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SCRREEN2

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SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

PHOSPHATE ROCK AND PHOSPHORUS

AUTHOR(S):

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PHOSPHATE ROCK AND PHOSPHORUS

OVERVIEW

Phosphate rock is the main anthropogenic source of phosphorus (chemical symbol P) and is in effect an “indicator” of phosphorus in different forms (mineral, organic) used in agriculture and industry (fertilizer chemicals or phosphoric acid, but also organic fertilizers, manures, crop products used as animal feed). Phosphorus is one of the six main building blocks of life (together with oxygen, hydrogen, potassium, nitrogen and carbon) and is vital for all life on planet earth, including plants, animals and humans, and so for the bio based economic processes that take place in the global economy.

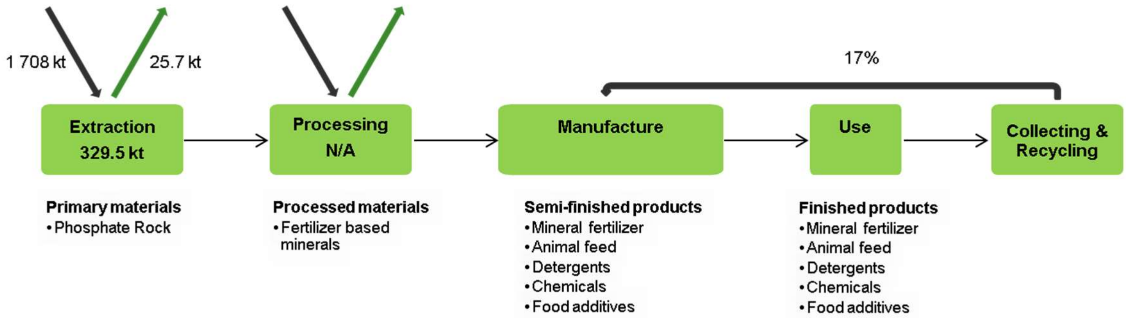

Figure 1. Simplified value chain for phosphate rock, data in tonnes of P_2O_5 for the EU, averaged over 2012-2016.

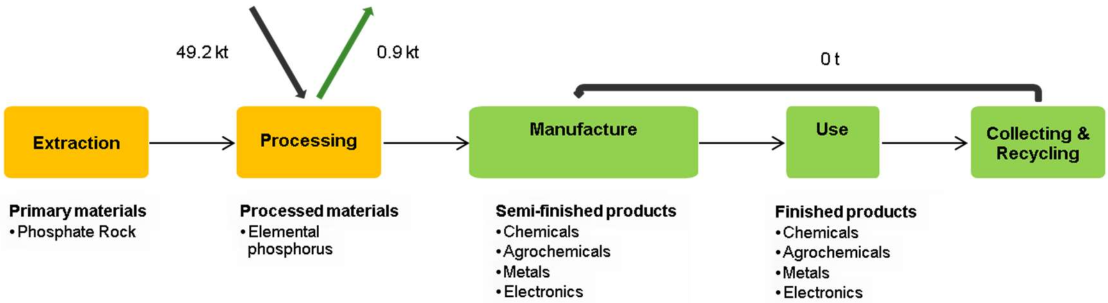

Figure 2: Simplified value chain for elemental phosphorus, data in tonnes of P_4 for the EU, average 2012-2016

Table 1 Phosphate rock supply and demand in million metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
75,215,040	China 44% Morocco 14% USA 10% Russia 7% Peru 4%	1,982,108	2.6%	Morocco 27% Russia 24% Finland 18% Algeria 10% Israel 7%	82%

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Table 2 Phosphorus supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
1,196,000	China 78% USA 11% Kazakhstan 6 % Vietnam 5 %	73,731	6%	Kazakhstan 65 % Vietnam 23 % China 10 %	100%

Prices: The price volatility of phosphate rock (f.o.b. North Africa) between February 2020 and January 2021, as reported by DERA (2021b), was 5.5%. This is significantly lower than the phosphate-rock-price volatility in the period 2016-2020, which was 13.9% (DERA, 2021b). The price decrease by 13.7% between 2013 and 2014 was the maximum (absolute) year-on-year price change in the period 2012-2020.

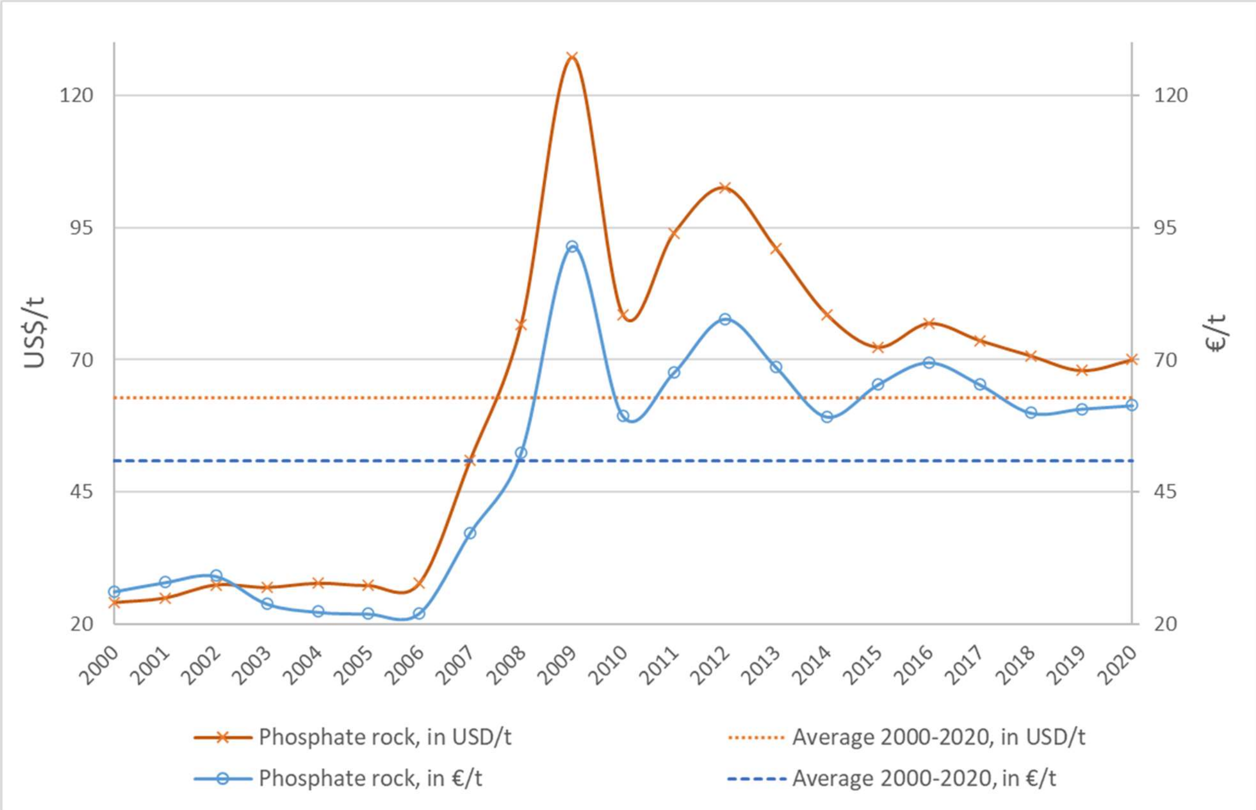

Figure 3. Annual average price of phosphate rock between 2000 and 2020 (USGS, 2021)[1].

Primary supply: The global annual production of phosphate rock between 2016 and 2020 was 75,200 kt of P_2O_5, on average (WMD 2021). Although most phosphate rock resources are located in Morocco, China is the dominant producer with a total amount of about 26.7 Mt of P_2O_5 in 2020 (WMD, 2021). The precise global production of elemental phosphorus is not known, it was estimated to be close to 1,200 kt per year (between

[1] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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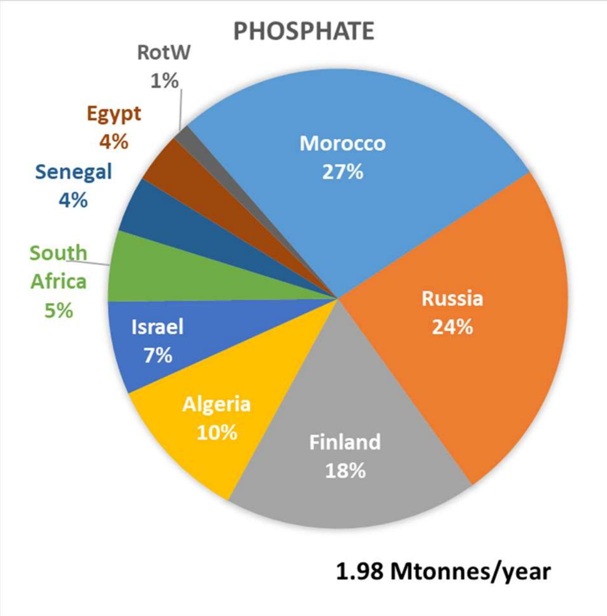
2012, 2013 and 2016). There are not more recent precise data concerning the production of elemental phosphorus. Morocco and Russia are the first EU suppliers.



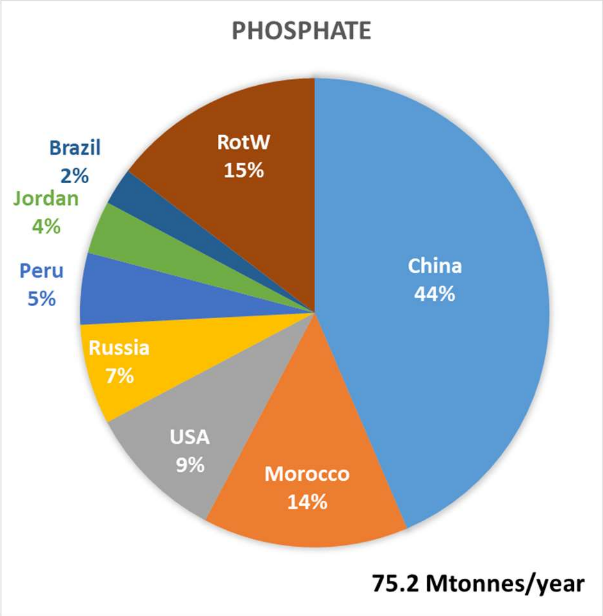
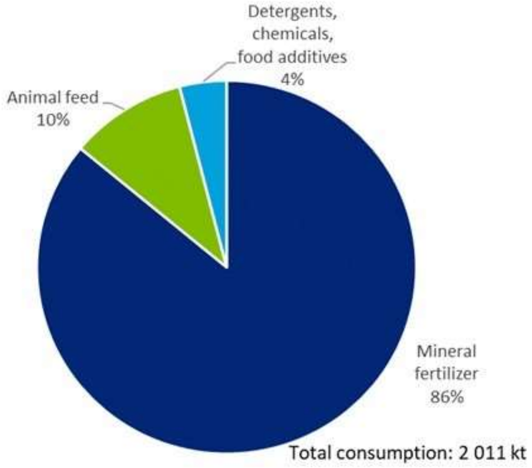


Figure 4. EU sourcing and Global mine production of phosphates, P2O5 content (average 2016-2020)

Secondary supply: For its applications in agriculture, phosphate rock can be replaced by secondary sources of phosphorous such as manure, sewage and food waste (biogenic waste flows).

Uses: Elemental phosphorus, obtained from phosphate rock, is used for the production of chemicals (e.g. flame retardants, oil additives, industrial water treatment, emulsifying agents). Phosphorus is a vital part of plant and animal nourishment. For fertilisers, phosphate is generally used with the other two main nutrients (sodium, potassium) and often with other nutrients (sulphur, magnesium, calcium, copper etc.).



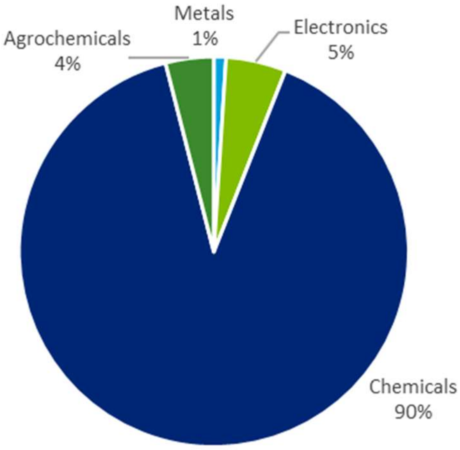


Figure 5 Left chart: EU end uses of phosphate rock (in P_2O_5 content). Average figures for 2012-2016 (ESPP, 2019) (JRC 2021). Right chart: EU end uses of elemental phosphorus, in P_4. Average figures for 2012-2016 (ECI, 2019), (ESPP, 2019) (JRC 2021).

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Substitution: There are no substitutes for phosphate rock in the production of fertilisers. (ESPP, 2019). Substitution of elemental phosphorous P_4 (and thus also of phosphate rock in other chemical applications) is also set to 0%, because many of these are specific phosphorus chemicals where no substitute is currently available to date (ESPP, 2019).

Other considerations: Phosphorous rock & elemental phosphorous may cause environmental impacts during the mining and production stages. Environmental impacts caused during the mining stage are: changes in land use patterns, habitat loss, dust emissions, water contamination and changes in aquifer regimes (Boeni et al. 2012; European Commission 2011). Contamination of water (underground and surface water) can be linked to products containing phosphorous such as fertilizers(de Ridder et al. 2012; UNEP et al. 2001). Phosphate and/or phosphate rock exports represent a significant value share of total export for Togo (8.8 %), Jordan (4.3 %) and Morocco (2.8 %).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3 Phosphate rock supply and demand in million metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
75,215,040	China 44% Morocco 14% USA 10% Russia 7% Peru 4%	1,961,184	3%	Morocco 27% Russia 24% Finland 18% Algeria 10% Israel 7%	82%

Table 4 Phosphorus supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
1,196,000	China 78% USA 11% Kazakhstan 6 % Vietnam 5 %	73,731	6.2%	Kazakhstan 65 % Vietnam 23 % China 10 %	100%

The most recent update of the EU Critical Raw Material List (2020) includes both "Phosphate rock" (in effect covering phosphorus P in different forms in fertilisers, animal feed, chemicals and other uses) and "Phosphorus" (referring to elemental phosphorus P4, often known as white phosphorus). Both materials are linked during their extraction phase, but white phosphorus is distinct in its downstream processing and end uses.

Globally, most phosphate rock is mined in China and Morocco and Western Sahara. While China is currently the world's largest producer of phosphorus, Morocco possesses an overwhelming majority of the known phosphate reserves on Earth (USGS 2021a)

The global supply of phosphate rock is thus contingent upon the geographic locations of key deposits, notably in China and Morocco. Meanwhile, the production of elemental phosphorus faces a bottleneck with respect to processing, which is only done at a limited number of sites. The European Sustainable Phosphorus Platform estimates that there are between 10 and 30 plants operating globally that produce P_4.They are located exclusively in Kazakhstan, Vietnam, China and the USA. China is the world's largest supplier of elemental phosphorus.

Global demand for phosphate rock is overwhelmingly driven by its applications in agriculture for fertilisers and animal feed. Current yields of global food production are in fact dependent on mined phosphate rock to produce fertilisers. Therefore, the future market of phosphate rock is in a great extent controlled by changes

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in supply and demand of fertilisers used in agriculture and strongly connected with the global population growth. Phosphorus is an essential element in the cells of all living plants and animals, and therefore phosphate rock cannot be substituted for its agricultural uses (USGS 2021a). Moreover, many of the specialty applications of elemental phosphorus also cannot be substituted (ESPP 2020).

The global market for phosphate rock is expected to become increasingly dependent on Morocco, as reserves in other countries are depleted in the coming years (Kasprak 2016). One potential consequence of this is that political conflicts in the disputed Western Sahara territory, which contains a significant portion of Moroccan reserves, could result in disruptions of the global supply of phosphate rock (Kasprak 2016).

The COVID-19 pandemic did not have a major effect on the phosphate rock market in 2020. The fertiliser industry and related agricultural businesses were considered essential industries in most countries, leading to a stability of global supply (USGS 2021a).

EU TRADE

Table 5. Relevant Eurostat CN trade codes for phosphate rocks and phosphorus

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
2510 20 00	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk: Ground	2804 70 10	Phosphorus: Red phosphorus
2510 10 00	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk: Unground		

For the purpose of this assessment, phosphate rocks and phosphorus are evaluated at both extraction and processing stage.

Figure 6, Figure 7 and Figure 8 present the EU trade of phosphate rock and phosphorus between 2000 and 2021. Over the whole period, the EU was a net importer of phosphates for unground (CN 2510 10 00), ground (CN 2510 20 00), and phosphorus (CN 2804 70 10). The imports of unground phosphates (CN 2510 10 00) varied from 1,545,891 t to 6,732,751 t, while exports ranged between 99 t and 23,145 t. For ground phosphates (CN 2510 20 00), EU imports fluctuated between 1,906,361 and 3,538,212 t, while exports ranged from 825 to 141,108 t. For phosphorus (CN 2804 70 10), EU imports varied from 16,262 to 79,618 t; and exports ranged from 13 to 7,291 t.

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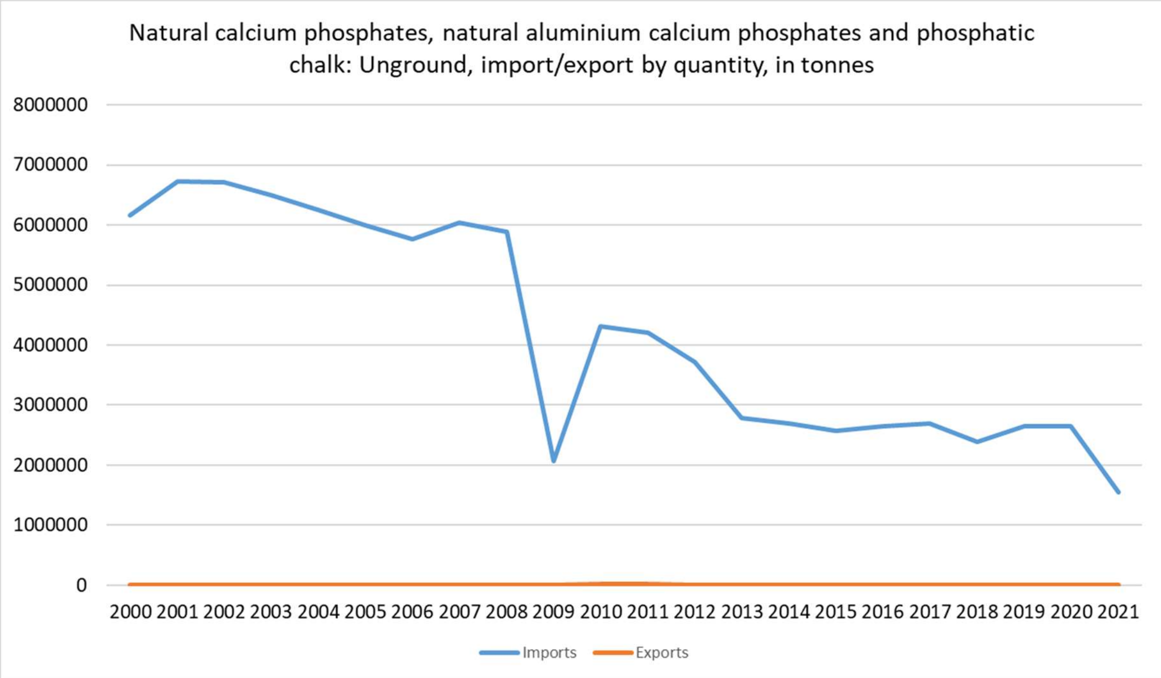

Figure 6 EU trade flows of natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, unground (CN 2510 10 00) from 2000 to 2021 (based on Eurostat, 2022)

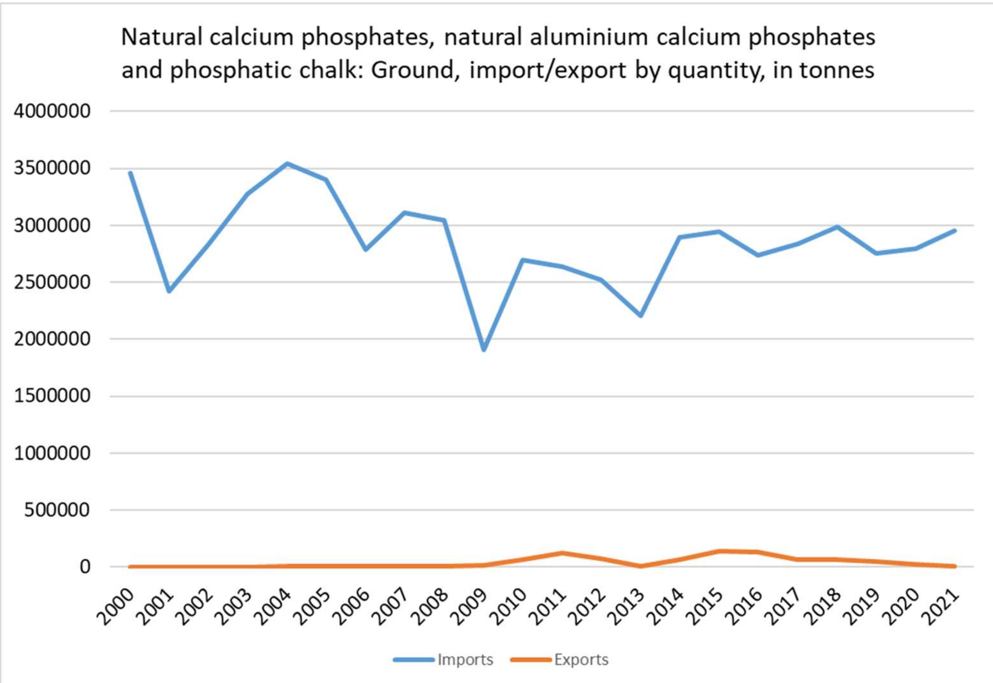

Figure 7 EU trade flows of natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, ground (CN 2510 20 00) from 2000 to 2021 (based on Eurostat, 2022)

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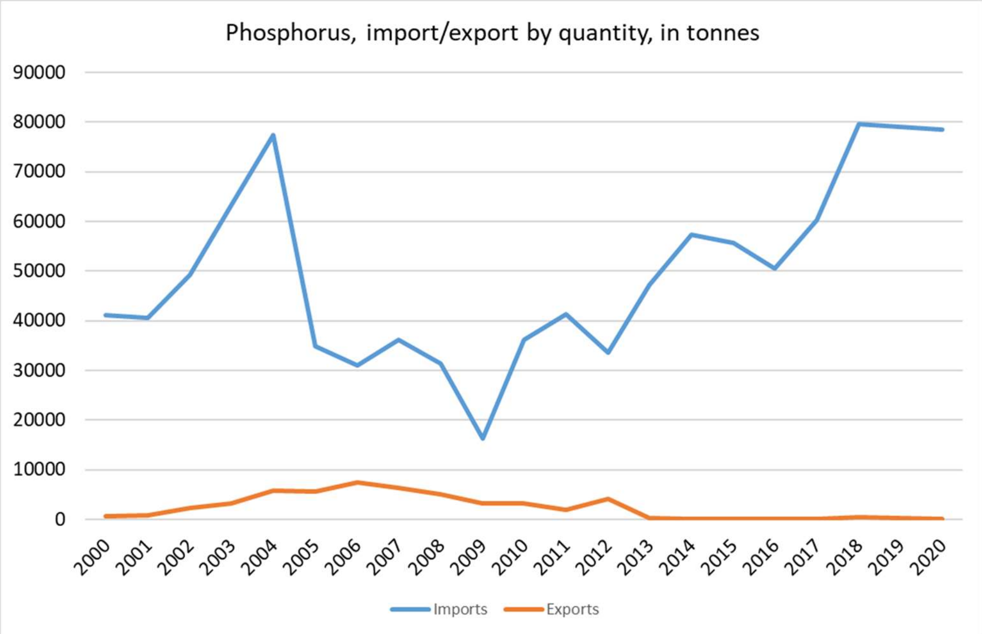

Figure 8 EU trade flows of phosphorus (CN 2804 70 10) from 2000 to 2021 (based on Eurostat, 2022)

Figure 9, Figure 10 and Figure 11 show the EU imports of phosphate rock and phosphorus by country in the period 2000-2021. For unground phosphates, the major EU supplier was Morocco, which corresponds to 43% of the total EU imports, followed by Russia (15%), Algeria (9%), Israel (9%), and Syria (7%). For ground phosphates, the major EU supplier was Russia, which corresponds to 36% of the total EU imports, followed by Morocco (35%), Syria (9%), Algeria (4%), and South Africa (4%). For phosphorus, the major EU supplier was Kazakhstan, which corresponds to 65% of the total EU imports, followed by China (18%), and Viet Nam (11%).

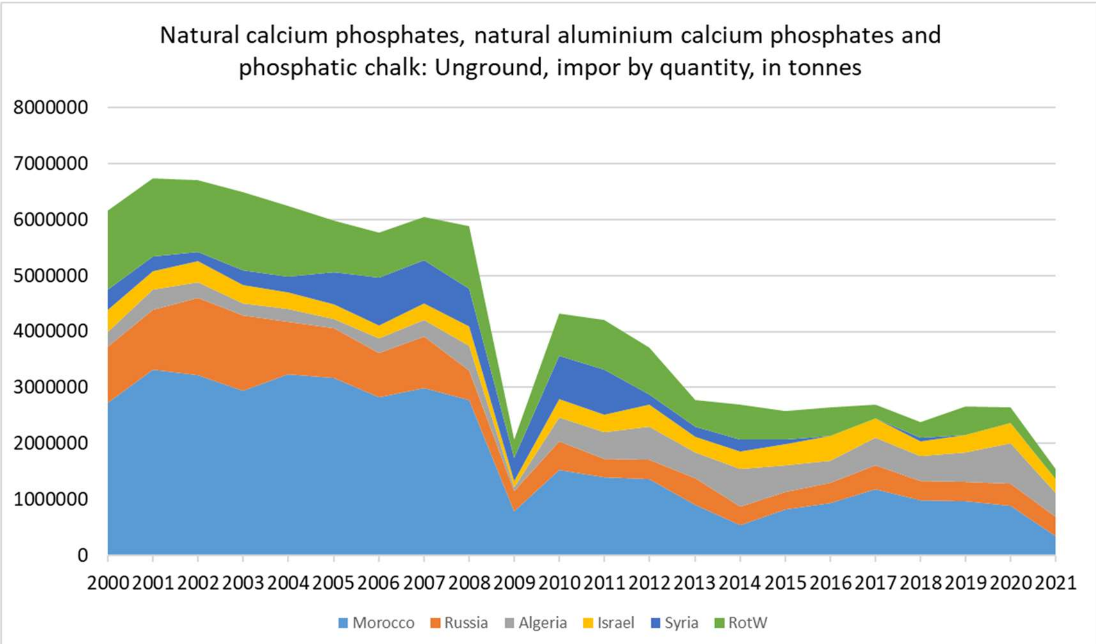

Figure 9 EU imports of natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, unground (CN 2510 10 00) by country from 2000 to 2021 (based on Eurostat, 2022)

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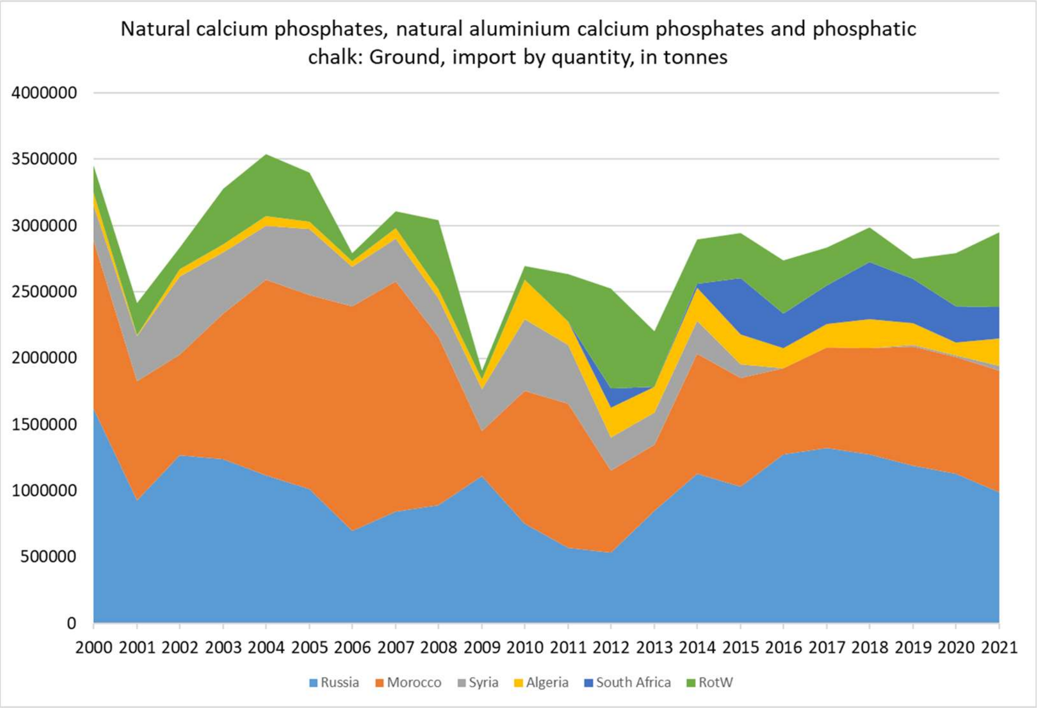

Figure 10 EU imports of natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, ground (CN 2510 20 00) by country from 2000 to 2021 (based on Eurostat, 2022)

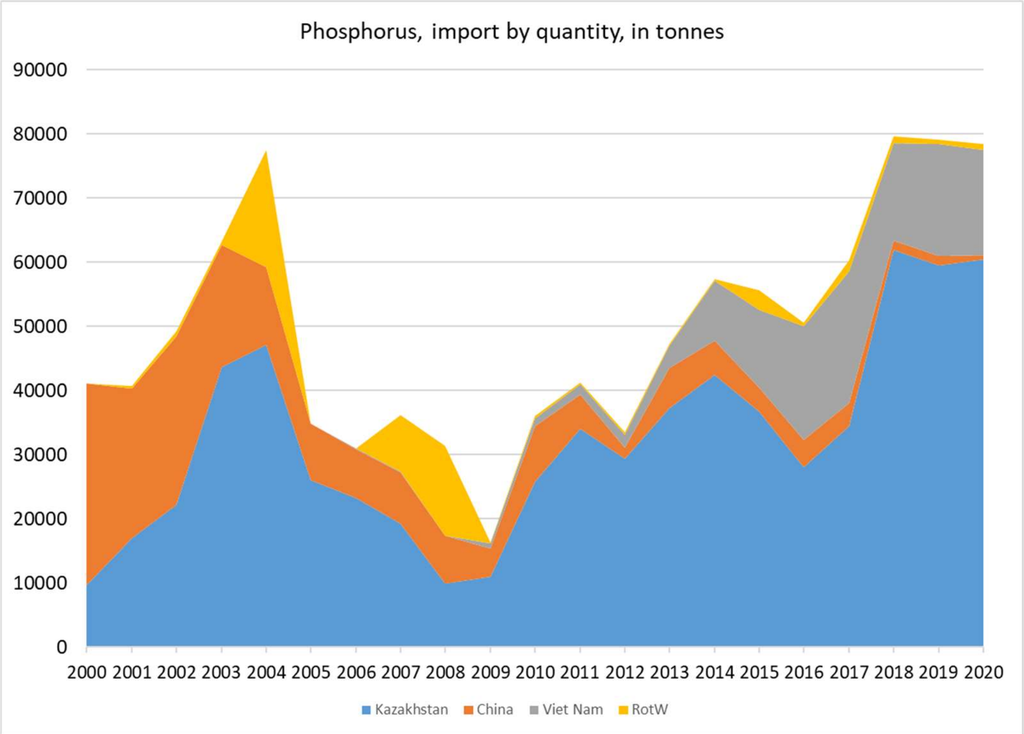

Figure 11 EU imports of phosphorus (CN 2804 70 10) by country from 2000 to 2021 (based on Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

The price volatility of phosphate rock (f.o.b. North Africa) between February 2020 and January 2021 was 5.5%. This is significantly lower than the phosphate-rock-price volatility in the period 2016-2020, which was 13.9% (DERA, 2021b). The price decreased by 13.7% between 2013 and 2014. It was the maximum (absolute) year-on-year price change in the period 2000-2020.

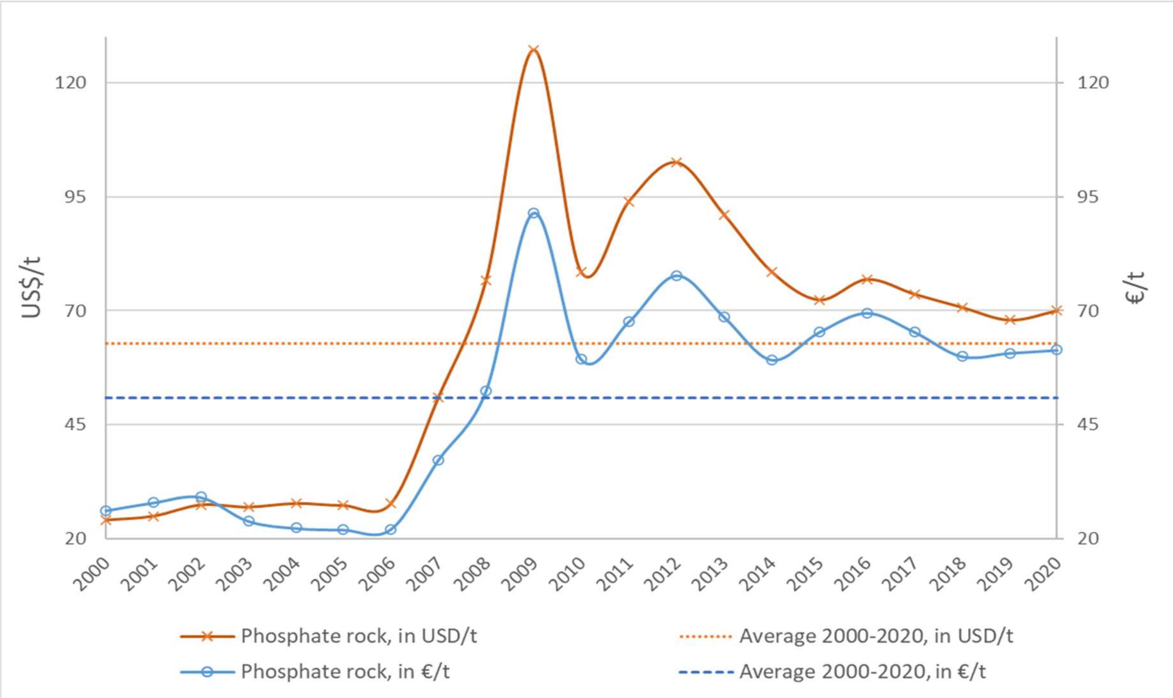

Figure 12 Annual average price of (marketable) phosphate rock (weighted value, all grades, f.o.b. mine) between 2000 and 2020, in US$/kg and €/kg (based on USGS, 2021b)[2]. Dash lines indicate average prices for 2000-2020.

In the long-run, the major driver of phosphate demand and, thus, phosphate price are population growth, the related growth in demand for food and the structure of this demand (vegetables, animal food, phosphate-intensive crops etc.), which are counterbalanced by the question of increasing supply by new mining projects and other phosphate sources (Heckenmüller et al., 2014; Williams, 2019). In the short and medium run, several price determinants/drivers have been reported, which affect supply and demand directly and via expectations forming. These price determinants include cyclical interaction between demand and supply (demand fluctuations, overcapacity building, capacity cuts) driven by differences in planning horizon between supply and demand; industrial policy measures (e.g., taxes and subsidies targeting imports and exports), which affect global phosphate prices particularly when large market actors are involved (as in the case of the recent USA-China trade tensions); changes in agricultural commodity prices and structure of agricultural production, which are affected by, e.g., weather conditions; escalating investment costs required by new mine capacity; demand

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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and production by the large actors (e.g., China); and many other (European Commission, 2020; Heckenmüller et al., 2014; Thornton, 2020; USGS, 2021a; Williams, 2019, 2021). There are reports of Covid-19-pandemy effects on phosphate supply (in, e.g., China and India) and, thus, on phosphate prices, but also reports of market recovery from these effects (see, e.g., Williams, 2021). It seems that the US-phosphate-rock market has not been (significantly) affected by the pandemic (USGS, 2021a).

OUTLOOK FOR SUPPLY AND DEMAND

Demand for phosphate rock is primarily driven by its use as a fertiliser (P_2O_5) for commodity crop production. The International Fertiliser Association forecasts a steady increase in global demand for phosphate until 2025, from 46,3Mt of fertilizer in 2020 up to 52,5Mt in 2025. This amounts to a compound annual growth rate of 1.8% (IFA 2021). According to the IFA, the primary factors driving medium term demand are increased demand for commodity crops such as soybeans, and cereals leading to increasing global surface under cultivation and demand for increased crop yields. Africa is the fastest growing market for mineral fertilisers, while Latin America is expected to be the region driving the increase in global demand (IFA 2021).

The IFA expects phosphate fertiliser (P_2O_5) production to increase by 3,6Mt by 2025. Near term capacity expansions in phosphoric acid are expected in Tunisia, Brazil, and China. Africa and East Asia are expected to drive future expansion in fertiliser production (IFA 2021).

In the longer-term horizon, demand for phosphorus is expected to be driven by macro trends related to global population growth and changing food consumption habits. The consumption of meat is the primary driver of phosphate demand, with an estimated 72% of the global average phosphorus footprint (Metson et al. 2012). Meat heavy diets are more resource intensive in terms of land and fertiliser use due to the fact that animals convert only a limited amount of their feed calories and nutrients into calories for human consumption. Increased demand for meat in rapidly urbanizing countries, such as China and India, is expected to remain the leading driver of increase phosphate demand in coming decades (ibid).

Meanwhile, some experts have raised concerns about the stability of phosphate rock supply over the longer term. Estimates of global reserves vary, but the International Fertiliser Development Centre has estimated that current reserves can sustain output for roughly 300 years. This estimate goes against other research that has predicted a phosphorus peak' scenario, where production is expected to peak after half of global reserves have been exhausted within the 21st century. However, studies exploring the ratio of phosphate reserves to consumption have indicated that within the next 30 years two of the world's three largest phosphate rock producers, China and the United States, will have largely depleted their reserves. This will result in Morocco having an increasingly dominant position over the global market, and any long term increases in primary supply will be driven by Morocco. In order to mitigate the geopolitical risks posed by having a single country dominating the market for an essential nutrient, there is also significant research being made into recovery of phosphorus from wastewater and animal manures. These efforts at recovering phosphorus from secondary sources could play a major role in increasing global supply and limit dependence on phosphorus mining (Daneshgar et al. 2018).

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DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

The EU annual apparent consumption of phosphate rock was 5,710 kt of P2O5 on average over the 2016-2020 period. The EU consumption of elemental phosphorus is 79.5 kt of P4 on average over the 2019-2020 period.

Phosphate rock (extraction stage) EU consumption is presented by HS codes CN 251020000 natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, ground and CN 25101000 Natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, unground. Import and export data is extracted from Eurostat Comext (2021). Production data is extracted from WMD (2022).

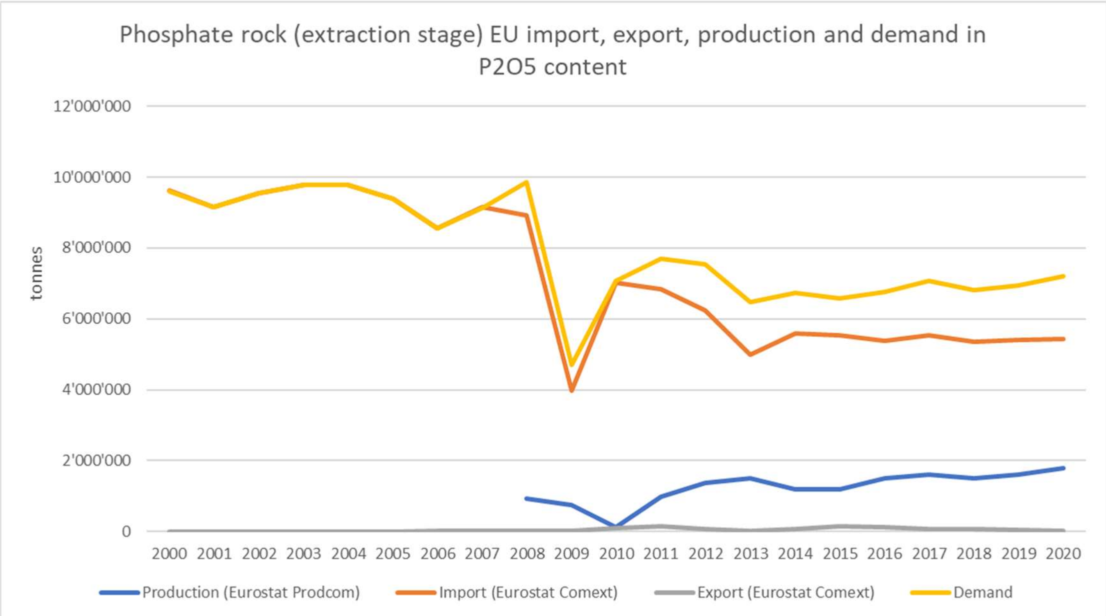

Figure 13. Phosphate rock (CN 251020000 natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, ground and CN 25101000 Natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, unground) extraction stage EU apparent consumption. Production data are available from WMD (2022). Consumption is calculated in P_2O_5 content (EU production+import-export). Global economic crisis 2008-2009 caused a significant drop in demand for phosphate rock in 2009 (USGS, 2010).

Based on Eurostat Comext (2021) and Eurostat Prodcom (2021) average import reliance of elemental phosphorus at processing stage is 82% for 2016-2020.

Elemental phosphorus (processing stage) EU consumption is presented by HS code CN 28047000 Phosphorus. Import and export data is extracted from Eurostat Comext (2021). Production data is extracted from Eurostat Prodcom (2021) using PRCCODE 20132181 Phosphorus.

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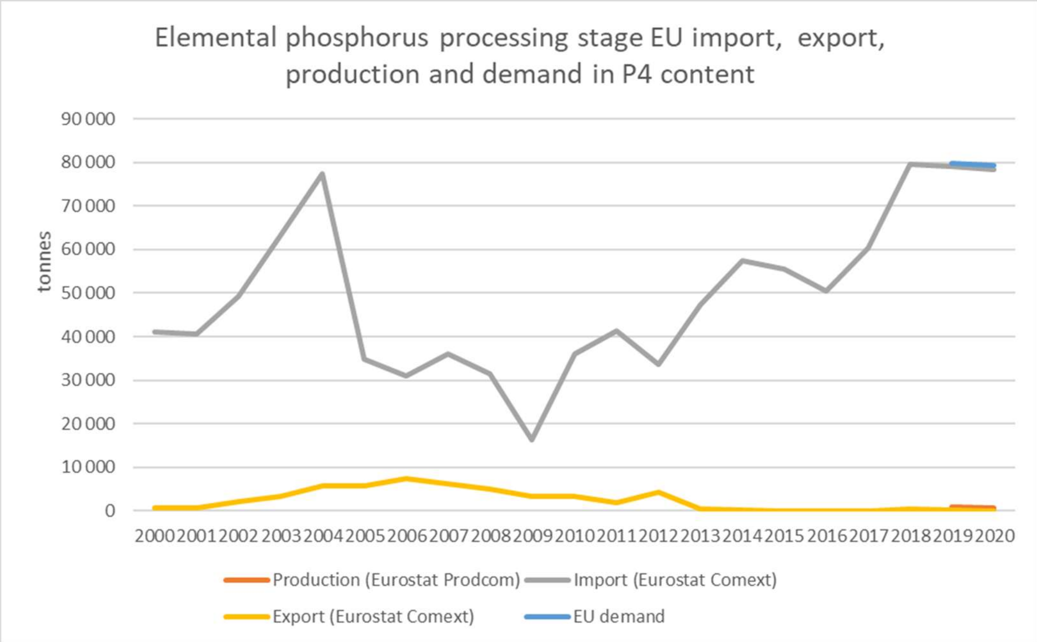
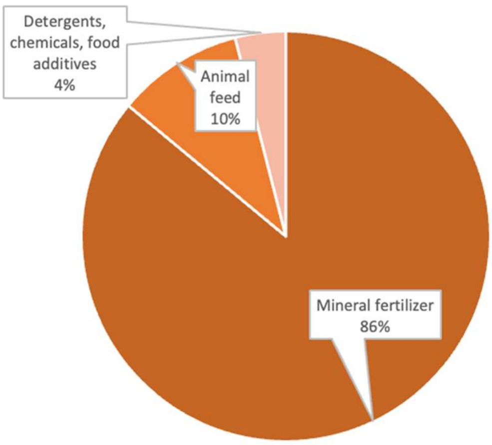


Figure 14. Elemental phosphorus (CN 28047000 Phosphorus) processing stage apparent EU consumption. Production data are available only for 2019-2020 from Eurostat Prodcom (2021). Consumption is calculated in P_4 content (EU production+import-export).

Based on Eurostat Comext (2021) and Eurostat Prodcom (2021) average import reliance of elemental phosphorus at processing stage is 98.9 % for 2019-2020.

EU USES AND END-USES

Phosphate rock is used in mineral fertiliser, animal feed and other applications such as detergents, chemicals and food additives



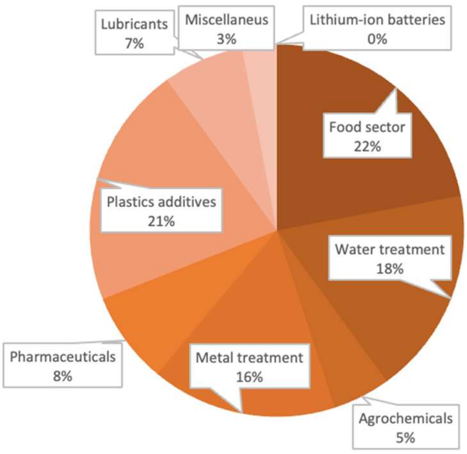


Figure 15 Left chart: EU end uses of phosphate rock (in P_2O_5 content). Average figures for 2012-2016 (ESPP, 2019) (JRC 2021). Right chart: EU end uses of elemental phosphorus. Figures for 2017 (Matos et al, 2021; SCRREEN experts, 2022).

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Elemental phosphorus, obtained from phosphate rock, is used for the production of chemicals (e.g. flame retardants, oil additives, industrial water treatment, emulsifying agents).

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 6).

Table 6 Phosphate rock or white phosphorus applications, 2-digit NACE sectors, associated 4-digit NACE sectors and value added per sector (Eurostat, 2022)

Applications	2-digit NACE sector	Value added of sector (millions €) 2019	4-digit NACE sector
Animal feed	C10 - 12 Manufacture of food products, beverages, tobacco products	251,015	All subsectors (meat, starch, dairy etc.)
Fertilisers, chemicals and detergents	C20 - Manufacture of chemicals and chemical products	117,150*	20.15 Manufacture of fertilisers and nitrogen compounds
Metals	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	25.61 Treatment and coating of metals
Electronic parts	C26 - Manufacture of computer, electronic and optical products	84,074*	26.11 Manufacture of electronic components

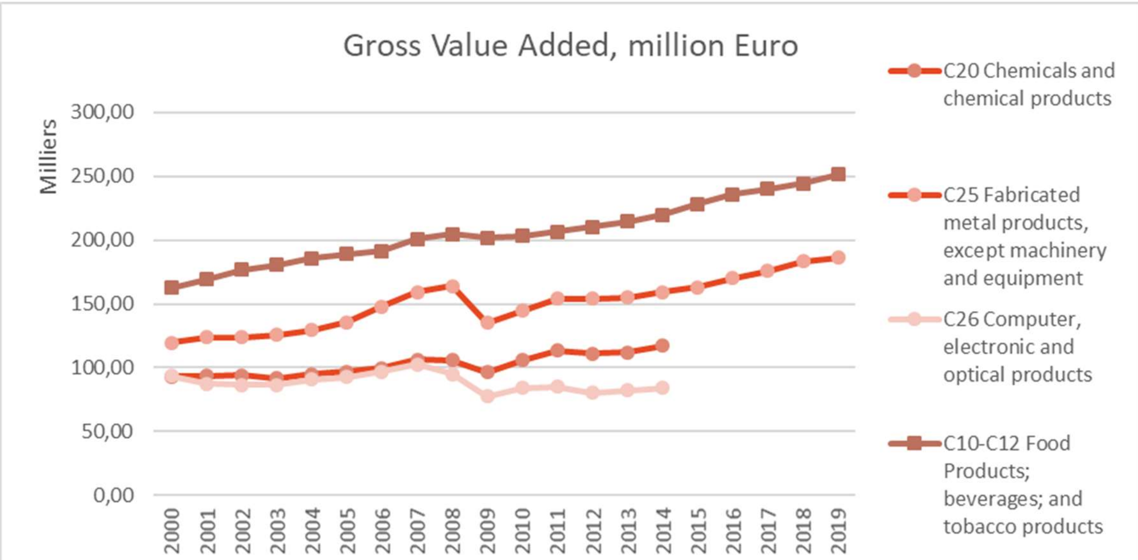

Figure 16 Value added per 2-digit NACE sector over time (Eurostat, 2022)

APPLICATIONS OF PHOSPHATE ROCK AND ELEMENTAL PHOSPHOROUS

Elemental phosphorus, obtained from phosphate rock, is used for the production of chemicals (e.g. flame retardants, oil additives, industrial water treatment, emulsifying agents). Phosphorus is a vital part of plant and animal nourishment.

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For fertilisers phosphate is generally used with the other two main nutrients (sodium, potassium) and often with other nutrients (sulphur, magnesium, calcium, copper etc.).

Industrial applications include:

- lubricant additives,
- pharmaceuticals (both in the pharmaceutical molecule, and as intermediates in drug synthesis)
- agrochemicals
- anti-scaling agents
- detergents
- flame retardants
- oil additives
- industrial water treatment
- emulsifying agents, matches and pyrotechnics
- nickel plating
- asphalt and plastic additives
- catalysts, luminescent materials
- metal extraction (most of the world's cobalt is produced using a phosphorus intermediate) (ECI, 2019)

Globally 91% of phosphate rock is utilised for production of fertilisers, while in the EU this share is 86%.

Approximately, 10% of phosphate rock used in the EU is in the production of nutritional supplements for animal feed mainly in form of mono- and dicalcium phosphate (Tercero et al., 2018).

A smaller fraction around 4% of phosphate rock is used in the production of detergents and other chemicals. There are different detergents, and their composition depends on their application purpose; laundry and dishwasher detergents contain phosphate mainly in the form of sodium tripolyphosphate (STPP). In 2018, its use in detergents has experienced a strong reduction due to concerns related with rising levels of phosphorus in surface waters which causes eutrophication (Tercero et al., 2018).

Around 5% of world phosphate rock production is used in applications other than agriculture (other than fertilisers and animal food).

SUBSTITUTION

Table 7. Potential substitution options for phosphate rock and elemental phosphorous in main uses

Use	Percentage*	Substitute	Comment on substitute
N/A	N/A	None identified for any sector, due to unique properties of phosphorous & therefore, the rock source. Only options are from recycling and recovery.[3]	N/A

[3] SCRREEN Expert Workshop, October 2021

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There are no substitutes for phosphate rock in the production of fertilisers. (ESPP, 2019)

The existing opportunities for other sources of phosphorus are represented by the applied end-of-life recycling rate of 17% (see section on secondary materials) rather than a reduction of supply risk from substitution.

Substitution of elemental phosphorous P_4 (and thus also of phosphate rock in other chemical applications) is also set to 0%, because many of these are specific phosphorus chemicals where no substitute is currently available to date (ESPP, 2019).

SUPPLY

EU SUPPLY CHAIN

The EU is an exporter of high value products and food products, between 6% and 7% of the value of total external EU exports per year (Eurostat data). All agro-food related activities cannot take place without a supply of phosphorous into the agricultural system. The imported amount of phosphate rock expressed as P2O5 in EU in 2020 reached 5.5 million tonnes, while the production, mainly by the valorization of secondary resources, was about 1.8 million tonnes (Eurostat, 2020). Finland is currently (2021) the only producer in EU with 336.200 tonnes of phosphateock (WMD, 2022). The only currently operating mine extracting Phosphate rock in the EU is located in Siilinjärvi and explored by the company Yara International. The concentrate produced in the mine is used for phosphoric acid and fertilizer production in the adjacent plant. The resource estimate (JORC) for the Siilinjärvi deposit is 1,617 Mt of ore with P2O5 content of 3.694% (FODD 2017).

Figure 17 show the phosphate material flows in the EU economy from the phosphate rock 2015 MSA study conducted by Bio by Deloitte (BIO Intelligence Service, 2015).

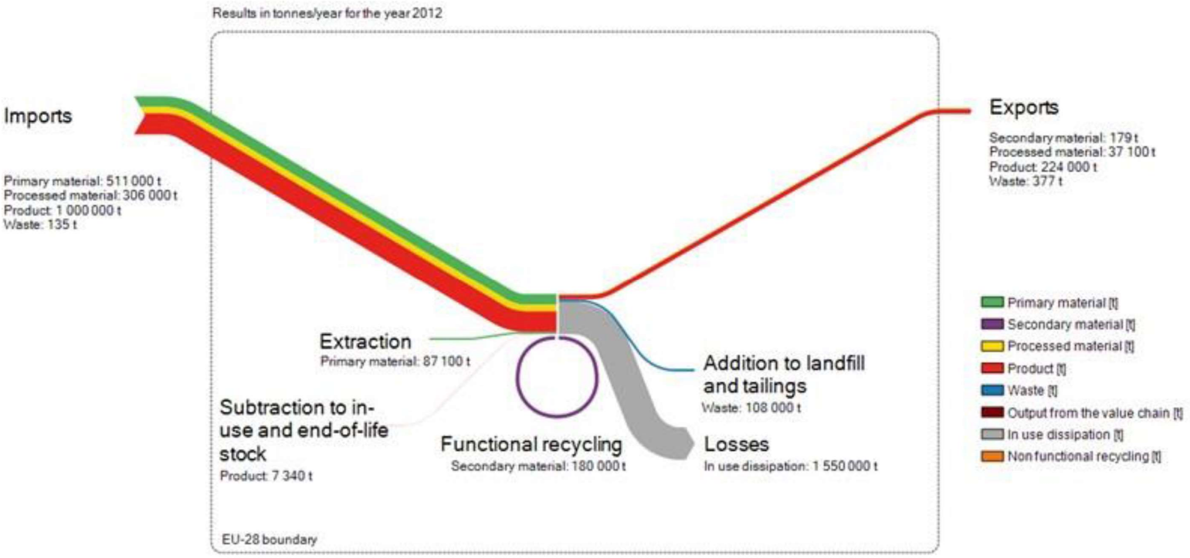

Figure 17 Sankey diagram showing the material flows of phosphate in the EU economy in 2012 (BIO Intelligence Service, 2015).

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGICAL OCCURRENCE/EXPLORATION

The abundance in the earth's crust of phosphorus pentoxide (P2O5) is about 0.13% of the total crust, which indicates a relatively high presence of P (Rudnick & Gao, 2013). Sedimentary marine phosphorites are the principal deposits for phosphate rock. Depending on the mineralogical, textural and chemical characteristics (e.g. ore grade, impurities), as well as the local availability of water around the mining site, different refining processes are applied to obtain phosphate rock concentrates. Although these resources are found worldwide, known reserves are highly concentrated (over 70% in Morocco). It is estimated that world resources of phosphate rock is 300,000 million tonnes (known world reserves are shown in Table 8). The biggest deposits are located in northern Africa, China, the Middle East, and the US. Large deposits of phosphates are also located on the continental shelf and on seamounts in the Atlantic and Pacific Oceans, but exploiting these deep-sea sources is under development (e.g., see Namibian Marine Phosphate, 2023).. Besides the sedimentary phosphate deposits, some igneous rocks are also rich in phosphate minerals. However, sedimentary deposits are more abundant and usually higher in grade (P content, but also higher in contaminants). About 80% of the global production of phosphate rock is exploited from sedimentary phosphate deposits (McKelvey, 2016; Kauwenbergh, 2010).

- Exploration activities and mine expansions took place in Australia and Africa in 2011. There are two major projects in Africa: the expansion of a phosphate mine in Morocco and a new project off the Namibian coast. Smaller projects are under various stages of development in several African countries, such as Angola, Congo (Brazzaville), Guinea-Bissau, Ethiopia, Mali, Mauritania, Mozambique, Uganda, and Zambia. Expansion of production capacity was planned in Egypt, Senegal, South Africa, Tunisia, and Togo. Other development projects for new mines or expansions are on-going in Brazil, China, and Kazakhstan (Jasinski, 2016). In the EU there is a mining operating in Finland (De Ridder et al., 2012). Rcent development at KABs apatatie iron ore operations in northern Sweden has revealed large amount of resources tha are under planning for extraction (LKAB, 2022). Apart from known geological reserves, organic sources of phosphorites are possible. Guano, bone meal or other organic sources are of less economic importance as phosphate rock sources, because of supply issues, processing costs, or simply because quantities available are much smaller.
- In Europe the ongoing exploration and development for extraction of the apatite phosphate rock in LKABs iron fields has been promising with current (LKAB, 2022) expansion of mineral resources to close to 4 billon tonnes with average grades ranging from 0,33% to 2.73%. The figures include both resources and reserves.

RESOURCES AND RESERVES

The resources are relatively abundant globally and known reserves are documented and sedimentary phosphate deposits occur on every continent (McKelvey, 1967) but known reserves are highly concentrated in a few countries, mainly Morocco, (Table 8). The amounts of the reserves by country have not notably been revised according to more recent documents (USGS, 2022).

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Resource data for some countries in the EU are available at Minerals4EU (2019), (Table 9), but cannot be summed as they are partial and they do not use the same reporting code. For reserves, Minerals4EU (2019) only reports phosphate rock reserves in Ukraine, with 115,800 kt of apatite ore, and 4,550 kt of P2O5 contained in the apatite ores according to Russian Classification (RUS)A.

Table 8 Global known reserves of phosphate rock in year 2021 (Data from USGS, 2022)

Country	Estimated phosphate rock known reserves (kt)	Percentage of total (%)
Morocco	50,000,000	70
China	3,200,000	4,5
Egypt	2.800.000	4
Algeria	2,200,000	3
South Africa	1,600,000	2
Brazil	1,600,000	2
Saudi Arabia	1,400,000	2
Australia	1,100,000	1,5
Finland	1,000,000	1
United States	1,000,000	1
Jordan	1,000,000	1
Russia	600.000	1
Kazakhstan	260,000	0,3
Peru	210,000	0,3
Tunisia	100,000	0,1
Usbekistan	100,000	0,1
Others	2,889,000	4
World total (rounded)	*71,000,000*	*100*

Table 9 Resource data for the EU compiled in the European Minerals Yearbook at Minerals4EU (2019), LKAB (2022)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Spain	Adapted version of the USGS Circular 831 of 1980	30.8	Mt	11.78%	Proven reserves
UK	None	100.7	Mt	2.19%	Historic Resource Estimates
Finland	JORC	540	Mt	4%	Total
Norway	JORC	14.6	Mt	5.18%	Indicated
Ukraine	Russian Classification	131,930	kt	-	(RUS)P1
Estonia	Nat. rep. code	2,935.74	kt	-	Measured+Indicated
Greece	USGS	500	kt	10-25%	Measured
Serbia	JORC	72	Mt	9%	Total
Sweden	PERC	3971	Mt	0.33-2.41%	Inferred, measured and indicated

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Finland disposes the most significant resources of phosphoric rock in EU, while it is the only EU member state where these resources are extracted (0.4% of global production). The reported resources amount to 2360 million tonnes of ore, with an average 4.0% phosphorus (P_2O_5) content. Finnish phosphorus resources are magmatic. Compared to sedimentary deposits, these have lower heavy metal concentrations. The largest known phosphate rock deposit, in terms of volume, is Siilinjärvi which was discovered in 1950 and quarrying began in 1979. On average, the ore consists of apatite (10%), phlogopite (65%), carbonate (20%), and richterite (5%). Siilinjärvi is Europe's only operating phosphate mine (operated by the Yara company) and processing plant. About 10 million tonnes of apatite ore are mined each year, producing about 1.0 million tonnes of apatite concentrate (Smol et al. 2020).

The amount of phosphorus deposits in northern Sweden are presented in Table 10**Erreur ! Source du renvoi introuvable.**. These resources consist iron ore mines where P occurs as apatite (Lkab, 2022). The feasibility of apatite extraction depends upon its concentration in the ore and the amount of the extracted iron. Lkab company estimates that P_2O_5 will be extracted as a by-product from the iron ore mining, while the extraction is planned for 2027 (ree-map.com).

Notable resources of phosphate rocks occur in Radom–Iłża–Annopol–Gościeradów–Modliborzyce region in Poland. The identified amount is 42.4 million tonnes of phosphorite with an average 14 wt.% in P2O5 (7.35 million tonnes P_2O_5). The above resources are not expected to be exploited in short term (Smol et al. 2020).

Table 10 Phosphoric resources in Sweden (Lkab, 2022)

Resource	Quantity (Mt)	Grade (JORC code %)
Kiruna	1.373	0.33
Malmberget	1.371	0.58
Svappavaara	769	0.49
Per Geijer	408	2.73
Total	3.921	0.33 — 2.73

WORLD MINE PRODUCTION

The global annual production of phosphate rock between 2012 and 2016 was 76,719 kt of P2O5, on average (WMD 2019). Although most phosphate rock resources are located in Morocco, China is the dominant producer with a total amount of about 26.7 Mt of P_2O_5 in 2020 (WMD, 2021). The world production of P_2O_5 by country since 1984 can be seen in Figure 18 (WMD, since 1984). USGS documents display the raw production of phosphate rock Figure 19 (USGS, since 2000).

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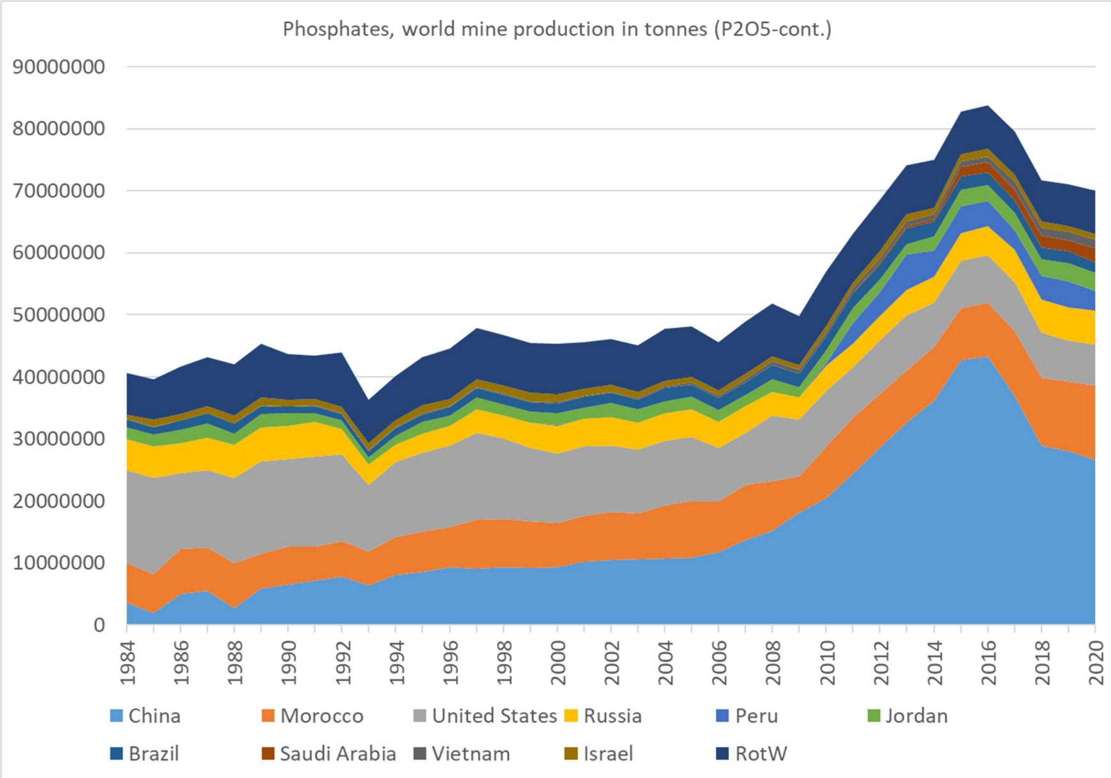

Figure 18 Global P_2O_5 production between 1984 and 2020 [WMD (2014)-(2021)].

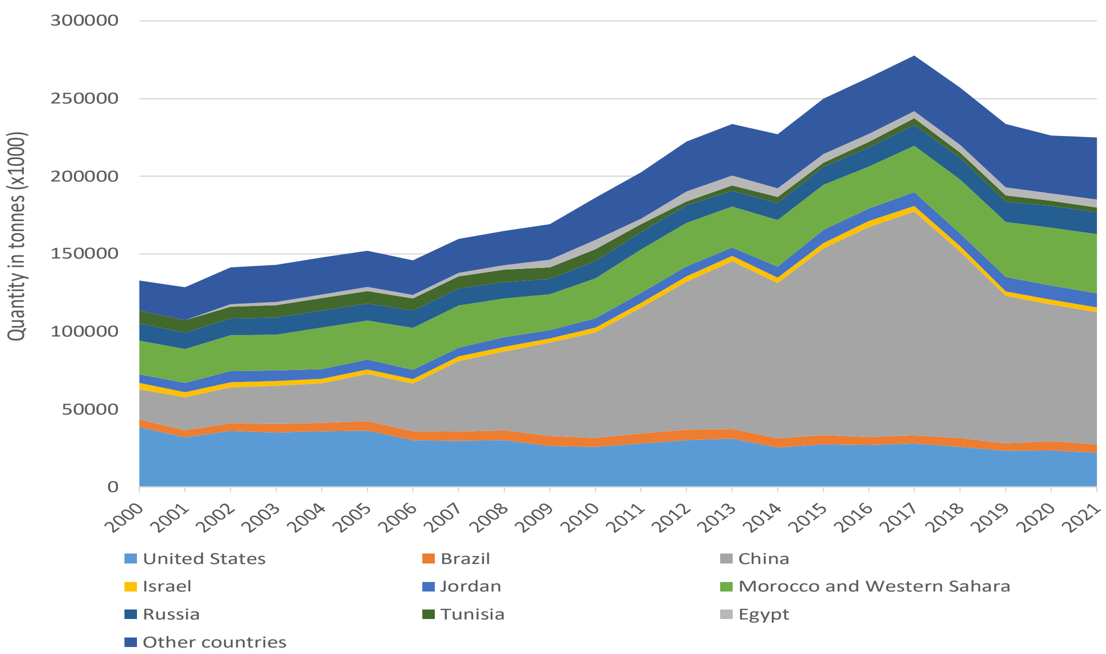

Figure 19 Global raw phosphate rock production between 2000 and 2021 [USGS (2003)-(2022)].

SCRREEN project listed the most relevant industrial actors beneficiating phosphate rock, see Table 11.

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Table 11 Some of the largest industrial actors beneficiating phosphate ores (Yang et al., 2018).

Company	Mine site (location)
Vale	Bayóvar (Sechura, Peru)
	Catalão (Goiás, Brazil)
OCP	Benguérir (Morocco)
	Youssoufia (Morocco)
	Khouribga (Morocco)
	Boucraâ (Western Sahara)
Mosaic Co.	Four Corners (Florida, US)
	South Ford Meade (Florida, US)
	South Pasture (Florida, US)
	Wingate Creek (Florida, US)
	Hopewell (Florida, US)
China Molybdenum Co.	Ltd Chapadão (Goiàs, Brazil)
Sinochem Yunlong Co., Ltd.	Aurora (North Carolina, US)
Nutrien (merger of Agrium and Potash Corp.)	Dry Valley (Idaho, US)
	Swift Creek (Florida, US)
P4 Production, LLC.	Blackfoot Bridge (Idaho, US)
Foskor	Phalaborwa (South Africa)
Yara	Siilinjärvi (Finland)
Apatit	Kola (Russia)
EuroChem	Kovdorskiy GOK (Russia)

The precise global production of elemental phosphorus is not known, it was estimated to be close to 1,200 kt per year according to HDIN Research (2019). The distribution of global production of elemental phosphorus is shown in Figure 20. The main producer in the world is China (78%) followed by USA (11%), Kazakhstan (6%) and Vietnam (%).

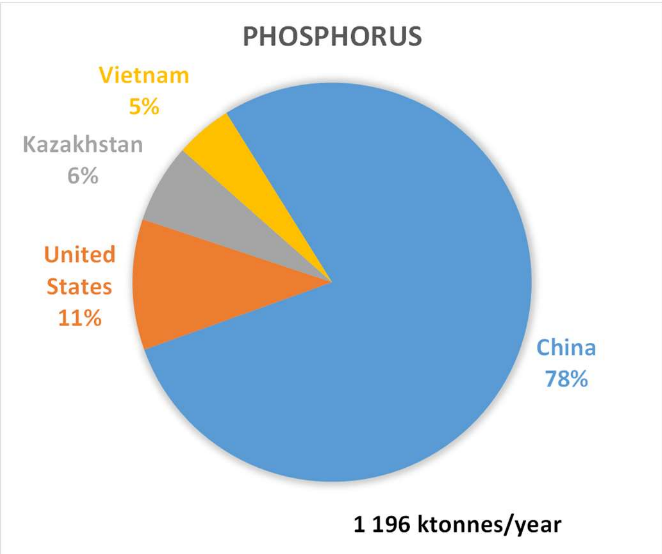

Figure 20 Global elemental phosphorus production, average of 2016-2020 (estimate based on HDIN research, 2019).

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Elemental phosphorus is produced only outside the EU. SCRREEN project listed the most relevant elemental phosphorus manufactures (Table 12).

Table 12 Some of the largest elemental phosphorus manufactures.

Company	Plant location
Yunphos (Taixing) Chemical Co., Ltd.	China
Changzhou Qishuyan Fine Chemical Co. Ltd	China
5-Continent Phosphorus Co. Ltd.	China
Taj Pharmaceuticals Ltd.	India
UPL Europe Ltd.	India
Viet Hong Chemical and Trading Co. Ltd	Vietnam
Kazphosphate LLC	Kazakhstan

OUTLOOK FOR SUPPLY

The COVID-19 pandemic did not have a major effect on the domestic phosphoric rock market in 2020. According to the estimations of industry analysts, the capacity of global phosphoric rock mines was projected to increase to 261 M tonnes in 2024 from 238 million tons in 2020. The most significant mining production increase is going to take place in Algeria, Egypt, Guinea Bissau, Morocco, Senegal, and Togo. Furthermore, new mining projects are planned in US (in Spanish Forks, UT) (USGS, 2021). Phosphoric rock deposits worldwide are considered as enormous. Only the deposits in Morocco are able to cover the world demand for hundreds of years. However, mining limitations are going to be presented due to the environmental impact. It is well known that around 150 Mt of toxic spoil residue is generated annually. Phosphate mine tailings frequently contain uranium, which leads to radon release (mining-technology, 2016).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

For its applications in agriculture, phosphate rock can be replaced by secondary sources of phosphorous such as manure, sewage and food waste (biogenic waste flows).

The EoL-RIR (End-of-Life Recycling Input Rate) should translate the % by which recycling of biogenic waste flows substitutes the use of mineral phosphate fertilisers (i.e. primary input material). An EoL-RIR of 17% was assumed for the criticality assessment based on the raw material system analysis performed in 2015 (BIO Intelligence Service, 2015). Various flows of phosphorus can replace the input from primary phosphate rock. The total size of this flow was estimated by to be around 180 kt of phosphorus in 2012 (BIO Intelligence Service, 2015) (listed as “G.1.2, the production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU”).

Other recycling rates indicators are also reported in the literature. Van Dijk et al. (2016) estimated recycling rates of 70% in crop production, 24% in animal production, 52% in food production and around 76% in non-food applications of phosphorous, in 2015.

There is evidence that increased flows of secondary phosphorous could potentially be extracted and recycled from current production and consumption flows (Sutton, RISE foundation, 2016); (van Dijk et al., 2016); (Leip et al., 2015). Estimates of potential sources of secondary phosphorous are provided by the DONUTSS project

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(2019). Fresh pig manure contains 0.4% of P2O5, whereas dry pig manure has 5% and after incineration the ash contains 18.8%. For chicken litter, these numbers are 1.9%, 3.9% and 15.3% respectively. Kitchen waste generally contains 18.8% of P2O5. Garden waste, another source from households, is much lower given a high cellulose and water content. Additionally, according with the literature the total amount of phosphorus in livestock manure potentially available for recycling in the EU28 from animal production is around 1,749 Mt phosphorus per year (van Dijk et al., 2016) to 1,977 Mt of phosphorus per year (Hermann, 2011).

However, today there is no useable data on the rate of effective reuse of phosphorus for manures and other organic forms, which replaces the use of fertiliser or other phosphate rock derived chemicals. Therefore, there is the need to generate appropriate data and define indicators for this recycling rate, in coherence with indicators for other policies (Circular Economy/Fertilising Products Regulation, Water Framework Directive, CAP, DG Research project impacts) (ESPP, 2019).

Processes exist to potentially produce elemental phosphorus P4 from phosphorus-rich waste streams (e.g. ICL Recophos process to produce P4 from sewage sludge incineration ash or meat and bone meal ash) but these are today only at the pilot scale and no industrial installation is yet under construction, nor operational, neither in the EU nor elsewhere (ESPP, 2019).

Several European countries have created legislation to ensure phosphate recovery, examples of such countries include Germany, Finland and Switzerland and the same is being considered.

Table 13 Material flows relevant to the EOL-RIR of phosphate rock data from 2012, tonnes of P (BIO Intelligence Service, 2015)

MSA Flow	Value (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	70 200
B.1.2 Production of primary material as by product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	511 000
C.1.4 Imports to EU of secondary material	0
D.1.3 Imports to EU of processed material	306 000
E.1.6 Products at end of life in EU collected for treatment	271 000
F.1.1 Exports from EU of manufactured products at end-of-life	377
F.1.2 Imports to EU of manufactured products at end-of-life	135
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU	0
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU	180 000

PROCESSING OF PHOSPHATE ROCK

The most phosphate rock production worldwide is extracted using opencast dragline or open-pit shovel/excavator mining methods, e.g. in the United States, Morocco, Russia and China. During surface mining, overburden is drilled, blasted, and removed by dragline to the side of the mining area for subsequent reclamation. Very large draglines, electric shovels, and bulldozers recover the upper ore body. The

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intercalating limestone layer is then blasted and removed to expose the phosphate bed, which is loaded onto special large volume trucks (MEC, 2016).

Further processing of phosphate rock is needed to produce elemental phosphorus. Elemental phosphorus may be made by several methods. In one process tri-calcium phosphate, the essential ingredient of phosphate rock, is heated in the presence of carbon and silica in an electric furnace or fuel fired furnace, elementary phosphorus is liberated as vapour and may be collected under phosphoric acid, an important compound in making super-phosphate fertilisers (ECI, 2019). Worldwide, a gradual shift to manufacturing high-purity phosphoric acid from wet process acid has taken place because it has lower production costs and none of the hazardous waste disposal issues that are associated with elemental phosphorus (Jasinski, 2016). Production by thermal acid still accounts for more than 50% of annual world production capacity of high-purity phosphoric acid, primarily in China. Further processing of elemental phosphorus will result in compounds such as phosphorus trichloride, acids, sulphides, sodium hypophosphite, phosphine, phosphides.

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Phosphorous is naturally present in the earth, food and is used as dietary supplement. Normal phosphate concentration in adults plasma is 2.5 to 4.5 mg/dL (0.81 to 1.45 mmol/L) (Antwi-Boasiako et al. 2019). Phosphorous deficiency can cause chronic kidney and cardiovascular disease(Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes 1997; Moe et al. 2006; Moore et al. 2015; Da et al. 2015; Hou et al. 2017; Murtaugh et al. 2012).

Table 14 .Recommendations for Consideration from Occupational Safety and Health Administration of the United States for phosphorus related CAS numbers

Chemical	CAS Number[4]	OSHA PEL[5]	CA 8 hr PEL[6]	REL TWA[7]	REL ST/C[8]	MAK ST/C[9]	mg/m^3	PPM
Phosphoric acid	7664-38-2	1	1	1	3ST		x	
Phosphorus (yellow)	7723-14-0	0.1	0.1	0.1			x	
Phosphine	7803-51-2	0.3	0.3	0.3	1ST			x
Phosphorus oxychloride	10025-87-3		0.1	0.1	0.5 ST	0.2		x
Phosphorus pentachloride	10026-13-8	1	0.1	1		1	x	
Phosphorus pentasulfide	1314-80-3	1	1	1	3ST	1	x	
Phosphorus pentoxide	1314-56-3					2	x	
Phosphorus trichloride	7719-12-2	0.5			0.5 ST	0.5	x	

[4] CAS Registry: http://www.cas.org/expertise/cascontent/registry/index.htm
[5] Title 29, Code of Federal Regulations (CFR) 1910, Occupational Safety and Health Standards, Subpart Z, Toxic and Hazardous Substances: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10147
[6] California Code of Regulations, Title 8, Section 5155. Airborne Contaminants. Table AC-1 Permissible Exposure Limits For Chemical Contaminants: http://www.dir.ca.gov/title8/5155table_ac1.html
[7] NIOSH Pocket Guide to Chemical Hazards: http://www.cdc.gov/niosh/npg/pgintrod.html
[8] Short Term/Ceiling
[9] Deutsche Forschungsgemeinschaft (German Research Foundation, DFG), .Maximale Arbeitsplatz-Konzentrationen, MAK-Collection for Occupational Health and Safety, 2010. More information at: http://osha.europa.eu/en/topics/ds/oel/members.stm

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The Occupational Safety and Health Administration of the United States in its Recommendations for Consideration by the U.S. Secretary of Labour on the Adoption and Use of Occupational Exposure Limits by Federal Agencies defined the following CAS Registry Number (Federal Advisory Council on Occupational Safety and Health (FACOSH) 2019):Environmental issues

Phosphorous rock & elemental phosphorous may cause environmental impacts during the mining and production stages. Environmental impacts caused during the mining stage are: changes in land use patterns, habitat loss, dust emissions, water contamination and changes in aquifer regimes (Boeni et al. 2012; European Commission 2011). Contamination of water (underground and surface water) can be linked to products containing phosphorous such as fertilizers(de Ridder et al. 2012; UNEP et al. 2001).

NORMATIVE REQUIREMENTS RELATED TO THE USE AND PROCESSING OF PHOSPHATE ROCK & ELEMENTAL PHOSPHORUS

No relevant normative requirements could be identified.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF PHOSPHATE ROCK & ELEMENTAL PHOSPHORUS FOR EXPORTING COUNTRIES

Table 15 lists the countries for which exports of phosphate and/or phosphate rocks represent a considerable share in the total value of their exports.

Table 15: Share of phosphate and phosphate rock exports in total exports

Country	Export value (USD)	Share in total exports (%)
Togo	85,786,353	8.8
Jordan	342,332,505	4.3
Morocco	772,625,898	2.8
Peru	192,757,015	0.50
Kazakhstan	212,738,827	0.45
Egypt	105,882,710	0.39

Source: COMTRADE (2022), based on data for 2020

For Togo (8.8 %), Jordan (4.3 %) and Morocco (2.8 %), the value of their phosphate and/or phosphate rock exports represent more than 1 % of the total value of their exports. Peru (0.5 %), Kazhakstan (0.45 %) and Egypt export phosphate/phosphate rocks whose value still accounts for more than 0.1 % of their total exports. For all other exporting countries, this share is below 0.1 %.

SOCIAL AND ETHICAL ASPECTS

The Moroccan exports include phosphate/phosphate rocks originating from Western Sahara. The (United Nations 1963) have been listing Western Sahara as Non-Self-Governing Territories since 1963. Starting from 1975 on, (Morocco 2022) has been controlling the largest part of the former Spanish colony which it considers

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to be Moroccan territory. As consequence of the armed Western Sahara conflict over the status of Western Sahara between Morocco and the POLISARIO[10] , the UN Mission (MINURSO 1991)) was established in 1991. The Mission's mandate includes a peacekeeping mission and to conduct a referendum as to the political status of Western Sahara.

Regarding the legality of Morocco's resource exploitation in Western Sahara, the (European Union 2015) "[…] abides by the UN position that 'where resource exploitation activities are conducted in non-self governing territories for the benefit of the people of those territories, on their behalf or in consultation with their representatives, they are considered as legal'."

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES (LCGT)

The Global Phosphorus Market size was valued at USD 9.8 billion in 2017 and is projected to grow at a CAGR of 3% from 2021-2028 (Data Intelo, 2022).

- Catalysis (TRL 2)

Acting as semiconductor photocatalysts, black phosphorous (BP) has been the subject of studies focused on water splitting and vapor removal processes paving the way to the use of solar light in hydrogen and reactive oxygen species production via photo-catalytic approach (Cheng et al. 2021, (Sa et al. 2014; Shen et al. 2015). Furthermore, BP is a promising material for photocatalytic CO_2 reduction applications due to its characteristics of tuneable bandgap, high charge carrier mobility, suitable electronic structure and remarkable photocatalytic activity (Zhao et al., 2021; F. L. Liu et al., 2020).

- Energy storage systems (Anode material-TRL 2-3)

Black phosphorus (BP) is still in its early stage but is a promising anode material for lithium-, sodium-, potassium- and magnesium-ion batteries, as well as lithium-sulphur batteries, lithium–air batteries and supercapacitors. The high specific capacity may lead to a breakthrough in energy storage materials (C. Liu et al., 2020). The use of BP in energy storage systems provides a remarkable market potential in the foreseeable future (Li et al., 2021) in the strongly growing global market for lithium-ion battery anodes of expected USD 21.0 billion by 2026, at a CAGR of 19.9% from 2021 to 2026. (MarketsandMarkets, 2022).

- Recycling of phosphorous from LFP batteries

There are examples of processes developed at laboratory scale on P recovery from End-of-Life LFP batteries to be reintroduced in new production cycles. For example, in the work of Sun *et al*. (2020) the resynthesized $LiFePO_4$/C materials display excellent physical, chemical and electrochemical

[10] Popular Front for the Liberation of Saguia el-Hamra and Rio de Oro

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performances, meeting the reuse requirement for LIBs. In the work of Zheng *et al*. (2016), the recovered $FePO_4$ was used as raw material to synthesize high performance $LiFePO_4$.

- Optoelectronics (TRL 2-3)

Two-dimensional BP (phosphorene) was proved to be ideal for photodetector applications in a significant advantage over graphene-based devices (Youngblood et al., 2015).
Additionally, BP-based heterostructures have been exploited as room-temperature LEDs (Chang et al., 2021). Introducing 2D materials into silicon photonic devices will greatly promote the performance of optoelectronic devices, including improvement of response speed, reduction of energy consumption, and simplification of fabrication process.

The widespread implementation of efficient lighting such as LEDs is expected to decrease for 85 % the current energy consumption related to lighting, i.e. 15 % of the world's electricity and 5 % of greenhouse gas emissions (United Nations Environment Programme, 2017). (Cheng et al. 2021). The size of the optoelectronics market is expected to reach USD 9.83 billion by 2026 with a CAGR[11] of 10.25 % since 2021 (Mordor Intellingence Opto, 2022).

- Photovoltaics (TRL 3)

PV systems are a low carbon green technology (Rabaia et al., 2021). BP is a promising material for solar cells allowing power generation for illumination wavelengths up to near-infrared spectrum. BP may play an important role in the solar cells research to achieve high power conversion efficiency and low cost (Buscema et al., 2014, Chen et al., 2020) with good perspectives in the global PV module market expected to reach $260.2 billion by 2030, growing at a CAGR of 7.4 % from 2021 (AlliedMarket Research Solar, 2022).

OTHER RESEARCH AND DEVELOPMENT TRENDS

PHOSPHOR[12] project (2017 – 2019, EU)

A longstanding problem in combustion research is that there is no means to simultaneously measure the temperature and velocity in high-temperature, chemically reacting flows, which is essential to probe complex turbulence-chemistry interactions found in advanced combustion systems. The aim of this project is to solve this problem using a novel laser-based temperature-velocity imaging technique which uses thermographic phosphor particles as a flow 'tracer'. The primary objective of the action is to increase the measureable temperature range via synthesis of new phosphor particles optimised for flow temperature sensing. Such sensors will enable completely new measurement capabilities for fundamental and applied research, allowing the design of cleaner, fuel-efficient engines in key automotive, aerospace and power generation industries, thereby using less resources and reducing environmental impact. The novel materials will also find uses in lighting and display technologies and biological sensing.

[11] Compound Annual Growth Rate
[12] See https://cordis.europa.eu/project/id/708068

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