

# Realising the Circular Phosphorus Economy delivers for Sustainable Development Goals

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## Abstract

While it remains debated if the mineral deposits mined for phosphorus fertilizer are running out, phosphorus insecurity is an emerging global issue. We explore how it is linked to the current linear phosphorus economy (LPE) and the historic and current implications. The problems are multifold: there are geopolitical concerns over phosphorus deposits held only by a few nations, sharply rising costs of phosphorus fertilizers, heavy metal contaminants affecting soil and food, problematic phosphorus mining wastes, and the widespread environmental degradation caused by fertilizer inefficiencies. A new phosphorus economy can resolve these problems. Transitioning to a sustainable use of phosphorus demands a circular phosphorus economy (CPE). A CPE supports several Sustainable Development Goals and enables countries without phosphorus deposits to achieve greater phosphorus autonomy. We illustrate current problems with case studies and outline opportunities for change. The CPE will feature phosphorus recovery facilities, waste valorisation technologies, and improved fertilizer formulations that are customised to crop systems. We highlight examples of the rapidly advancing CPE that forms an integral part of the bioeconomy and the circular economy.

# **Realising the Circular Phosphorus Economy delivers for Sustainable Development Goals**

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## **Key Points**

- 1) The Linear Phosphorus Economy (LPE) threatens food sovereignty, environmental integrity, and public health
- 2) A transition away from an LPE into phosphorus circularity requires innovation and institutional support
- 3) Adopting a Circular Phosphorus Economy (CPE) contributes to numerous Sustainable Development Goals

## **Abstract**

While it remains debated if the mineral deposits mined for phosphorus fertilizer are running out, phosphorus insecurity is an emerging global issue. We explore how it is linked to the current linear phosphorus economy (LPE) and the historic and current implications. The problems are multifold: there are geopolitical concerns over phosphorus deposits held only by a few nations, sharply rising costs of phosphorus fertilizers, heavy metal contaminants affecting soil and food, problematic phosphorus mining wastes, and the widespread environmental degradation caused by fertilizer inefficiencies. A new phosphorus economy can resolve these problems. Transitioning to a sustainable use of phosphorus demands a circular phosphorus economy (CPE). A CPE supports several Sustainable Development Goals and enables countries without phosphorus deposits to achieve greater phosphorus autonomy. We illustrate current problems with case studies and outline opportunities for change. The CPE will feature phosphorus recovery facilities, waste valorisation technologies, and improved fertilizer formulations that are customised to crop systems. We highlight examples of the rapidly advancing CPE that forms an integral part of the bioeconomy and the circular economy.

## **Index terms**

- 1) 0215 Economic Geology
- 2) 0402 Agricultural Systems
- 3) 0439 Ecosystems, structure and dynamics (4815)
- 4) 0470 Nutrients and nutrient cycling (4845, 4850)
- 5) 0478 Pollution: urban, regional and global (0345, 4251, 5325)

## **Keywords**

- 1) Phosphorus, Food security, Bioeconomy, Sustainable agriculture, Circular Nutrient Economy, Circular Phosphorus Economy

## 1. Introduction

Phosphorus (P), a focal point of economic, agricultural, and environmental challenges, is an essential, non-substitutable element required for all life on Earth. It is a central component of biochemicals such as DNA, cell membranes and proteins, a functional element for cellular energy cycles and the structural integrity of bones, stems and root systems (Plaxton & Lambers, 2015). In nature, P originates from the biogeochemical breakdown of parent material (rock) to form soils and sediments. Slow P regeneration via rock weathering and nutrient cycling, together with P losses through erosion and leaching, result in infertile soils over long geological times (Lizcano-Toledo et al., 2021). Much of the soils' P occurs as mineral or organic complexes with varying degrees of bioavailability. Because P bioavailability often limits crop growth, soils must be supplemented with P. Conventional high-production farming mostly uses mineral P-fertilizers (we use the term 'chemical' to distinguish other P form). The most common chemical P-fertilizers consist of immediately bioavailable formulations derived from P-rich mineral deposits which undergo physical and chemical processing. The efficiency of these chemical fertilizers is however low. It is estimated that approximately 70% of the 45 million tonnes of P fertilizer applied to soils annually are not used by crops (Brownlie et al., 2021; FAO, 2021b). Fertilizer is converted into largely inaccessible 'legacy P' in agricultural soils or lost from soil, polluting the hydrosphere. Thus, from mining and agriculture to human consumption, it is estimated that in total 95% of P is lost to inefficient utilization, epitomizing the current Linear Phosphorus Economy (LPE) (Geissler et al., 2018).

The inefficiencies associated with chemical P-fertilizers and P-containing wastes come at a cost. They have caused (i) global biogeochemical flows to push beyond the safe planetary boundaries (Steffen et al., 2015) and (ii) the circulation and accumulation of heavy metals (cadmium, uranium, lead, mercury) in agricultural soils and food (Kubier et al., 2019). Furthermore, they have caused imbalances that contribute to soil degradation and acidification (Lal, 2015). Despite these profound consequences, a level of apathy prevails regarding mineral deposits and P-fertilizer industries, which are characterized by monopolized markets, commodity exploitation and lower food production capacity in vulnerable nations (Cordell et al., 2021; Mayer et al., 2016; Schnug & De Kok, 2016). Furthermore, achieving the Sustainable Development Goals (SDG) in developing nations through adopting an LPE framework places greater pressures on an already fragile system (Právělie et al., 2021) and a heavy price on planetary boundaries (Randers et al., 2019).

Many of the 17 SDGs interconnect with agriculture, food security and environmental integrity (Brooks, 2016; El Wali et al., 2021). However, it has highlighted how difficult it will be to achieve the SDGs by 2030 with current strategies (Kruk et al., 2018; Leal Filho et al., 2018; Sachs et al., 2019; Salvia et al., 2019) while maintaining favorable economic, environmental, and social symbiosis (Ibeh & Walmsley, 2021). To achieve SDG targets, “urgent” and “bold” interventions are required (United Nations, 2019). In recent years, an increase in political conflicts, climate change and the Covid-19 pandemic have led to stagnation and, in some cases, to regression of SDG advancements (Sachs et al., 2021). Extreme poverty has increased for the first time in two decades (World Bank, 2020), with almost 1 billion people going hungry and the cost of food rapidly rising (FAO, 2021a; Laganda, 2021). Only one quarter of countries are on track to meet their 2030 child malnutrition targets (WHO, 2021), while 17% of global food is wasted (UNEP, 2021). Furthermore, the expansion of croplands, which cover 12-14% of the world’s ice-free surface, is forecast to further exacerbate biodiversity loss (Shukla et al., 2019; Zabel et al., 2019). Compounding the hurdles to achieving the SDG targets, the Covid-19 pandemic is expected to cause foreign investments to fall sharply and strongly impact developing countries (Giroud & Ivarsson, 2020). Together, these problems points to the urgent need for the current LPE to pivot into a framework of circularity and sustainability.

Drawing on historic and current circumstances, we explore the implications of the current LPE and possible strategies to transition into a Circular Phosphorus Economy (CPE). With principal themes of foreign market dependency, environmental degradation, and human health, we aim to illustrate these themes with case studies at country or region level. We address the SDGs with the four pillars of sustainable systems - governance, social, environment and economy - as a foundation for the CPE. Further, we outline the challenges and opportunities associated with a CPE to overcome initial investment limitations, support domestic nutrient autarky, optimise agricultural autonomy, and promote environmental integrity relative to SDG targets. Lastly, we summarise the challenges and opportunities associated with the successful adoption of a CPE.

## **2. Foreign market dependency – scarcity or insecurity?**

Largely defined by improvements to crop genetics, crop management and the widespread adoption of chemical fertilizers, the Green Revolution commencing in the 1950s represented

an inflection point for the rapid increase of agricultural productivity. Unlike synthetic nitrogen fertilizers that are generated through the conversion of atmospheric di-nitrogen gas, chemical P-fertilizers are manufactured by extracting and processing a finite supply of rock phosphate. Although rock phosphate deposits occur globally, 90% are inaccessible due to technological or economic limitations (Köhn et al., 2018), and the economically exploitable P deposits (reserves) are becoming increasingly monopolized and depleted (Brownlie et al., 2021; Cordell, 2013; Nassar et al., 2020).

Since the Green Revolution, food insecurity has largely affected developing nations, but the rapidly increasing human population, climate change and depleting resources, including declining availability of fertile land, has provoked a global food insecurity (Bobba et al., 2020; Hayes & McCullough, 2018; Wackernagel et al., 2021). Sustaining food production demands P fertilizers to replenish the P removed during harvest, and some scholars consider the monopolisation of the world's sporadically distributed P reserves as one of the greatest challenges facing humanity today (Cordell, 2013; Cordell & White, 2014; Nassar et al., 2020; Reijnders, 2014). A priority concern is the geopolitical positioning and trade agreements which have centralized control over domestic and international P trade and will likely intensify in the future (Nassar et al., 2020). Recent events reveal how the LPE influences price hikes and capitalises on global supply shortages. This caused a decline in P fertilizer use (FAOSTAT, 2021a), a rise in global food prices (FAO, 2021a), and sadly, tragic increases in farmer suicides in highly impacted regions (Cordell et al., 2009).

For *“those who cannot remember the past are condemned to repeat it”* (Santayana, 1910), the story of Nauru may serve as a warning. Nauru, a once pristine Pacific island that gained colonial attention in 1905 due to its vast deposits of P-rich seabird guano. Subsequent extensive guano mining stripped off over 83% of Nauru's land surface with catastrophic environmental consequences that have left much of its island degraded and devoid of vegetation (Gale, 2016; Kawatra & Carlson, 2013). Guano and its volatile market trading prices and bottlenecks, controlled and manipulated by a monopolized industry (Australian Parliament, 2009), eventually caused an abrupt market shortage and a decline in market share (Ulrich & Frossard, 2014). Once deemed the nation with the highest GDP *per capita* in the world, the economy of Nauru collapsed following the exhaustion of guano deposits in 2004 (Fenner, 2019).

While Nauru mirrors the fate of other Pacific islands and the Meso-American West Coast, where seabird-deposited guano has long been mined for fertilizer, most P-fertilizer originates from rock phosphate (Cordell et al., 2009). Leading up to the 2008 global financial crisis, the cost of rock phosphate and fertilizer commodities abruptly rose by approximately 800% (Figure 1). This coincided with a 25% Real Food Price Index increase during the same period (FAO, 2021a). Although this phenomenon has yet to be “completely understood” (Khabarov & Obersteiner, 2017), it is likely a compounding combination of global factors that include a steady growth in East Asian middle-class and associated demand for resource-intensive foods (Tie-jun, 2008), India’s import policy in 2007 encouraging the import and use of fertilizer (Khabarov & Obersteiner, 2017), the USA’s renewable energy production and consumption policy stimulating plant-based biofuel production (Sissine, 2007), record oil prices in 2007 increasing P fertilizer production and transportation costs (Hamilton, 2009), China’s response to global market disarray by imposing a 135% tariff on fertilizer exports (Cordell et al., 2015), and the aforementioned factors heightening market speculation and manipulation (*i.e.*, commodity hoarding). This 2007-08 episode has stressed the inability of rigid markets to adapt and meet higher demands while simultaneously profiting on the very shortfalls it created.

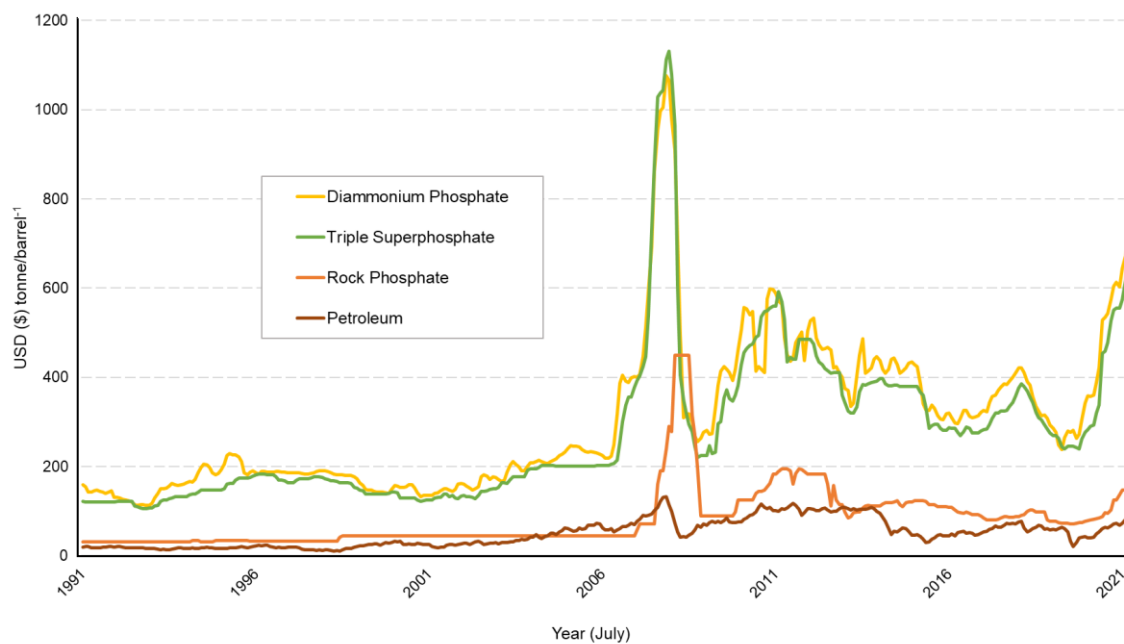


Figure 1 A 30-year period of global price respective to phosphorus commodities (USD tonne<sup>-1</sup>) rock phosphate (orange), triple superphosphate (green), diammonium phosphate (yellow), and petroleum (USD barrel<sup>-1</sup>) (maroon) (IndexMundi, 2021). The sharp price hike in 2007-08 was only mitigated shortly after the Global Financial Crisis. Prices of phosphorus commodities are yet to fall back and stabilise to pre 2007-08 price hike prices. Commodities since the Global Financial Crisis are in a constant state of flux causing much unpredictability. Prices have sharply risen beginning July 2020 to November 2021 and continue on an upward trend.

The United States Geological Survey (2021) details the monopoly of global national rock phosphate reserve ownership and rock phosphate mine production (

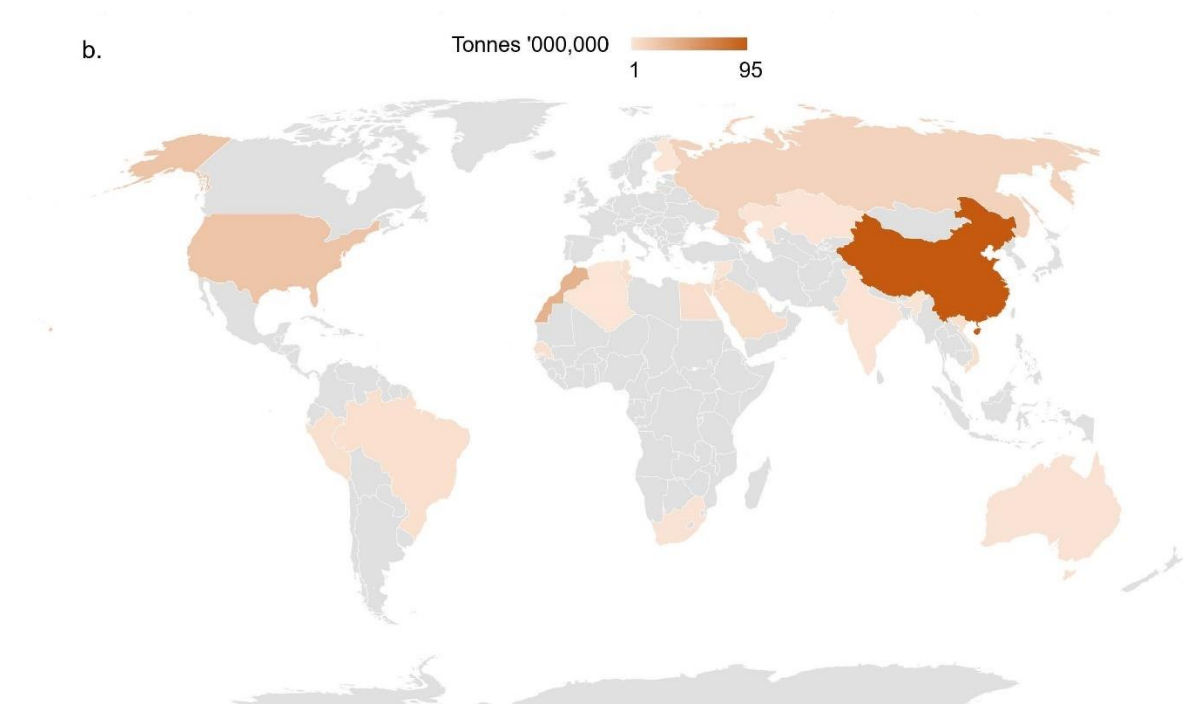
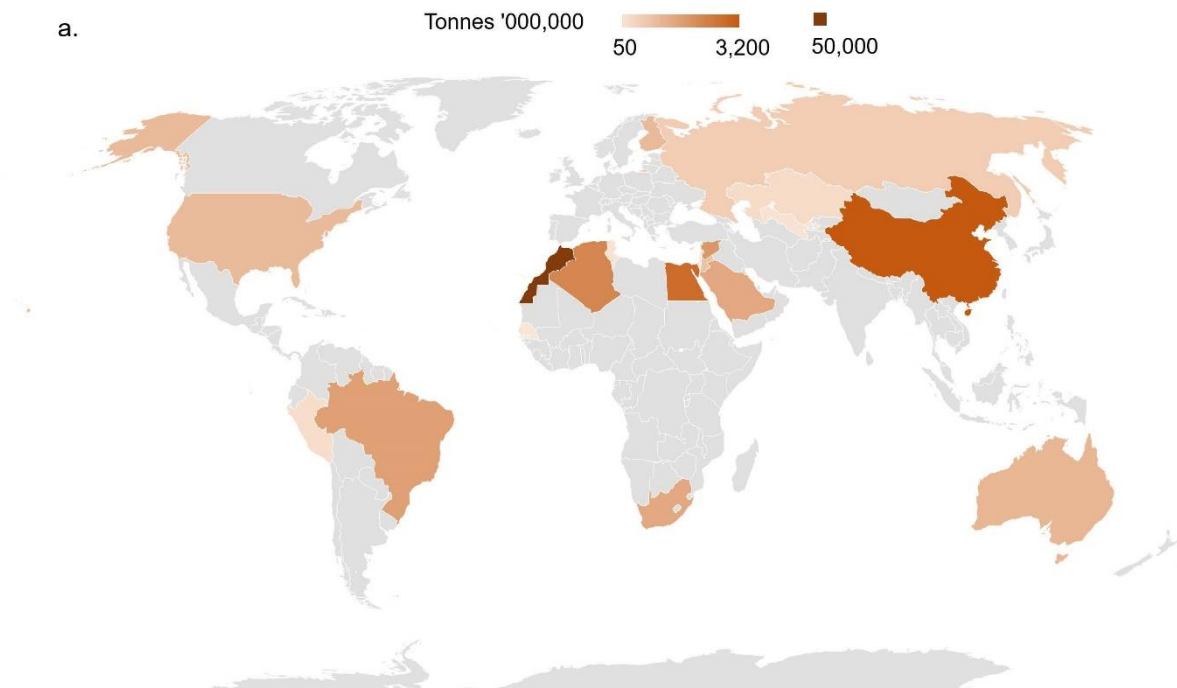


Figure 2). The reserve quantity of the top holding entities, Morocco and Western Sahara, China and Egypt, account for over 78% of the global reserves, and together with the USA, they generate 70% of total global production. Within Europe, only Finland has notable reserves and mine production (representing 1.4% and 0.43% of the global total, respectively). The rest of the EU and Britain are reliant on importing P-fertilizers or rock phosphate for their domestic fertilizer production industry (Geissler et al., 2019). In the USA, rock phosphate deposits represent 1.4% of global reserves and account for 10% of global output (USGS, 2021), although their reserves are expected to become depleted within the upcoming decades (Jasinski, 2014). Florida's ore grade, the USA's major rock phosphate-producing state, has been declining since the exhaustion of higher grade northern deposits and supplanted by the lower grade southern deposits (Steiner et al., 2015; Zhang, 2019). The USA's declining presence and contribution to the global markets (rock phosphate and P-fertilizers) has increased their import demand (Figure 3 a-b) (USGS, 2021) to supplement national P-fertilizer use (Figure 3 c) (FAOSTAT, 2021a). Declining P fertilizer exports from the USA and concomitant increase in imports may further monopolise producers such as China and Morocco, thus exacerbating geopolitical leveraging and commodity supply chain instabilities.

A recognized problem is that the rock phosphate industry has a long history of providing incomplete datasets (Ulrich & Frossard, 2014) and often overestimating reserve data (Cordell



& Neset, 2014; Geissler et al., 2015). The lack of transparency concerning reserves, resources and ore grades prevents a holistic understanding of the LPE and subsequently reduces our ability to accurately plan for the future (Cordell et al., 2009; De Ridder et al., 2012; Ulrich & Frossard, 2014; Van Kauwenbergh et al., 2013). Shortly after ‘*The story of phosphorus: global food security and food for thought*’ (Cordell et al., 2009) was published, Morocco and Western Sahara revaluated and increased their reserve estimations by 877% from 5,700 to 50,000 million tonnes (USGS, 2011). These estimations did not comply with standardized geological reporting used by the geoscience governing bodies of the United Nations (Kommission et al., 2015), USA (USGS, 2021), Australia (JORC, 2012) and Britain (BGS, 2015), drawing criticism over its legitimacy (Edixhoven et al., 2014). Rather than fostering transparency, reserve data and information disclosed by the Moroccan rock phosphate industry remains, however, ambiguous.



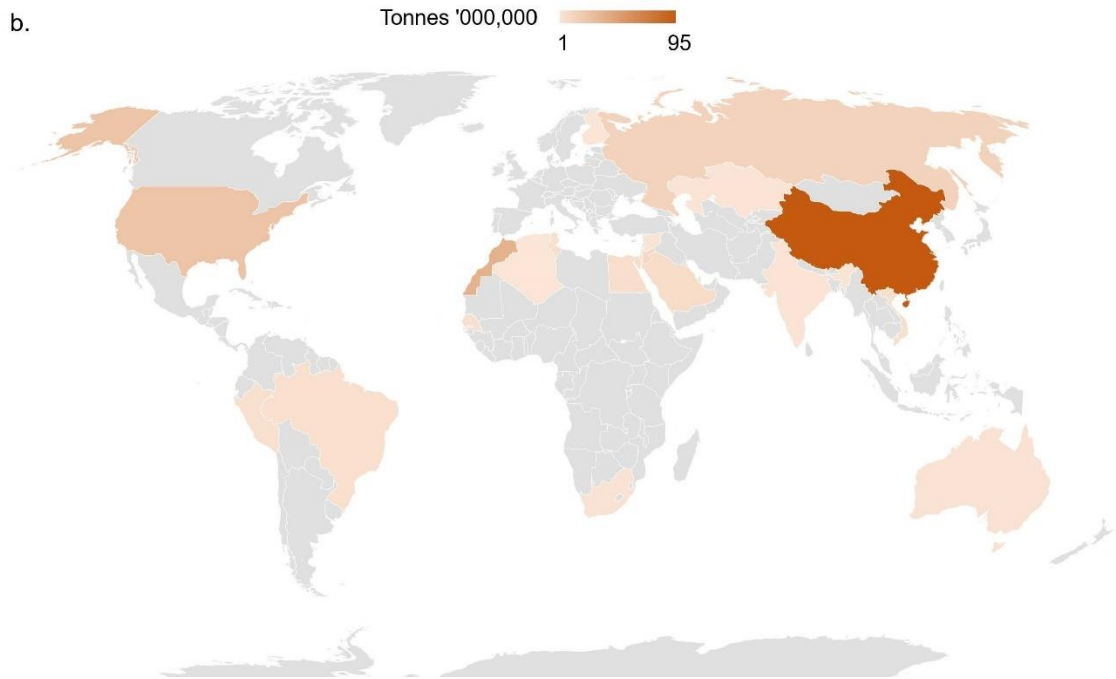
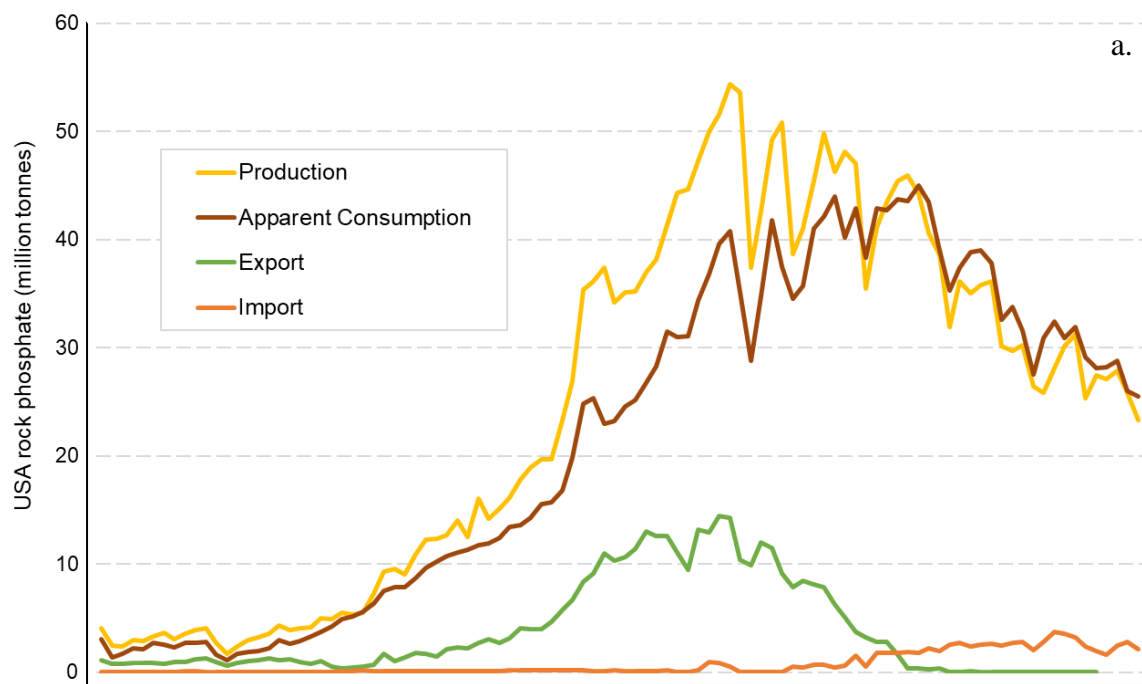


Figure 2 a) Global rock phosphate reserves in the leading 20 countries in 2019 (million metric tonnes) (USGS, 2021) b) Global rock phosphate mined from reserves in the leading 20 countries in 2019 (million metric tonnes) (USGS, 2021)



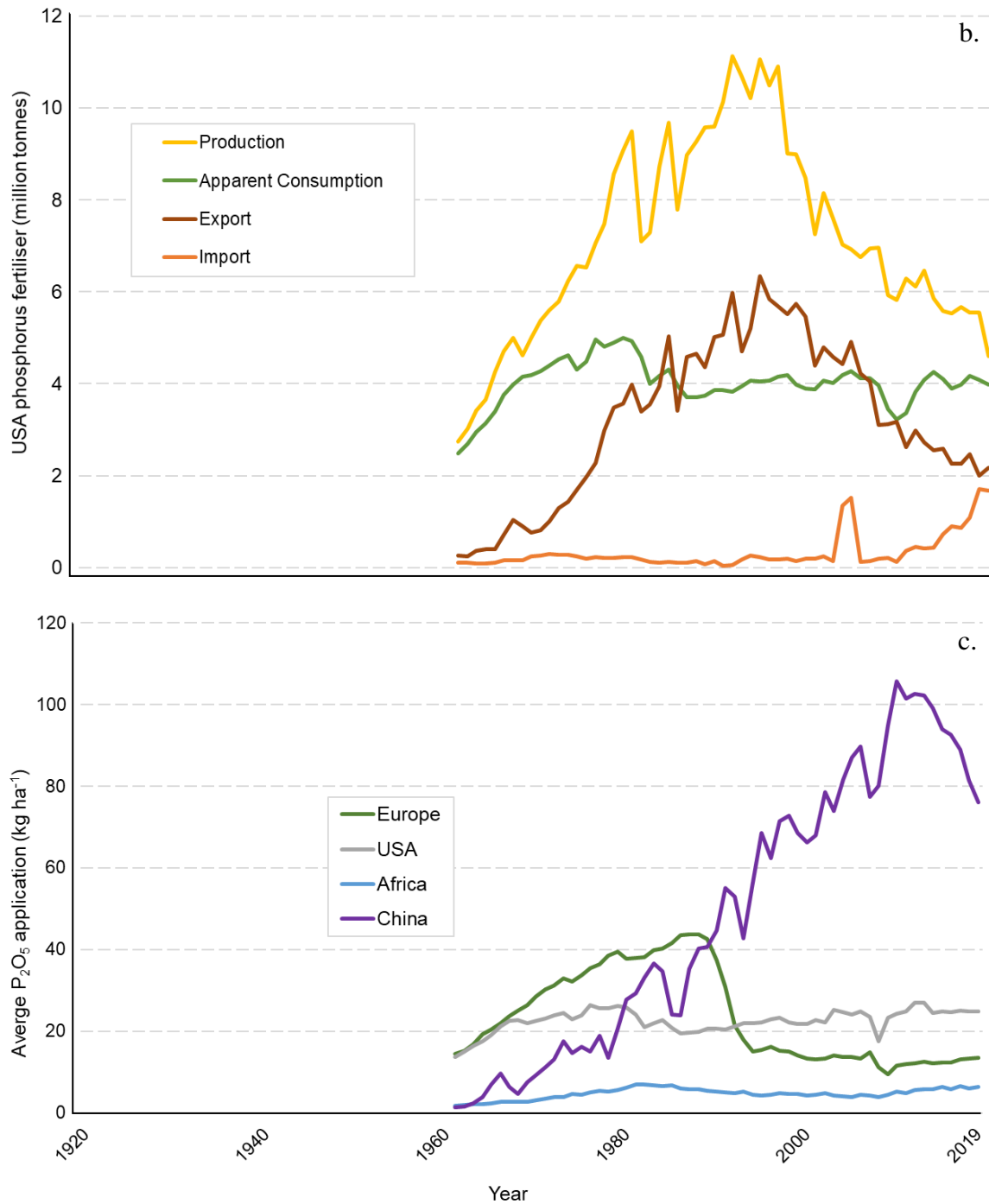


Figure 3 Global trends in rock phosphate and P-fertiliser from 1920-2019 a) USA's rock phosphate industry; b) USA's P-fertiliser industry; c) Average P-fertiliser use of Europe, USA, Africa and China from 1960-2019 (Buckingham & Jasinski, 2020; FAOSTAT, 2021a; USGS, 2021).

Moroccan deposits and mine production are solely owned and operated by the Office Chérifien des Phosphates, which itself is owned by the Moroccan government (95%) and the Banque Populaire du Maroc (5%) (OCP, 2021). Unlike publicly listed companies that disclose deposit grades and quantities to attract investment, shareholders, and trade alliances, or adhere to

international standards and public disclosure policies, the Office Chérifien des Phosphates is not obliged to provide such information. Morocco has made two amendments to their reserve estimations since 1994 (Figure 4) (USGS, 2021), which is substantially less compared to that of other major reserve holders such as Australia, China, USA and Jordan (9, 8, 7 and 7 amendments, respectively). A portion of Morocco's reserves reside in the geographically contested region at the Western Sahara border (Allan & Ojeda-García, 2021). The region was annexed by Morocco in 1975 and de-escalated 16-years later through a UN-brokered truce promising regional independence (United Nations, 2020). International discussions, however, continue debating the ethics of extracting rock phosphate in mines located in the contested region of Boucraa (Irwin, 2021; Kutz, 2021). In 2017, two Moroccan cargo ships containing rock phosphate mined at this location were stopped and detained on route by South Africa and Panama on the grounds of cargo illegalities (Ruys, 2019). In December 2020, the Trump Administration's decision to recognise Morocco's claim over the region was widely criticised

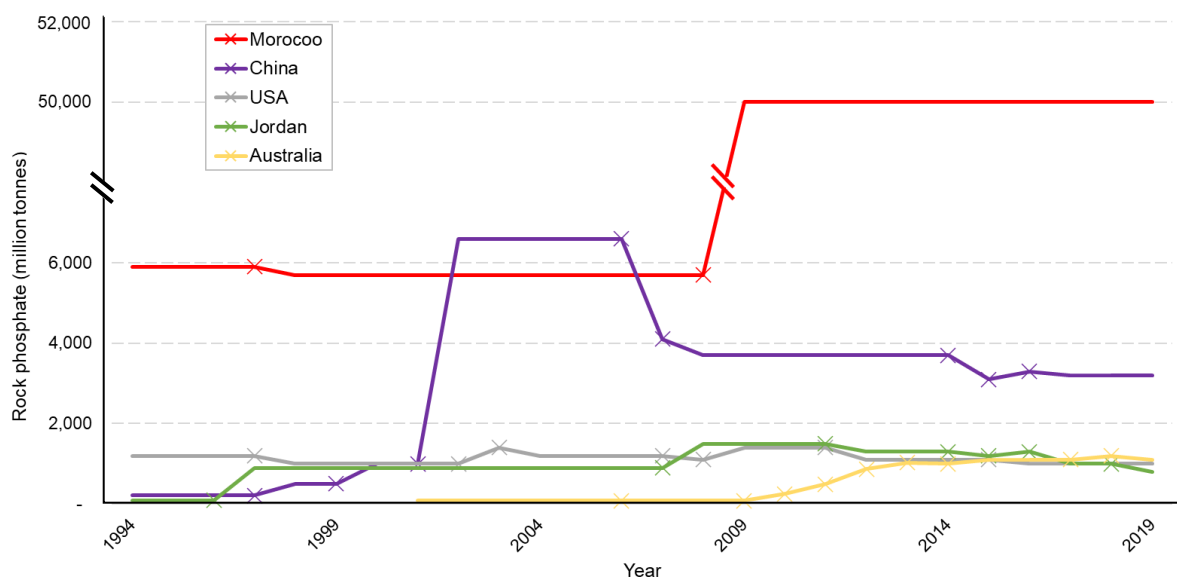


Figure 4 History of amendments to rock phosphate reserve estimations per country (USGS, 2021). Crosses along the coloured lines indicate time points of the amendments respective to the individual country. Since 1994, Morocco and Western Sahara, China, USA, Jordan, and Australia have amended their reserve data 2, 8, 7, 7, and 9 times, respectively.

and was met with considerable resistance from the African Union, neighboring Algeria and Sahrawians (Bradley, 2021). The above examples illustrate the problems relating to the reporting, exploitation and trading of P reserves and fertilizers. They also highlight the lack of industry transparency, the hazards of deposits residing in disputed territories, the exacerbation

of monopolized markets and their evident fragility illustrates the P insecurity for many nations reliant on imports worldwide.

### **3. Environmental soil degradation soil and phosphorus management**

There is global consensus on recognizing the fundamental role of soil in safeguarding sustainable food production and environmental integrity (FAO et al., 2020). Considered a non-renewable resource due to slow regenerative processes (Pennock et al., 2015), soil preservation and integrity must become an essential component of circular agriculture frameworks. Currently, poor land use management and unsustainable agricultural practises are causing soil degradation and decrease our ability to produce food (Dubois, 2011; Právělie et al., 2021). Following aridity, soil erosion is the single greatest factor responsible for soil degradation in agricultural land (Právělie et al., 2021) and a primary cause of P flows into waterways. Intensive agriculture can cause soils to erode at a rate up to 1000-times that of natural rates (Pennock et al., 2015) and, as a consequence, a global average of 5.9 kg P per hectare is lost to the hydrosphere every year (Alewell et al., 2020). Tillage, nutrient stoichiometric imbalances and harvesting are major anthropogenic causes inducing soil erosion (Lehman et al., 2015). In Europe alone, harvesting crops causes 14.7 million tonnes of soil loss every year (Panagos et al., 2019).

Soil and nutrient loss from agricultural land and inadequate sewage treatment are primary factors for the disruption of marine nutrient cycles (Malone & Newton, 2020; Withers et al., 2019). The impact of P pollution in marine systems manifests in many regions. Examples are the infestations of coral-predating Crown of Thorns starfish in Australia's Great Barrier Reef and toxic algal red tides along Florida's coastline, killing marine life and causing other detrimental effects (Brodie et al., 2017). In the Baltic Sea, partial or complete cessation of P and other nutrient inputs are predicted to take centuries before pre-anthropogenic conditions are reached (McCrackin et al., 2017). Anthropogenically-induced eutrophication is responsible for coastal ecological degradation and is considered as one of the greatest threats to marine ecosystems worldwide (Malone & Newton, 2020), thus demanding the strict management of nutrient inputs and the development of water quality strategies to mitigate the rapid deterioration of coral reefs (Chazottes et al., 2017; Withers et al., 2019; Wooldridge, 2020). The projected increase in global demands for food, energy, clean water and waste will,

however, exacerbate anthropogenic pollution and place even greater stress on fragile aquatic ecosystems (Glibert, 2020; Randers et al., 2019).

Algal blooms (*i.e.*, green tides, red tides, phototropic blooms) are the result of nutrient enrichment caused by agricultural run-off, municipal and industrial waste, aquaculture and biogenic recycling (Figure 5) (Gladyshev & Gubelit, 2019). Correlating with the initiation of intense farming and the use of chemical fertilizers, the first recorded instances of anthropogenic eutrophication in the Baltic Sea commenced in the 1950s (Andersen et al., 2017). Today approximately 22,000 tonnes of P flow into the Baltic Sea annually (Svendsen & Gustafsson, 2020). Although localized eutrophication management commenced in the 1980s, the low burial and high remobilization potential of deep biogeochemical P sediments are largely responsible for reoccurring green tide cycles (Kuliński et al., 2021; Savchuk, 2018). The biochemical breakdown of algae during nightfall causes a reduction in dissolved oxygen creating hypoxic conditions (*i.e.*, dead zones). Dead zones in the Baltic Sea are estimated to impact an area of similar size to that of Ireland (Meier et al., 2019). If nutrient reduction is met according to the

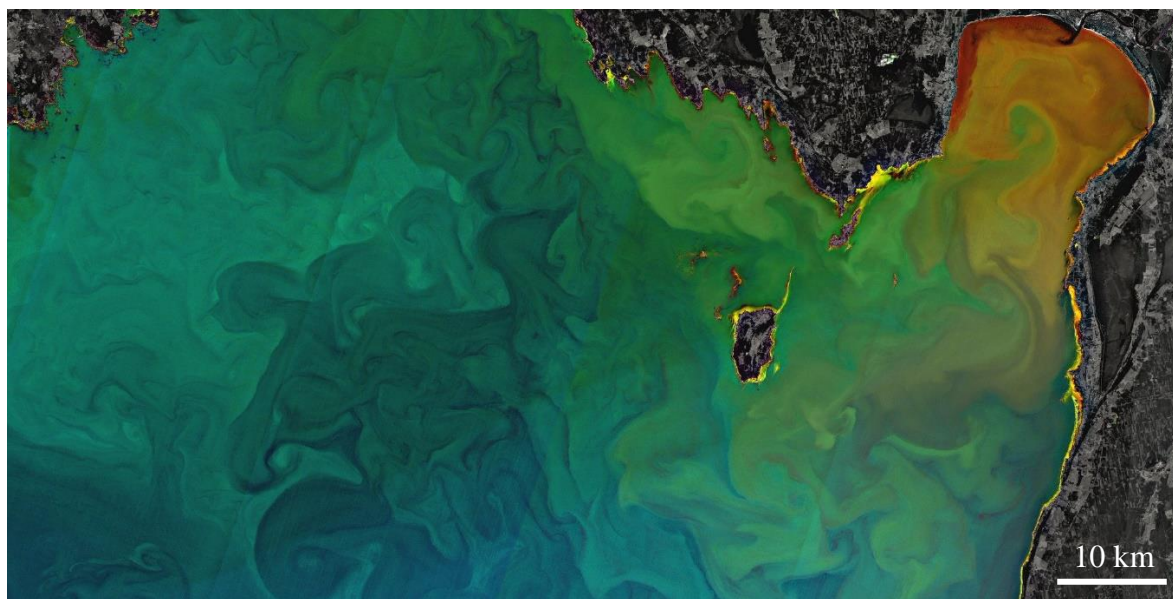


Figure 5 Satellite image showing eutrophication caused by nutrient rich run-off from neighbouring countries Estonia and Latvia in the Gulf of Riga, Baltic Sea (image credit: European Union - contains modified Copernicus Sentinel data [2020]. The image is reproduced with permission from Valters Žeižis).

Baltic Sea Action Plan (2007), most of its oceanic basins are forecast to become clean from eutrophication in 180 years (Murray et al., 2019).

The accumulation of reactive P in the biosphere is a global problem and is likely to magnify considering world fertilizer trends (P, nitrogen, potassium) experienced a 33% increase from 141.7 to 188.5 Mt between 2002 and 2019 (FAOSTAT, 2021a) in parallel to rising food demands. The European Commission's strategy to combat nutrient loading will require the reduction of fertilizer use by 20% by 2030 (European Commission, 2020). Achieving this through preventing P fertilizer inefficiencies and avoiding losses from agricultural soils requires innovative strategies, some of which we outline in later sections.

#### **4. Heavy metal contaminants in phosphorus deposits and fertilizers**

Sedimentary rock phosphate, geologically distinctive from its counterpart igneous rock phosphate, constitutes the major deposits in China, Morocco and the USA (USGS, 2021). Sedimentary rock phosphate contains varying levels of toxic heavy metals including cadmium, uranium, mercury and lead (De Boer et al., 2019). The production of phosphoric acid, the chemical precursor for commercial triple superphosphate fertilizer and other P fertilizer blends, is produced through the physical and chemical treatment of rock phosphate to remove constituent undesirable minerals (Revuelta, 2018; Wingate & Kohmuench, 2016). The process of removing predominant constituent minerals, notably different from extracting P as a pure element, causes associated heavy metal contaminants to remain within the fertilizers. The concentrations of these contaminants vary depending on the parent ore and fertilizer manufacturing processes (Gray et al., 1999; Kratz et al., 2016). There are currently no economically viable methods or technologies to remove these heavy metals from the ore and consequently up to 80% supersedes into the phosphoric acid (Kouzbour et al., 2019). Contaminants such as cadmium and uranium are considered to have the most detrimental effects for toxicity, accumulation in soils, plant bioavailability and leaching potential (Taylor et al., 2016). Here we focus on cadmium due to its recognized consequences for public health.

Cadmium is considered a non-threshold toxin which can induce negative health effects at low concentrations (CDC, 2017; Rahman & Singh, 2019). Exposure can have grave effects including kidney disease, cancer and, in some cases, death (Adams & Newcomb, 2014; WHO, 2019a). The extent of cadmium exposure is largely determined by an individual's smoking status, dietary habits and consumption of foods produced in proximity to cadmium pollution (Pizzol et al., 2014; WHO, 2000). In Europe, approximately 45-60% of soil cadmium derives

from P-fertilizers and 55% of human cadmium exposure originates from consuming contaminated foods (Smolders, 2017; Ulrich, 2019).

Although native geogenic concentrations of cadmium in soils vary, its presence in soils and water is largely associated with soil applications including chemical P-fertilizer, manures, wastewater and biosolids, and also atmospheric deposition from industrial processing (Hou et al., 2020; Kubier et al., 2019). With a high solubility and desorption potential, cadmium is one of the most mobile heavy metals in soils, a primary reason for its high bioavailability to plants and fast migration into groundwater (Kubier et al., 2019; Nino-Savala et al., 2019). Promisingly, cadmium concentrations in the upper layers of European soils are decreasing as less P-fertilizer is applied (Figure 3C) and regulations on industry emissions have tightened, although clear trends are still difficult to establish due to variable data (Smolders, 2017). Furthermore, since cadmium bioavailability increases with soil acidity (FAOSTAT, 2021a; Shahid et al., 2016), and agricultural soils acidify with unsustainable practices (Tkaczyk et al., 2020), formerly inaccessible cadmium in soils may become bioavailable, stressing the importance of comprehensive risk mitigation strategies. A comparison between Europe and the USA illustrates the complexity of the problem. While the average application of P-fertilizer by farmers in the USA has remained relatively constant since the 1970s (Figure 2C) (Adams & Newcomb, 2014; Kowal et al., 1979), it has substantially declined in Europe since the early 1990s (FAOSTAT, 2021a). Furthermore, cadmium levels *via* aerosols in Europe have reduced four-fold since the 1960s (Smolders & Six, 2013). Thus, the combined impact of decreased input from aerosols and P-fertilizers over several decades would be anticipated to lead to a decrease in cadmium concentrations in European topsoils. However, no clear decrease in the bioavailability of cadmium is apparent (Figure 6).



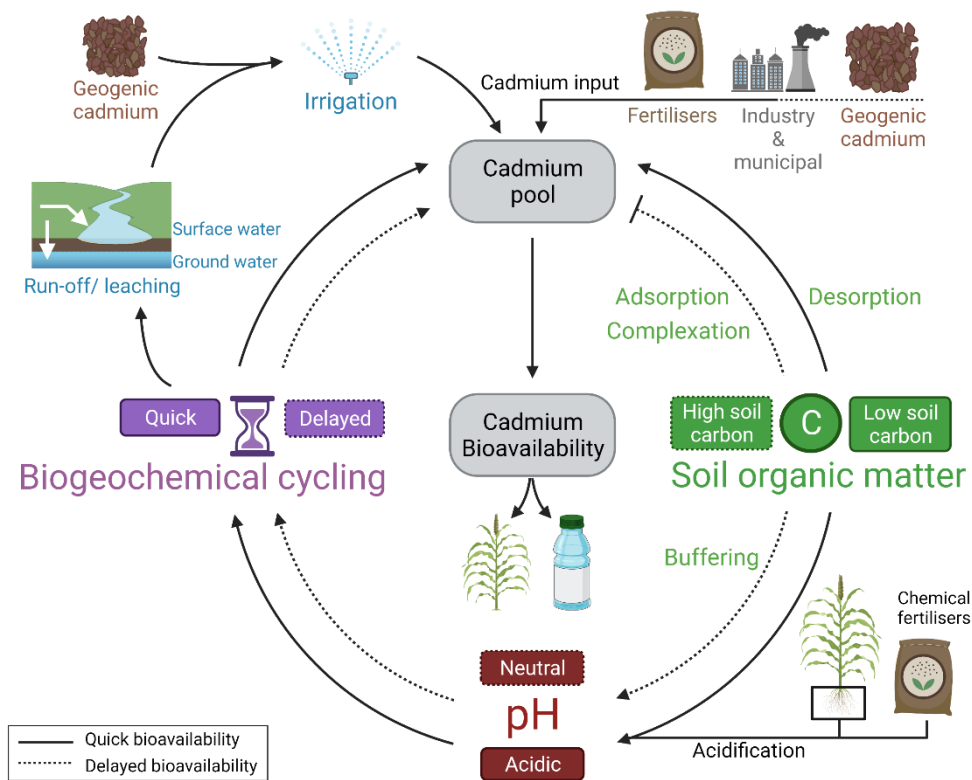


Figure 6 Conditions influencing the plant bioavailability and mobility of cadmium in soils. The dotted lines represent a delay in the biogeochemical cycle. The solid line represents the potential hastening of cadmium's biogeochemical cycling agriculture. The arrow direction represents the feedback direction. Inputs into the cadmium pool include phosphorus fertilisers, industry and municipal aerosols and waste, natural geogenic deposits, and irrigation using contaminated water. The primary contributing factors of cadmium bioavailability influenced by anthropogenic farming is soil carbon, pH, and input.

The risks associated with dietary cadmium exposure is amplified for individuals in developing nations, especially in women and children (CDC, 2017; Kowal et al., 1979). Largely determined by lower iron reserves, gastrointestinal absorption of cadmium is twice as high for women than men (10% and 5% absorption rates, respectively), and up to 15% for anaemic individuals (CDC, 2017; Nordberg, 2004; WHO, 2000). In areas such as Africa, over 30% of women suffer from anaemia due to dietary limitations (FAO et al., 2021). Therefore, using P-fertilizers contaminated with cadmium will likely increase the rate of exposure and further exacerbate health complications in compromised populations. However, it needs to be reiterated that cadmium exposure is not limited to the developing world. Although data of increasing levels of cadmium exposure over time in Europe are still largely inconclusive

(Lundh et al., 2016), a recent analysis found cadmium levels in French citizens are still above national health recommendations in almost half the population (Oleko Amivi et al., 2021).

Since 2015, China has pursued a ‘Zero Increase of Fertilizer Use’ strategy to flatline the extremely high use of chemical fertilizers and reduce the environmental and health consequences of over-fertilization (Ji et al., 2020). Cadmium is considered China’s most abundant inorganic soil pollutant (MEP, 2014) with 10-50% higher average concentrations than native geogenic levels since analyses began in 1986 (L. Wang et al., 2015). Cadmium analysis in North China soils identified P-fertilization as the primary factor to the 41-62% increase in cadmium concentrations from 1989 to 2009 (Qi et al., 2018). On a national level, P-fertilizers are recognized as a primary cause of cadmium contamination of China’s soil (Nino-Savala et al., 2019), which correlates with the steady and comparatively steep rise in the average use from 41 to 95 kg ha<sup>-1</sup> over the same period of time (Figure 3C) (FAOSTAT, 2021a).

Due to the known consequences of contaminated P-fertilizers, the European Commission has proposed a universal limit on cadmium concentrations to 60 mg Cd/kg P<sub>2</sub>O<sub>5</sub>, with a tiered reduction to a maximum of 20 mg Cd/kg P<sub>2</sub>O<sub>5</sub> by 2032 (Ulrich, 2019). The proposal has been met with some resistance by the fertilizer industry stating the reduction plan is “impossible” (Fertilizers Europe, 2017). A review conducted by Bloem et al. (2017) found average cadmium concentrations in mineral P-fertilizers sold in Europe ranging from 32-348 mg Cd/kg P<sub>2</sub>O<sub>5</sub>. Furthermore, other OECD countries have been slow to adopt similar regulations. California (the USA’s most regulated state for P-fertilizer contamination) has set its limit to 400 mg Cd/kg P<sub>2</sub>O<sub>5</sub> (CDFA, 2020), and Australian states and territories have adopted a voluntary limit of 644 mg Cd/kg P<sub>2</sub>O<sub>5</sub> (Warne et al., 2007). Considering these vastly different standards and practices, and keeping in mind the significant health hazard posed by cadmium, it is now imperative that a global approach is developed to minimize heavy metal contaminants in P-fertilizers.

## **5. Wastes from phosphorus fertilizer production**

Current technologies to process rock phosphate for the manufacture of chemical P-fertilizers are plagued by inefficiencies and waste production. Depending on the ore grade and processing technology, P recovery from rock phosphate ranges from 65-90% (Ruan et al., 2019). This is

a substantial improvement from pre-1990s recovery rates of 40.5-79% (Van Kauwenbergh et al., 2013). However, while some technologies can increase P recovery to more than 95% (Günther et al., 2018; Hobert et al., 2020; Wingate & Kohmuench, 2016), implementing them on an industrial scale presents theoretical and practical challenges (Wingate & Kohmuench, 2016). Industry standards generally require the beneficiation of low to medium grade ores to improve P concentrations, which inevitably increases production costs, energy demand and associated waste (Steen, 1998).

The process of manufacturing chemical P-fertilizers involves the mixing of crushed rock phosphate with sulfuric acid to produce phosphoric acid, the base ingredient required for P-fertilizers such as superphosphates, mono- and di-ammonium-phosphate. During the process of phosphoric acid production, the hazardous waste by-product phosphogypsum, hydrated calcium sulfate, is produced at a quantity 5-times that of phosphoric acid (Taylor et al., 2016). In Europe and the USA, disposal of phosphogypsum into waterways has been outlawed due to the associated environmental impacts (Environmental Protection Agency, 2021). In 2010, the European Commission sent Spain a final warning concerning Rio Tinto's illegal dumping of 120 million tonnes of phosphogypsum into a local waterbody (European Commission, 2010). It is reported that a portion of Morocco's operations still disposes their phosphogypsum into the Atlantic Ocean (Taylor et al., 2016). Globally, approximately 10% of phosphogypsum is dumped into marine environments (Jupp et al., 2021) which equates to 16 million tonnes per year (Rashad, 2017).

Phosphogypsum has minimal recycling utility due to its contaminants including cadmium, uranium, and other radionuclides. The USA's phosphogypsum waste is held in over 70 mountainous 'stacks' up to 3.2 km long and 60 m high (EPA, 2021). In 2005, Florida, the USA's primary rock phosphate mining and fertilizer-producing state, has 1.1 billion tonnes of phosphogypsum spread over 1820 km<sup>2</sup> (Taylor et al., 2016). The high solubility of phosphogypsum, its leaching potential, acidity, combined with its poor management by the industry has caused numerous environmental disasters. Since 1994, leaching, sink holes, stack breakages and overflows have caused water contamination and polluted drinking reservoirs, aquifers and waterways (Taylor et al., 2016). In 2015, the EPA and Florida's environmental agencies successfully sued the largest operating company, Mosaic, for US\$1.8 billion for law violations, clean-up costs and future mitigation strategies (EPA, 2015). In 2021, the Governor

of Florida declared a State of Emergency and evacuated local residents when a fragile phosphogypsum stack holding 2.3 billion liters of fluid was on the verge of collapse (Center for Biological Diversity, 2021; FDEP, 2021).

The ongoing legacy of mining waste that is disposed into waterbodies or stored over large areas of land is clearly of concern. Where regulators can instigate and enforce change, marine pollution through the dumping of phosphogypsum can be prevented, although storage on land, as the Florida example shows, is not an adequate alternative. The cost of such waste disposal practices should be considered as part of the negative externalities of the LPE.

## **6. Reimagining phosphorus in a circular phosphorus economy**

Orchestrating a P framework which sustains humanity throughout the 21<sup>st</sup> century and beyond will require the transition into a CPE. This must be achieved through greater agricultural efficiencies, soil management strategies and adoption of circular P technologies (Garske & Ekardt, 2021; Köhn et al., 2018; Koppelaar & Weikard, 2013; Lal, 2015; Mogollón et al., 2021; Smol et al., 2020; Van Vuuren et al., 2010; Withers, 2019). It will take careful deliberation how best to achieve an intersect between high agricultural demand and output through a circular framework while maintaining environmental integrity and economic feasibility (Gerten et al., 2020; Hebinck et al., 2021; McDowell et al., 2020; Mogollón et al., 2021; Walsh, 2021). This must, however, be a priority for global objectives to reduce the ongoing cropland expansion into natural ecosystems, which target fertile lands in critical areas hosting concentrated levels of clean water, biodiversity and carbon stocks (Jung et al., 2021).

The continued use of chemical P-fertilizers combined with the likelihood of increasing extreme weather events caused by climate change has strong potential to lead to even higher rates of P losses from soil due to intensified erosion (Ockenden et al., 2017), and exacerbate the degradation of marine ecosystems and the loss of biodiversity (Meier et al., 2012; Takolander et al., 2017). Therefore, improving P efficiency in agriculture must be a central consideration for all societies and nations.

Advancing the CPE requires innovative measures to successfully implement a framework required for achieving circularity. A proposed strategy to alleviate foreign market dependency, environmental degradation and public health deterioration can be achieved through adopting such a framework (

Figure 7). This interconnected system aims to achieve three primary goals, (i) Food Sovereignty, (ii) P Autonomy and (iii) Ecosystem Preservation, which are facilitated by three principal levers: (a) Nutrient Recovery Facilities, (b) Valorisation Technologies and (c) Sustainable Agriculture and Soil Management strategies. A CPE will support several SDGs, *i.e.*, Zero Hunger (2), Clean Water and Sanitation (6), Decent Work and Economic Growth (8), Life Below Water (14) and Partnerships for the Goals (17). Furthermore, the CPE contributes to achieving No Poverty (1), Good Health and Well-Being (3), Industry, Innovation, and Infrastructure (9), Sustainable Cities and Communities (11), Responsible Consumption and Production (12) and Life on Land (15) (see Supporting Information, Table 1). The successful transition into a CPE will, however, require the addressing of existing endemic economic, technological, and agronomic constraints. Below we elaborate on the three principal levers.

### **6.1. Nutrient Recovery and Valorisation Technologies**

Resource accessibility and security is fundamental for eradicating poverty and transitioning nations into a circular economy (Wackernagel et al., 2021). Government legislation plays a central role in catalyzing innovation and initiation. However, many governments have historically been hesitant to introduce legislation that demands greater resource security (Wackernagel et al., 2021). This is notable considering that adoption of waste treatment technologies by the industry is largely compelled by legislative compliance, not economic incentives (Campos et al., 2019; Chrispim et al., 2020). Therefore, the adoption of nutrient recovery and valorisation technology requires policy-driven support and economic incentives to alleviate high upfront capital and ongoing costs (De Boer et al., 2018). Examples of this can be seen in Europe, where ongoing projects facilitate (i) collaborative partnerships between

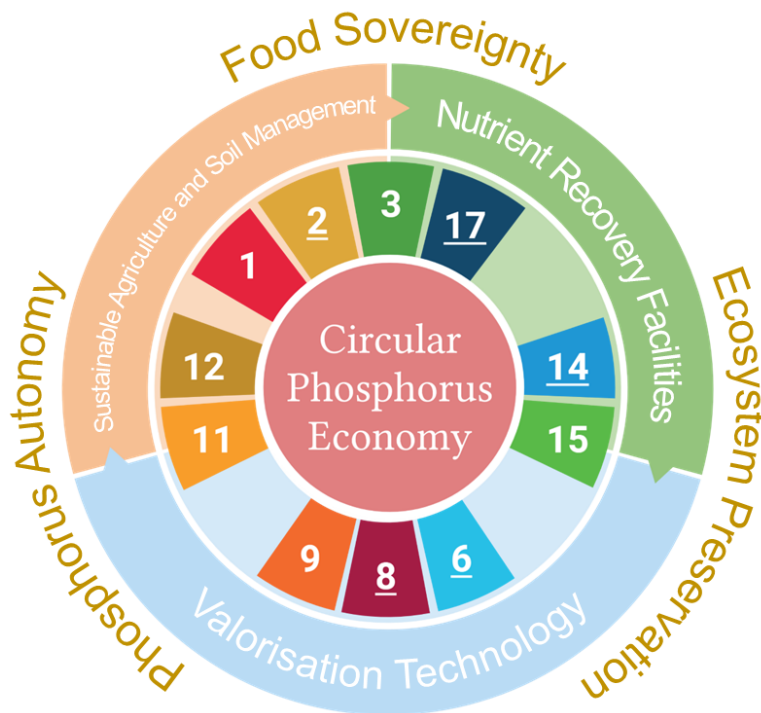


Figure 7 Circular Phosphorus Economy: *Goals* Food Sovereignty (i), Ecosystem Preservation (ii), Phosphorus Autonomy (iii) can be achieved through *Levers* Nutrient Recovery Facilities (a), Valorisation Technology (b), and Sustainable Agricultural and Soil Management strategies (c), respectively. SDGs No Poverty (1), Zero Hunger (2), Good Health and Well-Being (3), Clean Water and Sanitation (6), Decent Work and Economic Growth (8), Industry, Innovation, and Infrastructure (9), Sustainable Cities and Communities (11), Responsible Consumption and Production (12), Life Below Water (14), Life on Land (15), and Partnerships for the Goals (17) are position respective to the Levers in which they are accomplished. Underlined SDG numbers represent immediate SDG targets met through a Circular Phosphorus Economy (see Supporting Information Table 1); non-underlined SDG numbers represent Circular Phosphorus Economy Levers which contribute to achieving SDGs targets.

governments, academic institutions and industry (European Commission, 2021), but also (ii) assess and potentially declare recycled materials (such as struvite and ashes) as fertilizers and soil conditioning agents (EU, 2019).

Governments must factor in the environmental and public health consequences associated with an LPE into their broader socio-economic analyses. When considering public health (Pizzol et al., 2014; WWAP, 2017), the potential for resource recovery (Nižetić et al., 2019), the UN Impact Categories of ‘terrestrial acidification potential’ and the ‘freshwater eutrophication

potential' (Campos et al., 2019; Sud, 2020), moving beyond current chemical P-fertilizers and P recovery from waste streams can become economically beneficial. Conventional waste management and valorisation technologies for P-wastes include (i) enhanced biological P removal, (ii) chemical precipitation, (iii) thermal- or wet-chemical treatment, (iv) mono- and (v) thermo-chemical incineration (Adam et al., 2009; Jupp et al., 2021). Techno-economic advantages and disadvantages are dependent on relevant processes, which include P recovery efficacy, upfront and upkeep costs, and additives (such as chemicals) required for valorisation (Nättorp et al., 2017). Many of these technologies have yet to reach techno-socio-ecological maturity (Robles et al., 2020; van der Kooij et al., 2020) with continuous improvements including (i) greater extraction and resource recovery efficiencies, (ii) smaller scale operations which can be established at a closer proximity to P-waste feedstocks, (iii) lower upfront capital investments, and (iv) desired properties of the final product (Cieřlik & Konieczka, 2017; Zhao et al., 2020).

Valorisation technologies can remove harmful pollutants from feedstocks while concentrating P in the final product (Hall et al., 2020; Herzel et al., 2016). Technologies such as advanced thermo-chemical incineration, for example of sewage-derived materials, removes undesired heavy metals from biowastes to produce a pollutant free P-fertilizer (Hermann & Schaaf, 2019). This supports the aim of achieving a negative soil-cadmium mass balance which requires cadmium concentrations in fertilizers to be limited to below 20 mg cadmium kg<sup>-1</sup> P (Smolders, 2017). Heavy metal removal technologies to produce low contaminant P-fertilizers from wastes form an essential component of the CPE by reducing the current and ongoing input of heavy metals into agricultural soils.

## **6.2. Improving phosphorus use efficiency in agriculture**

The Green Revolution launched the widespread use of chemical nitrogen-phosphorus-potassium (NPK) fertilizers and related technological innovations. Input of such concentrated and immediately crop-available nutrients left soil health and biology largely ignored (Lehman et al., 2015). Soils are complex systems governed by a multitude of interconnected biogeochemical characteristics influenced by soil type, climate, vegetation and, in the case of agricultural systems, management. Chemical fertilizers lack carbon (unlike manures and other organic materials), which can cause biogeochemical stoichiometric imbalances and a series of undesirable soil and agronomic consequences (Bui & Henderson, 2013; Kopittke et al., 2017). Organic carbon has a key function for soil structural integrity (Kay, 2018), soil fertility (Herrick

& Wander, 2018), water retention and availability (Eden et al., 2017), soil biological health (Brackin et al., 2017; Lehman et al., 2015), reducing uptake of contaminants (*e.g.*, cadmium) by crops (Prokop et al., 2003; Q. Wang et al., 2014) and pH-neutralising effects in acidic soils (Qi et al., 2018). Thus, carbon and the other crop essential nutrients must be part of the solutions aimed at achieving greater P efficiency in agriculture (Arif et al., 2017; Schneider et al., 2019).

Many of the P recovery technologies are primarily focused on the extraction of nutrients in the most efficient and economically viable manner with secondary consideration for desirable agronomic characteristics (Mayer et al., 2016). The agronomic efficacy of valorised P-materials are largely influenced by their respective chemical and physical characteristics (González et al., 2021) and respective relationships to soil properties (Hertzberger et al., 2020). For example, the agronomic performance of the precipitant struvite (magnesium-ammonium-phosphate), a by-product of P-rich effluent treatment which removes P and nitrogen, is largely influenced by its particle size (González et al., 2021) and soil pH (Ahmed et al., 2018; Hilt et al., 2016). Raniero *et al.* (2022) found that the solubility of the valorised P materials struvite, AshDec© (thermo-chemical product) and hazenite (chemical precipitant) was largely influenced by soil pH and exposure to different solvents. Therefore, enhancing the agronomic efficacy of valorised P-materials requires tailoring their physiochemical properties to complement soil conditions and the crop's P-mobilisation efficiency (Talboys et al., 2016; Y. Wang & Lambers, 2020). Improving P-fertilizer formulations thus requires empirical research and modelling to design crop-system targeted P-fertilizers (Bindraban et al., 2020; Das et al., 2019).

The improvement of P bioavailability of recycled materials can also be achieved *in situ* without prior processing. For example, improving P bioavailability from organic wastes such as manures can be achieved through the use of phosphate-liberating enzymes (*e.g.*, purple acid phosphatases or organophosphate-degrading enzymes) (Feder et al., 2020; Pedroso et al., 2014) deployed, for instance, on nanoclays (Calabi-Floody et al., 2012; Menezes-Blackburn et al., 2014). The availability of inorganic P, such as chemical precipitates and ash, can also be potentially improved with P-solubilizing microbes that excrete particular organic acids (Saeid, 2018).



### **6.3. Realising a Circular Phosphorus Economy in the developing world - Africa**

The Covid-19 pandemic highlighted that communities with food insecurity live at the mercy of foreign markets (Andam et al., 2020). This was especially prevalent in Africa, where many countries rely on imports for their staple food supply (Sachs et al., 2020). In 2020, Africa saw 800 million people suffer from moderate to severe food insecurity, with one in five persons undernourished, and one third of children had stunted growth due to malnutrition (FAOSTAT, 2021b). To further compound this issue, the true socio-economic consequences of heightening resource insecurity and the subsequent repercussions on food production may have been underestimated by previous reports (Wackernagel et al., 2021). Furthermore, the increasing adoption of an LPE framework is likely to generate a spectrum of contemporary complications observed across the developed world.

The challenges and respective antidotes facing the developed world are fundamentally different when compared to developing nations such as those experienced in Africa. While there is a universal desire for food security, high yields and economic affluency enables the developed world to focus its efforts on mitigating the environmental degradation caused by an LPE, while developing nations delay environmental concerns in favor of achieving socio-economic objectives detailed in the SDGs. Dissimilar to developed nations, achieving a CPE within Africa is not a process of retrofitting pre-existing infrastructure or implementing novel technologies, but a process of introducing the systems, technologies and frameworks required for fertilizer production, application, and management. This process is necessary to address the primary limitations associated with food production and insecurity caused by the lack of access to fertilizers necessary to produce and sustain high yields.

#### **6.3.1. Nutrient Recovery and Valorisation Technologies**

For Africa, it is estimated that adequate wastewater management systems could save 325,000 lives annually through reducing the spread of diseases, while a reduction of nutrient loading into waterways could mitigate a further 613,000 annual deaths caused by poor quality drinking water and insufficient sanitation (WHO, 2019b). However, the development of efficient wastewater management systems and the provision of basic sanitation facilities poses a great logistical and economic challenge (African Development Bank et al., 2020), especially when considering the requirements necessary for establishing infrastructure in areas with pre-existing municipal buildings in high density areas. Currently, much of the sewage produced in African cities ends up in local waterways due to the lack of wastewater management facilities (Nyenje

et al., 2010) leaving this potential nutrient resource largely unexploited. The direct reuse of humanure does, however, offer a low economic and technological solution with a potentially high return on investment (Sharma et al., 2019). In contrast, technological and infrastructure requirements for rural African communities present unique challenges due to low density and sporadic populations (Oloo & Asbon, 2020). Feedstocks excluding wastewater management can be sourced from a variety of other P-rich biowastes other than humanure, including livestock manure, composts, food waste and digestates (Kratz et al., 2019). However, consideration must be given to such resources as they may already serve a secondary purpose such as use for shelter or livestock feed.

### 6.1.3. Sustainable agriculture and soil management

Agricultural run-off is considered a primary contributing factor of Africa's declining water quality (WWAP, 2017) and thus demands improved agricultural and soil management strategies. Reaching high agricultural output without mirroring the chemical P-fertilizer inputs seen in the developed world (Figure 3C) will require great agricultural methodological and industrial innovations. The development of localized management strategies should include the recruitment of local farmers to ensure integration of indigenous knowledge which can help mitigate biodiversity loss (Vogliano et al., 2021) and identify localized best management practises (Prober et al., 2011). Through education, access to technological resources that promote soil management schemes, and nutrient biofortification targeting P-deficient soils, the loss of biodiversity to agricultural expansion can be eliminated in sub-Saharan Africa (Mogollón et al., 2021). However, due to the complexity of P in soils, previous analyses may have underestimated the quantity of P required to meet the agricultural demands in this region (Haygarth & Rufino, 2021). The high variability in soil characteristics and environmental conditions across Africa requires an advanced approach to articulate a farmer's unique fertilizer requirements, especially when considering that conventional methods that rely on single point soil analyses are highly variable and largely inaccurate (Schut & Giller, 2020). Providing advanced resources such as spatial data (*e.g.*, Africa Soil Information Service) can be used to help calculate the required quantities of P-fertilizer (Hengl et al., 2021). Other immediate and low-barriers to adoption solutions which can conserve soil P and moderate nutrient loading into waterways are linked to regenerative agricultural techniques that include (i) cover cropping, (ii) conservation tillage and (iii) precision fertilizer management strategies (Ahmad et al., 2020; Bradford et al., 2019; Karlen & Cambardella, 2020; Shi & Schulin, 2018).

## **7. Conclusions**

The LPE continues to undermine food security, public health, and environmental integrity across the globe. Adopting an LPE framework to accomplish SDGs will encounter contemporary global challenges while exacerbating the shortfalls of an already fragile system. Continued monopolisation and resource nationalism, increasing demands from emerging economies, and the USA withdrawing from the global market will likely further undermine supply security and exacerbate P access inequality. Furthermore, without advancing P management in agro-ecosystems, reducing heavy metal contamination and limiting the continued loss of biodiversity through agricultural land expansion and eutrophication, these issues will likely intensify in the future. By harnessing P in waste streams that currently contribute to environmental degradation, the successful pivot into a CPE based on nutrient recovery and valorisation technologies can promote P autarky and, therefore, agricultural autonomy. Policy and financial support from governments and cooperative partnerships must be the backbone behind CPE innovation and implementation.

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No new data has been generated or used for writing this article

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**Realising the Circular Phosphorus Economy delivers for Sustainable Development Goals**

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**Additional Supporting Information (Files uploaded separately)**

Table 1 Circular Phosphorus Economy contributions to Sustainable Development Goals  
(SDGs) sub-categories

**Introduction**

Table 1 is supporting information for Figure 7 *Circular Phosphorus Economy*, and how adopting this system can contribute to achieving the Sustainable Development Goals



## Supporting Information

Table 1: Circular Phosphorus Economy contributions to Sustainable Development Goals (SDGs) sub-categories (United Nations, 2021)

#	SDG and sub-category	Explanation	Achieved through:		
			Nutrient Recovery Facilities	Valorisation Technologies	Sustainable Agriculture and Soil Management
<u>Immediate</u> SDG targets met (in ascending SDG number order)					
2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and input, knowledge, financial services, markets and opportunities and value addition to non-farm employment	Precision fertiliser management has the ability to substantially increase food production and offer small-scale farmers the opportunity to produce surplus goods. Moreover, a CPE would promote fertiliser security, education and knowledge into nutrient stewardship, access to financial services including grants, carbon schemes and sponsorships, and provide local skilled and unskilled job opportunities		✓	✓
2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought,	Introducing soil and phosphorus management schemes can help mitigate the effects of climate change respective to soil erosion and the succeeding implications to marine environments. Moreover, producing higher yields through soil fertility can reduce the need for agricultural land expansion and ecosystem loss	✓	✓	✓

	flooding and other disasters and that progressively improve land and soil quality			
6.3	Improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	The development of nutrient recovery facilities can circumnavigate untreated wastewater destined for local marine environments. Furthermore, the use of valorisation technologies can help reduce ecological degradation through reducing mining excavation, fertiliser bi-production waste (phosphogypsum), and resources associated with fertiliser production	✓	✓
6.a	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	Nutrient recovery facilities and valorisation technologies can be implemented through supportive cooperative and co-sponsorship programs. These partnerships are critical for encouraging sustainable practise and helping communities overcome financial barriers	✓	✓
8.4	Improve progressively, through 2030, global resource efficiency consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead	Increasing agricultural output through enhanced management strategies and fertiliser application can contribute towards improving [agricultural] resource efficiencies and mitigate biodiversity loss through agricultural land expansion. Moreover, the CPE is aligned with the 10YFP, specifically Sustainable Lifestyles and Education, and Sustainable Food Systems		✓
14.1	By 2025, prevent and significantly reduce marine pollution of all kinds, in particular	Nutrient recovery facilities, and improved soil and fertiliser management can help reduce nutrient loading and pollution into marine environments	✓	✓

	from land-based activities, including marine debris and nutrient pollution				
17.16	Enhance the Global Partnership for Sustainable Development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement of the Sustainable Development Goals in all countries, in particular developing countries	Developing cooperative partnerships which include all facets of knowledge and stakeholders in critical for the development of sustainable systems including a CPE	✓	✓	✓
<hr/>					
<u>Contributing towards SDG targets (in ascending SDG number order)</u>					
1.5	By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	Implementing soil and phosphorus management strategies can help mitigate the consequences of climate change including extreme weather events and eutrophication intensification. Domestication of resources can decrease the necessity of foreign trade and therefore reduce economic shocks and its implications to food production.		✓	✓
2.1	By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	Increasing resources such as fertilisers and education can help promote sustainable agriculture which can provide sufficient foods all year round		✓	✓
2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and	Malnutrition can be mitigated through (i) food production diversification, and (ii) food biofortification through increasing soil integrity			✓

	address the nutritional needs of adolescent girls, pregnant and lactating women and older persons	and nutrient profile through the use of nutrient rich fertilisers			
2.a	Increase investment, including through enhanced international cooperation, in rural infrastructure, agriculture research and extension services, technology development and plant and livestock gene banks in order to enhance	Attracting investment for waste recovery and valorisation technologies through cooperative and co-sponsorship programs. Furthermore, bridging the gap between farmer and science through education and resource facilitation	✓	✓	✓
3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Reducing sewage and nutrient rich sediments entering waterbodies can drastically reduce the transmission of faecal and waterborne diseases. Moreover, the reduction of heavy metal contamination (e.g. cadmium) from fertilisers	✓		✓
6.b	Support and strengthen the participation of local communities in improving water and sanitation management	Improved water quality can be achieved through the mitigation of raw sewage entering local waterbodies through nutrient recovery facilities. Moreover, sustainable agricultural practises can reduce run-off and erosion causing eutrophication	✓		✓
9.1	Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	Nutrient recovery facilities and valorisation technologies can contribute to developing sustainable infrastructure which support economic development and human well-being. Moreover, domesticating production can contribute to equitable access among communities and individuals alike	✓	✓	
9.4	By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with	Developing and/or upgrading pre-existing infrastructure into a Circular Phosphorus Economy	✓	✓	

	increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	can enhance the potential for use and recycling of phosphorus in a sustainable manner			
11.6	By 2030, Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	Developing nutrient recovery facilities can contribute to lowering the environmental impact of cities and communities through the treatment of waste, especially sewage	✓		
12.5	By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	With a focus on recycling and reuse, Valorisation Technologies can utilise the resources generated from Resource Recovery Facilities		✓	
12.a	Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production	The advancement of cooperative shareholder partnerships can enhance the sharing of knowledge, innovation, and strategies from developed to developing nations		✓	✓
15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	Soil erosion and degradation reduces the fertility of agricultural soils leading to (i) eutrophication causing the destruction of marine life, and (ii) the clearing of natural habitats to pioneer fertile land causing biodiversity loss			✓
17.17	Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships	Cooperative shareholder partnerships including government, private, and academia can enhance resource sharing, knowledge, and innovation strategies	✓	✓	✓

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