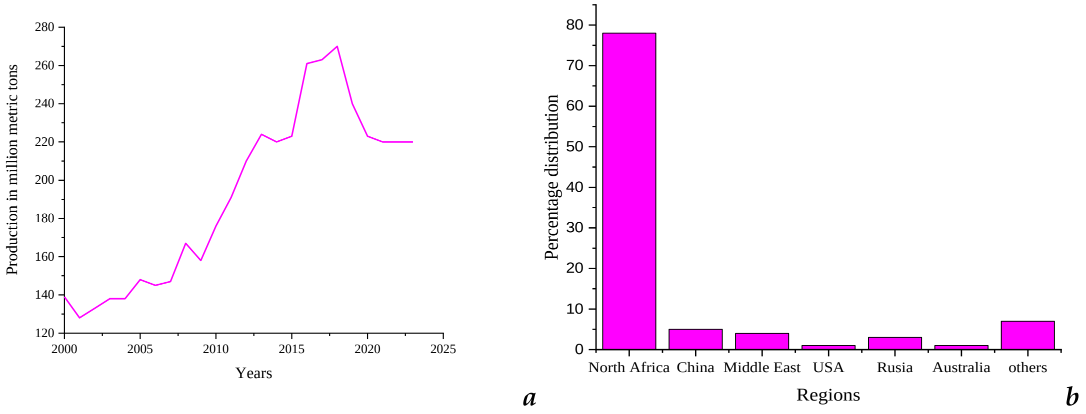
Humans have significantly impacted the global phosphorus cycle by importing or exporting phosphate minerals, using phosphate fertilizer, and transporting food from fields to cities, where it is lost as effluent. The analysis of the flow of phosphorus across the global food production and consumption system reveals that we are mining five times the amount of phosphorus that humans eat in food (Cordell, Schmid-Neseta, *et al.,* 2009). Yet, we consume just around one-tenth of the phosphorus that enters the agricultural system (Tirado and Allsopp, 2012). The lost phosphorus ends up in streams, causing eutrophication, a catastrophic kind of water pollution (Akinnawo, 2023). When phosphate fertilizer is applied, only a tiny quantity is immediately available to plants, while the rest is stored in soil colloidal with varying degrees of availability. To make phosphorus more available to plants, farmers had to apply fertilizers in excess (Schröder et al., 2011). Excess fertilizer use increases the risk of the majority of phosphorus being lost by leaching, run-off, or soil erosion, eventually ending up in rivers, dams, lakes, seas, and oceans, where they generate pollution(Cordell, Drangert, *et al.,* 2009; Tirado and Allsopp, 2012). Phosphorus is also used in detergents, tooth paste, pesticides, and the food industry. Waste water from these sectors is high in phosphorus, which can be transported to streams via sewage. Animal and human waste are also high in phosphorus, thus residential waste water is a source of phosphorus loss. Phosphorus losses during mining, processing and transportation accelerate depletion as most of the phosphorus mined ends up in mineral wastes. This disrupts the normal phosphorus cycle and accelerates depletion.

Rising global production

Global phosphorus production has been increasing since 2004 (Figure 4a), when it was at 138 million metric tons, and peaked at 270 million metric tons in 2018, after which it began to slow to 220 million metric tons in 2021, which was maintained until 2023. The production trend shows a sharp increase since 2004

Figure 4

*Global phosphate production in million metric tons from 2000 to 2023 (**a**), and regional reserve distribution in percentage (**b**), all data from USG S*



China is the world's largest phosphate producer, accounting for 41% of worldwide phosphorus production in 2023 at 90 million metric tons. Aside from China, the other leading producers in 2023 are Morocco (35 million metric tons), the United States (20 million metric tons), Russia (14 million tons), Jordan (12 million tons), and Saudi Arabia (8.5 million tons) (S. M. Jasinski, 2024).

The regional phosphorus production aggregates suggest that in 2023, North Africa, China, the Middle East, the United States, Russia, Australia, and other regions produced 22, 41, 11, 9, 6, 1, and 9 percent of phosphorus, respectively (Figure 4b). As the population rises, fertilizer demand for food and biofuel production increases, and farmers' access to fertilizers in developing nations improves, so will phosphorus output and consumption. All these together will accelerate phosphate reserve depletion

Population boom

The global population is expected to rise by 2 to 3 billion people during the next 50 to 80 years, from 8.1 billion presently to 9.7 billion in 2050 and around 10.4 - 11 billion by 2100 (Dorling, 2021; Lal, 2016).This means that more food, both in quantity and quality, is necessary to support the world's rising population, and growing more food per unit area necessitates the widespread use of phosphate-based fertilizers (Illakwahhi et al., 2024). Because food production is heavily reliant on phosphatic fertilizer supplies, global demand for phosphorus is increasing and will continue to climb in the future (Cordell and White, 2014a). As the world's population grows and supply continues to diminish, demand will outstrip supply, causing prices to rise. Once more, as the world's population grows, so does the number of farmers in developing countries with more purchasing power, access to, and use of phosphate-based fertilizers. Likewise, it will also result in increased per capita fertilizer use as people alter their diets to phosphorus-rich meat and dairy products. These will compel several nations or regions to take actions similar to those done by the United States and China to safeguard their resources and internal supplies. It should be noted that the only way to feed the world's ever-increasing population is to use phosphate-based fertilizers extensively and correctly. Convincingly, phosphorus is a nutrient without an alternative to human survival as it is critical for food production, making it an excellent target for geopolitical weaponization. In this sense, particularly in light of resource scarcity and protectionism, as well as to safeguard their internal supplies, North African governments are likely to weaponize phosphorous for political purposes.

Concentration of reserve to one geographical location

What will happen between now and the estimated period of reserve depletion is that phosphorus resources will be concentrated in a certain geo-location before real depletion occurs. Currently, major phosphorus producers and consumers are the United States, and China whose reserves are expected to run out in 2073, and 2065, respectively, assuming a static reserve to production ratio. The resources of Russia, and the Middle would exhaust before 2194, and 2134 respectively. The North Africa (Morocco, Algeria, Tunisia, Egypt, Senegal, and Togo) reserves would last for more than 400 years, according to current knowledge (Table 1). On average, with 74 billion tons of global phosphate rock reserves and an annual production of 220 million tons in 2023, there will be enough supply for around 300 years. In this sense, by 2100, North Africa will dominate the global market, accounting for around 95% of supply and likely to use the resources for political leverage.

Global phosphate resources are unevenly distributed, with some regions having a larger share than others (Figure 6). For example, only five nations, Morocco, China, South Africa, Jordan, and the United States accounted for more than 90% of total global phosphate reserves in 2010, with Morocco alone accounting for 85% of the reserves by then (Van Kauwenbergh, 2010). China might have larger phosphate deposits than is currently declared.

Currently, the top five countries with large reserves are Morocco, Egypt, Tunisia, Algeria and South Africa; all of which are in Africa. According to the 2024 USGS assessment, North Africa, China, the Middle East, Russia, the United States, Australia, and other regions have 78, 5, 4, 3, 1, 1, and 7 percent of global reserves (Figure 5) (S. M. Jasinski, 2024). In 2022, African reserves accounted for up to 82% of the world's recoverable resources (S. Jasinski, 2023), but by 2023, they accounted for 80% of total global reserves (S. M. Jasinski, 2024). In 2022, Africa's phosphate reserves were assessed to be 59,180,000,000 metric tons, while Asia, South America, North America, Europe, and Australia (Oceania) reserves were estimated at 4,796,000,000, 1,600,000,000, 1,030,000,000, 3,000,000,000, and 1,100,000,000 metric tons, respectively (S. Jasinski, 2023). Northern African countries (Morocco, Egypt, Tunisia, Algeria, Senegal, and Togo) had 57,580,000,000 out of 59,180,000,000 metric tons of total Africa, which is equivalent to 78% of total global phosphate reserves. Morocco alone holds 50,000,000,000 metric tons, which accounts for 84% of African resources and 69% of global reserves. While deposits in the United States, China, and Russia have begun to dwindle, North Africa, notably Morocco will become the future source phosphorus. Conclusively, North Africa is and will continue to be a global phosphorous powerhouse in the future. This disproportionality raises the question of whether the North Africa will use it as a geopolitical weapon.

Given the current rate of mining and consumption, the United States, and China will deplete their supplies first, followed by the Middle East, leaving Africa as the sole supplier of phosphate for fertilizer production. This means that by 2100, more than 95% of the phosphorus used in fertilizer production will be sourced from North Africa, especially Morocco. However, the majority of the Moroccans resources are concentrated in Western Sahara, a politically sensitive territory (Khakee, 2011). Concentration of vital resources like phosphorus in a single geographical location might have political consequence in the future particularly during the times of intense resource competition and political instability (Cordell, Schmid-Neseta, *et al.,* 2009; McGill, 2012). The Arab Spring and Islamic extremist ISIS are recent examples of how resource supply can be disrupted. The Arab spring impacted phosphorus supply from many Arab countries. To put it brief, the uneven distribution of phosphate resources has already sparked widespread concern among stakeholders that it could be used as a geopolitical tool (McGill, 2012). Based on this, Vaccari (2009) correctly stated that phosphorus should be regarded as a "geostrategic ticking time bomb."

Resources as a political tool

It is widely acknowledged that, a number of countries have used resources to advance their political objectives in relative to other countries. Example of countries with resources they use as political tool are Russia (oil and gas), China (rare earth element and phosphorus), Venezuela (oil and gas), Iran (oil and Strait of Hormuz), and the United States of America (technology and its currency dollar). Countries with abundant natural resources, such as oil, gas, or minerals, may use their control of these resources to gain geopolitical advantage (Baran, 2007; Gokce, 2019; Mahdavi, 2014; McDowell, 2021). Likewise, agricultural resources can also be used as geopolitical tools (Woertz, 2018). Countries with strong agricultural capacities may control food supply chains or use trade policies to manipulate prices or exert influence over food dependent nations (Brown, 2011; Woertz, 2018). By controlling supply or manipulating prices, they can influence other countries' economic and political agenda. These actions can have serious social, economic, and environmental consequences. However, resource-rich countries may use it to pursue their political will through sanctions and trade restrictions. This could entail trade restrictions between nations, among other things, and has become a tool of choice to respond to key geopolitical challenges. This can put strain on the economy of the target country, compromising its stability and potentially forcing it to comply with certain demand or policies. By controlling supply, they can build political alliances (Moran, 2016), exert economic pressure, or even manipulating commodity prices to achieve their desire ends (Alhajji and Huettner, 2000; Colgan, 2014). However, many international organizations and agreements aim to regulate the use of resources as political instrument to maintain stability and cooperation among nations.

The cause of resource competition, conflict, and weaponization

Competition for access to scarce resources, such as water, land, minerals, oil, or other valuable commodities, is a common cause of resource-driven conflict (Mildner *et al.,* 2011; Ojakorotu, 2018), competition, and weaponization. The idea of exploiting critical resources as a political instrument is not new; several major world powers have done so for decades (Maihold, 2009; Pollard, 1985; Qingqing and Panyadee, 2023). Due to resource dependency, countries with plentiful natural resources may use their control over these resources to obtain geopolitical benefits by controlling supply or manipulating prices. These can affect economies and political agenda of other nations. For instance, resource-rich countries might enforce sanctions on others in order to limit their access to vital resources. This can put strain on the economy of the target country, compromising its stability and potentially pushing it to comply with specific demands, policies or any other desired political outcomes. Phosphorus reserves can also be used in a similar manner. China is a good example in this regard; it is now using export levies to protect its own phosphate stocks. In reaction to the 2008 fertilizer price increase, for example, it imposed a 135% export levy on phosphate fertilizers (Cordell and White, 2014b). The geopolitical implications of these issues on food security are largely in the hands of countries that produce phosphate and fertilizers. It is widely acknowledged that factors such as regional war, sanctions, scarcity, resources protectionism policies and disasters like disease outbreak can disrupt supply chain and trade in phosphorus resources. More over regional instability due to domestic or regional wars, civil unrest, terror groups, can significantly disrupt phosphorus and fertilizer supply chain. These components are likely to interact differently in different parts of the world, making it difficult to anticipate the effects on markets as phosphate reserves decrease and concentrated to North Africa.

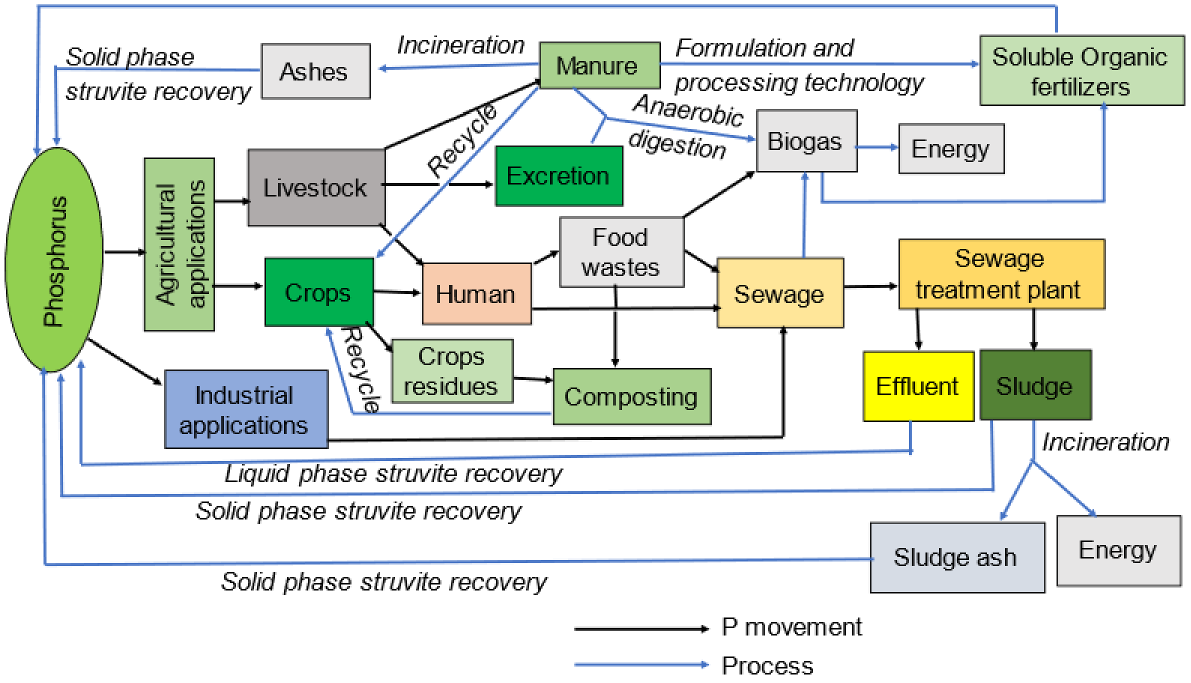
Approach and solutions for the problem

Close the cycle

Once mined, phosphate rock is beneficiated and processed into phosphorus, which is then used in fertilizer manufacturing as well as many other industries such as food and chemical production. All of these goods have applications in agriculture and at home. Working to close the broken phosphorus cycle can ensure that phosphorus is available for future generations' food production while also preventing contamination in water systems. This requires substantial measures in two primary areas: minimizing phosphorus losses, especially from agricultural lands; and improving phosphorus recovery and reuse from all sources, including livestock wastes, food waste, and human excrement (Figure 5). Maximizing phosphorus recovery and reuse from all types of waste, primarily animal and human excreta, hence reducing the demand for phosphorus mining. The excessive use of synthetic fertilizers on agricultural land should be stop by switching from mineral fertilizers to organic fertilizers and fertilizer use efficiency. Plant residues, residential garbage, food leftovers, and animal waste should all be repurposed and recycled. Minning waste should be processed to recover phosphorus and other valuable minerals. Nutrients from home and industrial waste water, as well as sewage treatment plants, should be recovered from either the waste water or the sludge/sludge ashes in form of a struvite and reapplied again.

Figure 5

A closed phosphorus cycle



Minimizing losses

Phosphorus losses have been recorded across all production and consumption networks. Losses occur during the mining, shipping, and processing of phosphate rocks. Since over 85% of phosphate mined is used to manufacture fertilizers, losses due to fertilizer manufacturing, transportation, and application account for a significant portion of lost phosphorus. Losses are also incurred during chemical manufacturing and processing, food production, waste disposal, livestock management, and crop cultivation. All of this drains phosphate rock reserves and accelerates depletion, while also causing eutrophication to streams.

To minimize losses, it is critical to reduce phosphorus losses during phosphate rock mining and processing by: i) using efficient processing technology; ii) reprocessing phosphorus from mining stockpiles; iii) inventing phosphorus concentrating technology; and iv) establishing a fertilizer manufacturing plant at the mining site. Overall, phosphate mining is a low-efficiency process.A study by Zhang et al. (2008), found that in China, only around 40% of the phosphorus mined in rock phosphate is used as phosphorus fertilizers, with the other 60% stockpiled or dumped. Fertilizer misuse is a cause of phosphorus loss, therefore improving fertilizer usage efficiency could lower the quantity lost due to fertilizer application, field runoff, and erosion. Fertilizers should be used based on soil phosphorus deficiency and plant requirements, unless excess is lost.

Precipitating struvite from industrial and municipal wastewater, manure, sludge ashes, and meat and bone meal ashes can also help to cut losses (Figure 5). To close the cycle, agricultural practices such as re-application of manure, composting organic and food waste, and ploughing up crop residues might help reduce losses. The first priority should be to improve capacity and support farmers in implementing steps to decrease phosphorus misuse. These would not only address the issue of phosphorus reserves, but would also protect the global aquatic ecosystem and benefit farmers financially.

Conclusion

One of the most important realities and issues that humanity will face in the future is the depletion and concentration of phosphorus in a single geographic area. It should be noted that phosphorus deposits are unevenly distributed over the planet, despite being the most limiting and critical ingredient for food production, with no natural alternatives. The significance of phosphorus for food production and human survival has been acknowledged. As reserves dwindle and deplete in most parts of the world, they will eventually concentrate in North Africa before total depletion is realized. The study found that on average, at constant consumption, the global reserves would last for 336 years, i.e., will deplete in 2359. Besides, China and the United States will consume their stocks by 2065 and 2073, respectively. Likewise, by 2100, large portion of phosphorus reserves will be in North Africa, which will account for 95% of global phosphorus reserves and output. With time, phosphorus shortage will increase, and the consequences of unequal distribution of phosphorus resources around the world will be felt when supplies cannot meet demand, or when there is resource competition or political instability. If the assumption that “the scarcer and more unevenly distributed the resource, the more desirable it is for weaponization”, is true, then North Africa is very likely to use phosphorus and fertilizer production as geopolitical instrument to gear their political will. If the notion that "the scarcer and more unevenly distributed the resource, the more desirable it is for weaponization" is correct, North Africa will most likely employ phosphorus and fertilizer production as a geopolitical instrument to gear up their political interest in countries. Besides, any political unrest in this region will disrupt and seriously destroy food production systems. Inequality in resource availability between rich and poor countries can lead to major geopolitical consequences, such as the outbreak of resource-based conflict or war. In this context, a better understanding of future phosphorus and fertilizer demand and supply, as well as indispensable mitigation, is required; otherwise, humanity risks encountering geopolitical consequences for which the world is unprepared.

Recommendation

The model and statistical tools used in this study are appropriate for the specified conditions. However, multiple interrelated factors influence phosphorus production and supply chains. Because the methodologies used in this study cannot address all aspects of phosphorus production and supply chain, a more complex and comprehensive model is proposed to meet demand.

Regulatory frameworks governing mining, usage, and environmental implications can have an impact on phosphorus production and supply chains. This area was not covered in this study, hence a study that might anticipate their impact on future phosphorus production and supply chains is recommended.

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