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Perspective

Sulfur, Not Phosphorus: The Hidden Bottleneck in Wet-Process Phosphoric Acid Production—A Risk to Sustainable Food Security

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Abstract

Phosphorus is essential for food production and cannot be substituted, so a secure, sustainable phosphate supply is central to food security (SDG 2). We argue that, for the wet process that dominates phosphoric acid production, the binding short-term constraint has shifted from phosphate rock to sulfur. Wet-process phosphoric acid consumes 2.30 t of sulfuric acid per tonne of P_2O_5 stoichiometrically and an estimated 2.7 t in practice, and phosphate fertilizers account for roughly half of world sulfuric acid consumption. The static lifetime of phosphate rock reserves is about 290 years, whereas sulfur is mainly a by-product of oil and gas processing, regionally concentrated and exposed to maritime chokepoints. The closure of the Strait of Hormuz in 2026, amid Russian and Chinese export controls, provided a real-world test: sulfur prices reached record levels, the estimated value of sulfur consumed per tonne of diammonium phosphate rose, at spot prices, from under 7% to about 49% of its price, and producers relying on sulfur imports curtailed output. As decarbonization reduces by-product sulfur, climate action and food security pull in opposite directions. Criticality assessments should include the sulfur dependency of phosphorus production, and sulfur-free routes must turn calcium into a product, not waste.

Keywords: critical raw materials; phosphate; sulfur; sulfuric acid; fertilizer; supply chain resilience; Strait of Hormuz; process replacement

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1. Introduction

Phosphorus (P) is essential to all life and cannot be substituted in agriculture. Phosphate rock and elemental phosphorus (P_4) are both listed as critical raw materials in the Critical Raw Materials Act of the European Union (EU) [1]. A raw material is considered critical when it combines high economic importance with a high risk of supply disruption, and when substitution, recycling, stockpiling or alternative sources cannot sufficiently mitigate that risk [2]. What society needs, however, is not a raw material as such but the function it provides, namely soil fertilization. Demand for phosphate fertilizer will continue to rise:

the United Nations projects the world population to grow from 8.2 billion in 2024 to about 9.7 billion in 2050, peaking at about 10.3 billion in the mid-2080s [3], and dietary transitions in emerging economies increase per capita demand for fertilizer-intensive foods [4]. A secure supply of phosphate fertilizers is therefore central to Sustainable Development Goal 2 (zero hunger), and producing them with fewer fossil inputs and less waste is part of Goal 12 (responsible consumption and production) [5]. Phosphorus supply also links these goals with Goal 13 (climate action): the decarbonization of the energy system reduces the supply of by-product sulfur on which most phosphate fertilizer production depends (Section 3.2), so that progress towards one goal can put another at risk.

Criticality assessments of phosphorus usually focus on phosphate rock: its geological availability, the concentration of reserves, above all in Morocco, and of production in China, and the long-running "peak phosphorus" debate [6,7]. Material-flow analyses further show that, although global phosphate flows appear only moderately concentrated, the import dependence of individual countries can be considerably higher [8]. Much less attention has been paid to the chemistry by which phosphate rock is turned into usable products. In this Perspective, we argue that this chemistry shifts the critical short-term dependency of the dominant production route from phosphate rock to sulfur. The claim is specific: it concerns the wet process and the producers that depend on traded sulfur, and it does not imply that phosphate rock carries no supply risk (Section 2). The dominant production route for phosphoric acid—the precursor for most phosphate fertilizers and many phosphorus chemicals—consumes large amounts of sulfuric acid, which is made predominantly from sulfur recovered as a by-product of oil and gas processing.

Our argument builds on, and differs from, the work of Maslin et al. [9], who warned that decarbonization will reduce the supply of by-product sulfur while demand for sulfuric acid grows, notably for metal leaching in the energy transition. Maslin et al. focus on a long-term structural shortfall. We add two elements: a process-chemistry perspective, in which criticality is a property of the production route rather than of the element, and a short-term perspective, in which sulfur supply is exposed to chokepoints and trade policy. The events of 2025 and 2026 which comprise Russia's sulfur export ban, the closure of the Strait of Hormuz, and China's export restrictions on sulfuric acid and phosphate fertilizers, allow us to examine this argument against observed market behavior. Our earlier Perspective [10] showed that phosphoric acid production depends on sulfuric acid derived from fossil by-products, discussed its environmental burdens, including phosphogypsum, and presented sulfur-free alternative digestion routes. The present paper extends that analysis in three respects: it documents the disruptions of 2025 and 2026 and their transmission to phosphate production, distinguishes three channels through which sulfur supply can be disrupted, and compares nine process routes on common criteria, examining the fate and saleability of each route's calcium by-product (Section 5.4). Box 1 summarizes the phosphorus terms and units used in this paper.

Box 1. Phosphorus terms and units.

P, P_4: Phosphorus as an element, and elemental (white or yellow) phosphorus, which is produced by the thermal process in electric furnaces.

P_2O_5: The convention by which phosphate contents are expressed. One kilogram of P corresponds to 2.29 kg of P_2O_5.

Phosphate rock: The mined ore, mainly apatite, $Ca_5(PO_4)_3(F,OH,Cl)$. Its grade is given in % P_2O_5.

Wet chemical process (WCP): Digestion of phosphate rock with sulfuric acid, which yields phosphoric acid and phosphogypsum ($CaSO_4 \cdot 2H_2O$). Merchant-grade acid contains 52–54% P_2O_5.

Phosphate fertilizers: Nutrient contents are given as N–P_2O_5–K_2O in %. DAP, diammonium phosphate (18-46-0). MAP, monoammonium phosphate (11-52-0). TSP, triple superphosphate (0-46-0). SSP, single superphosphate (about 16–20% P_2O_5). SSP is made by digesting rock directly with sulfuric acid, TSP by digesting rock with phosphoric acid.

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2. Phosphorus Criticality Reconsidered

Geological scarcity of phosphorus is not imminent. World phosphate rock reserves are estimated at about 73 billion tonnes and resources at more than 300 billion tonnes, compared with a mine production of about 250 million tonnes in 2025 [11]. The static reserve lifetime is thus about 290 years and the static resource lifetime about 1200 years. Earlier "peak phosphorus" warnings of imminent scarcity [6] have been challenged on methodological grounds, and reserves have repeatedly been revised upward as exploration and processing technology advance [7].

Supply is, however, highly concentrated (Figure 1). Morocco holds about 68% of world reserves, while China accounts for about 44% of mine production [11]. Criticality may therefore arise from economic accessibility, trade policy and geopolitical disruption rather than from geological availability. The static lifetime is a global indicator of geological sufficiency. It says nothing about the availability of rock of suitable grade and impurity content in individual markets, which depends on mining and beneficiation capacity, transport and trade policy. These rock-related risks remain, and our argument does not replace them. It adds a second, chemically determined dependency that has received less attention.

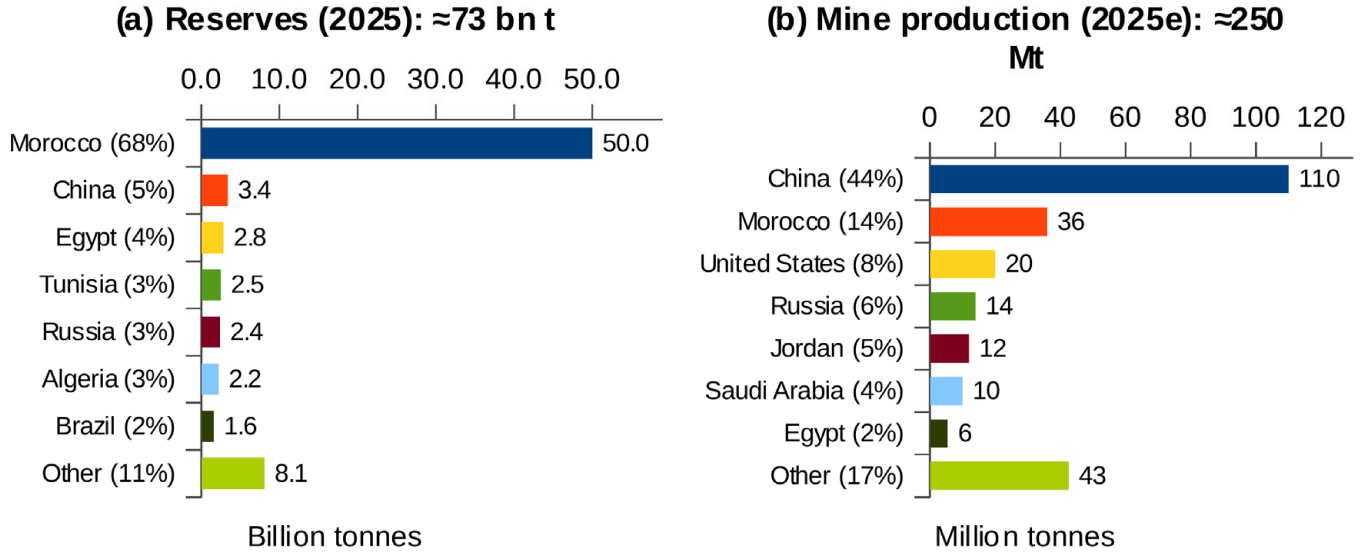


Figure 1. Phosphate rock reserves (**a**) and mine production (**b**) by country, 2025; gross weight. World resources exceed 300 billion tonnes (data from Jasinski [11]).

The data shown in Figures 1, 2 and 4 were compiled from the cited sources with the assistance of Claude (Anthropic) and checked by the authors against the original publications. All values, sources and calculations are documented in Supplementary Files S1 and S2.

Phosphate fertilizer prices have been volatile (Figure 2). The annual average price of triple superphosphate (TSP) rose from about 265 USD/t in 2020 to about 716 USD/t in 2022 (+170%) and has since remained at roughly twice its pre-2020 level. Several drivers contributed. For the 2008 price peak, Khabarov and Obersteiner [12] identified a sharp decline of India's domestic production of phosphate fertilizers, particularly diammonium phosphate (DAP), which substantially increased import demand. This disruption was amplified by an Indian fertilizer subsidy scheme that limited farmers' demand response to rising prices, and by protective export measures of major suppliers, including China's introduction of a 100% export tax on fertilizers in April 2008. China has restricted phosphate fertilizer exports again since 2021, and in 2026 suspended most monoammonium phosphate (MAP), DAP and nitrogen–phosphorus–potassium (NPK) fertilizer exports [13]. Mew et al. [14] confirm these drivers. They find that, unlike in 1975, oil prices and the US dollar

played no major role in 2008, and they note that a market in which few suppliers can enforce higher prices leaves room for future peaks.

Figure 2 also shows a recurring co-movement that has received less attention: the price of sulfur. The average US unit value of elemental sulfur rose about sevenfold between 2007 and 2008, from 36 to 262 USD/t, and roughly doubled between 2021 and 2022 [15–22]. In 2026, spot prices on international benchmarks reached about 800–1200 USD/t depending on market and quotation basis (Table 1) [23,24], whereas triple superphosphate averaged about 705 USD/t in the third quarter of 2026, 22% above its 2025 average [25]. Phosphate rock, by contrast, stayed at 170 USD/t throughout the third quarter of 2026, only about 11% above its 2025 average of 152.5 USD/t [25]. Since 2024, DAP prices in the US Corn Belt and spot sulfur prices at Vancouver have been correlated with a coefficient of 0.70 [24]. The remainder of this article explains why this co-movement is structural rather than coincidental.

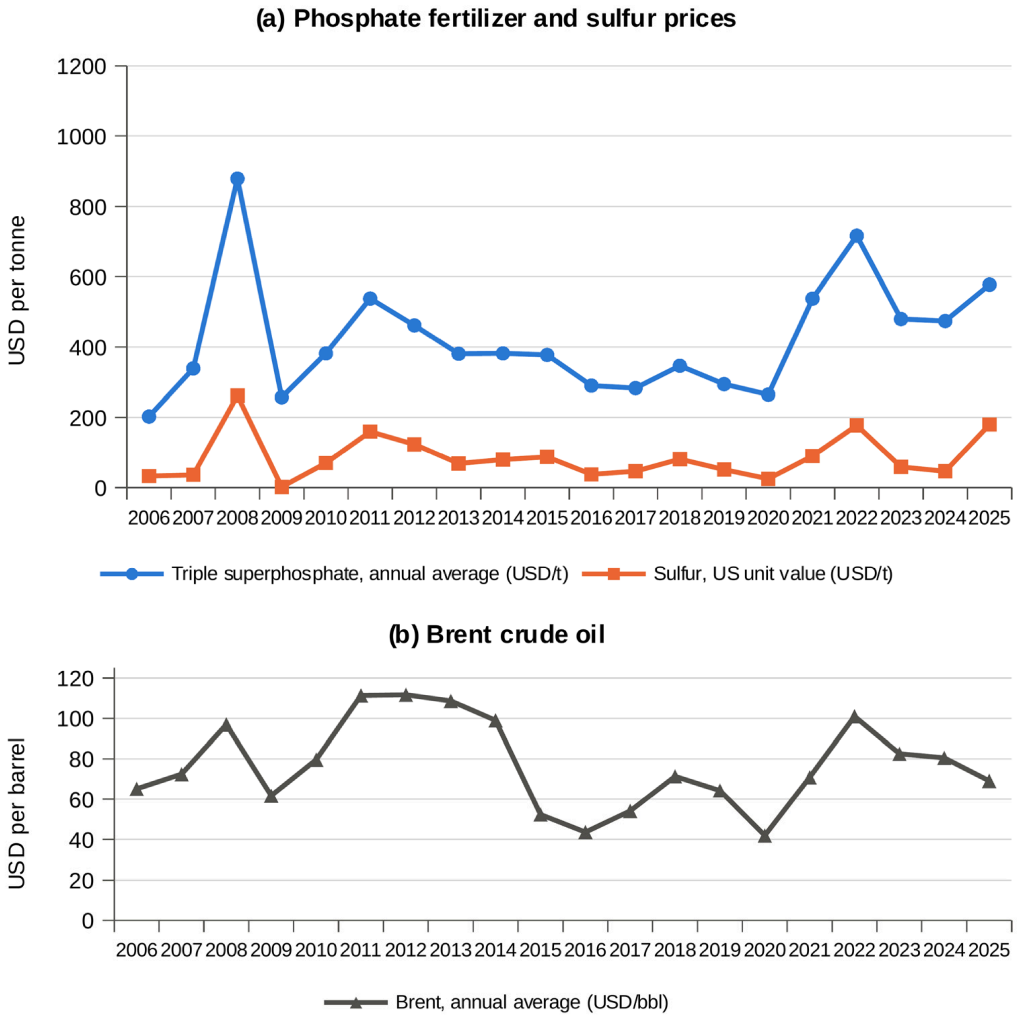


Figure 2. (**a**) Annual prices of triple superphosphate (TSP) and sulfur, 2006–2025. (**b**) Brent crude oil price, 2006–2025. The panels use separate axes because the units differ (USD per tonne and USD per barrel). Sulfur: US average unit value, f.o.b. mine/plant [15–22]. Triple superphosphate: World Bank data via Indexmundi [26], 2006: August–December only; Brent: EIA [27,28]. Values for 2026 are spot quotations, contract prices or partial-year averages from different markets. They are not comparable with the annual series and are therefore given separately in Table 1.

Table 1. Price quotations for 2026 by market, basis and period, shown separately from the annual series in Figure 2.

Product	Market and Basis	Period	Price	Source
Sulfur	Middle East, spot, FOB	End of May 2026	815–820 USD/t	[23]
Sulfur	Brazil, spot, CFR	End of May 2026	1200 USD/t	[23]
Sulfur	Vancouver, spot	August 2026	About 1040 USD/short ton	[24]
Sulfur	Middle East, monthly contract, FOB	October 2026	820–890 USD/t	[29]
Sulfur	United States, quarterly contract (Mosaic)	Q3 2026	705 USD/long ton	[30]
Sulfur	Average consumed price, Mosaic, Brazil	Q1 2026	466 USD/long ton	[31]
Sulfuric acid	United States/Germany/Brazil, quarterly average	Q2 2026	276/290/403 USD/t	[32]
Sulfuric acid	Chile, spot	Mid-April 2026	About 380 USD/t	[33]
Sulfuric acid	IEA benchmark	April 2026	283 USD/t	[34]
DAP	US Corn Belt	August 2026	About 850 USD/short ton	[24]
Triple superphosphate	World Bank, average	Q3 2026	704.6 USD/t	[25]
Phosphate rock	World Bank (Morocco), average	Q3 2026	170 USD/t	[25]
Brent crude oil	Europe Brent spot, average	Q3 2026	96.3 USD/bbl	[27,28]

FOB = free on board, CFR = cost and freight, long ton = 1.016 t, short ton = 0.907 t. Paulson et al. [24] give prices per ton. As a US source with prices converted by the authors, we read these as short tons. The quotations differ in market, basis and period and are not directly comparable with each other or with the annual series in Figure 2. Underlying values: Table S3.

3. The Sulfur Bottleneck in Phosphoric Acid Production

3.1. Sulfuric Acid Dependency of the Wet Process

Phosphoric acid (H_3PO_4) is produced predominantly by the wet chemical process (WCP), in which phosphate rock is digested with sulfuric acid (Figure 3). In the United States, for example, more than 95% of mined phosphate rock is used to make wet-process phosphoric acid [11]. For fluorapatite, the overall reaction is

$$Ca_5(PO_4)_3F + 5\,H_2SO_4 + 10\,H_2O \rightarrow 3\,H_3PO_4 + 5\,CaSO_4{\cdot}2H_2O + HF \quad (1)$$

The stoichiometric demand calculated from Equation (1) is 2.30 t H_2SO_4 per tonne of P_2O_5. Practical consumption is not reported consistently, so we estimate it indirectly from the sulfur input of about 0.4 t per tonne of DAP (46% P_2O_5) stated by industry sources [23,24]. This corresponds to about 0.87 t of sulfur, or 2.7 t H_2SO_4 (100%), per tonne of P_2O_5, roughly 15% above stoichiometry, because carbonates and other impurities in the rock also consume acid. The figure of 2.7 t is therefore an estimate, not a measured plant value. The process generates about 5 t of phosphogypsum per tonne of P_2O_5 (stoichiometric minimum: 4.0 t), most of which is stacked [10,35]. The acid also carries rare earth elements and uranium from the rock, whose recovery as by-products has been studied [36]. The wet process itself requires only about 120–180 kWh of electricity and 0.5–2.2 t of steam per tonne of P_2O_5 [35]. In integrated plants, this steam comes largely from burning sulfur in the sulfuric acid plant, and Belboom et al. [37] show that this energy integration reduces the climate-change impact of a Belgian plant by 80%. A modern sulfur-burning double-contact plant can recover 5.2–5.8 GJ of steam per tonne of H_2SO_4, of which 3.1–3.4 GJ is high-pressure steam (energy balance for 1000 t/d H_2SO_4) [38]. This is close to the standard reaction enthalpy of about 5.4 GJ per tonne (Table S7). At 2.7 t H_2SO_4 per tonne of P_2O_5,

this corresponds to roughly 8–9 GJ of high-pressure steam and 14–15 GJ of total recoverable steam, compared with the phosphoric acid plant's reported steam demand of 0.5–2.2 t per tonne of P_2O_5 (approximately 1–6 GJ, depending on steam conditions), so an integrated wet-process complex is a net energy exporter. In practice, OCP reports that cogeneration from the waste heat of sulfuric acid production provides 380 MW of thermal energy and has made its Jorf Lasfar site self-sufficient in electricity, with a surplus supplied to the national grid [39]. The vulnerability of the wet process therefore lies not in its energy demand but in its sulfur supply. This conclusion depends on the energy-integration boundary, actual steam utilization and site-specific operating conditions. Recoverable steam is not automatically equivalent to exported useful energy.

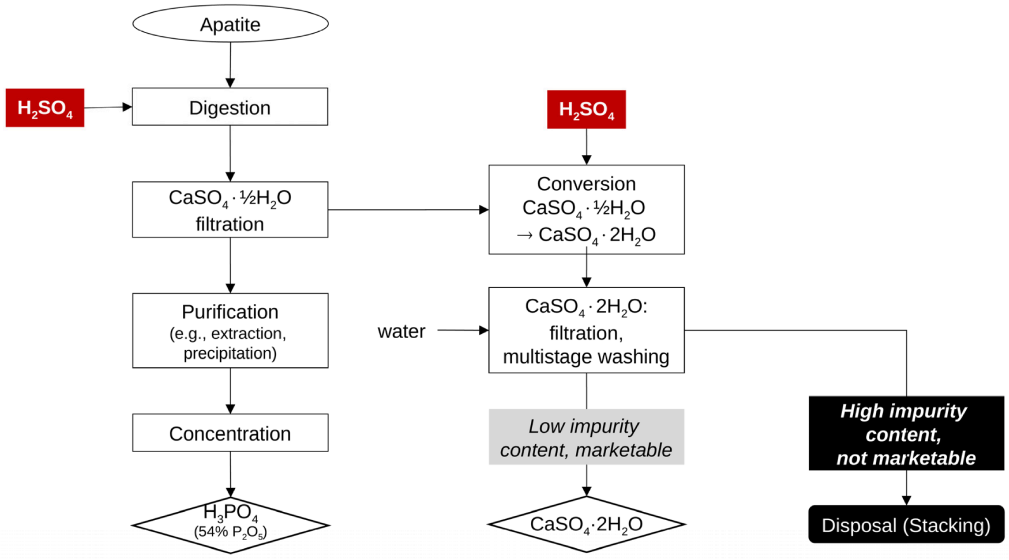


Figure 3. Simplified wet chemical process (WCP) for phosphoric acid production (hemihydrate–dihydrate variant). Purification removes impurities such as heavy metals. Sulfuric acid inputs are shown in red. Only phosphogypsum with a low impurity content is marketable, while the remainder is stacked. Modified and adapted from [10].

Within the wet process, sulfuric acid cannot be substituted: it supplies both the protons for digestion and the sulfate that removes calcium as gypsum. The sulfur dependency is therefore a property of the dominant production route. Alternative digestion routes that avoid sulfuric acid exist (Section 5.3), but together they account for only a small share of global phosphoric acid production.

3.2. Sulfur Supply: By-Product Status, Concentration and Market Exposure

World sulfur production in all forms was about 84 million tonnes in 2025 [40], and about 90–95% of the elemental sulfur recovered is used to manufacture sulfuric acid [41]. Unlike phosphate rock, sulfur is rarely mined for its own sake: about 95% of elemental sulfur is recovered as a by-product of oil refining and natural-gas processing [9,42,43], and in the United States the share is about 97% [40]. Burning this sulfur supplied about 60% of global sulfuric acid production in 2022. A further 30% came from sulfur dioxide in the off-gas of non-ferrous metal smelters, and the remaining 10% from pyrite roasting (6%), spent-acid recycling (2%) and other processes (2%) [42], as shown in Figure 4. About 90% of the world's sulfuric acid therefore depends on by-products of the oil, gas and metals industries, whose output is not driven by acid demand [42].

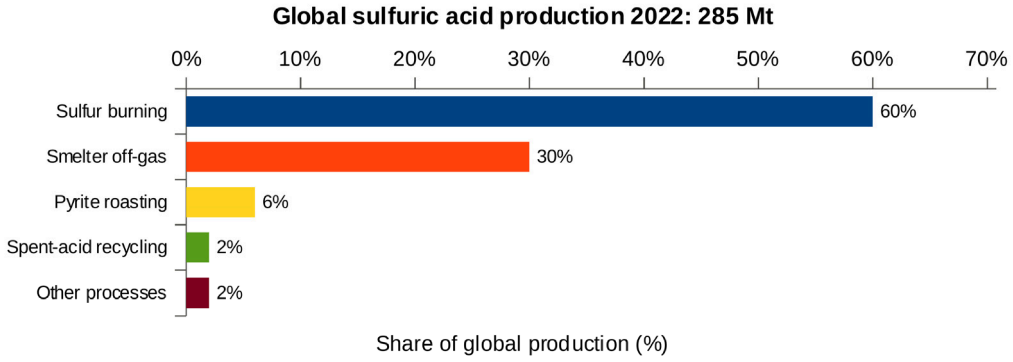


Figure 4. Sources of global sulfuric acid production in 2022 (total 285 Mt): sulfur burning 172 Mt, smelter off-gas 86.3 Mt, pyrite roasting 17.8 Mt, spent-acid recycling and other processes about 2% each [42]. Stoichiometrically, 1 t of sulfur yields 3.06 t of H_2SO_4 (100%).

Global sulfuric acid production was about 285 Mt (100% H_2SO_4) in 2022 and has grown by 2.2% per year since 2010 [42], whereas Maslin et al. [9] give an earlier and lower estimate of 246 Mt. Estimates of the phosphate share differ with the definition used. S&P Global puts phosphate fertilizers at about 60% of world sulfuric acid consumption in 2023 [44]. CRU gives 47% for phosphate fertilizers in 2022, while acid demand for all phosphoric acid production, including non-fertilizer grades, was 146.7 Mt and for single superphosphate 10.3 Mt, together 55% of world production [42]. We therefore use "roughly half" as a robust figure. Sulfur statistics also use different bases: sulfur in all forms (including sulfur recovered in smelter acid and from pyrite), elemental sulfur, and sulfuric acid expressed as 100% H_2SO_4. Table 2 brings the available figures together with their year, basis and source. Public data do not allow the balance to be closed, and inventories in particular are not available as a consistent series. Smelter acid cannot easily fill a sulfur gap. It is produced wherever the smelters are, and most of it is consumed on site or sold under long-term contracts, and only about 7% of world sulfuric acid production enters trade [44], roughly 17–20 Mt per year or about a tenth of the phosphate industry's needs.

Table 2. Global sulfur and sulfuric acid figures with their basis, year and source. The figures cannot be combined into a closed balance.

Quantity	Value	Basis	Year	Source
Sulfur production, all forms	84 Mt	S, incl. sulfur recovered in smelter acid and from pyrite	2025	[40]
Sulfur supply	70.8 Mt	S, CRU definition	2025	[45]
Sulfur demand	72.8 Mt	S, CRU definition	2025	[45]
Global sulfur trade, all modes	39–40 Mt	S	2025	[45]
Seaborne sulfur trade	29.4 Mt	S	2025	[46]
Share of the Gulf states in seaborne sulfur trade	Nearly half	—	2025	[23,47]
Sulfuric acid production	285 Mt	100% H_2SO_4	2022	[42]
Sulfuric acid entering trade	About 7% of production (17–20 Mt)	100% H_2SO_4	Recent years	[44]
Acid demand of phosphoric acid production	146.7 Mt (≈48 Mt S equivalent)	100% H_2SO_4, all grades of phosphoric acid	2022	[42]

Table 2. *Cont.*

Quantity	Value	Basis	Year	Source
Acid demand of single superphosphate	10.3 Mt	100% H_2SO_4	2022	[42]
Sulfur and acid inventories	Not available	No consistent public series	—	Not available

1 t S yields 3.06 t H_2SO_4 (100%). The sulfur equivalent of acid demand includes acid made from smelter off-gas and pyrite, which does not require elemental sulfur. Production and demand figures from different sources use different definitions and are not additive.

Sulfur supply is also concentrated. China is the largest producer (about 23% of world output) but is itself a net importer. The Gulf states (Saudi Arabia, the United Arab Emirates, Qatar, Kuwait and Iran) produce about 24% of the world's sulfur but, because their domestic demand is small, account for nearly half of global seaborne sulfur trade [23,40,47]. Russia, the third-largest producer after China and the United States, accounts for about 9% [40].

Sulfur is not geologically scarce: resources associated with fossil fuels and sulfide ores are about 5 billion tonnes, and gypsum and anhydrite contain almost limitless amounts [40]. Large stockpiles have accumulated in the past, for example in Canada and Kazakhstan. The supply risk therefore arises not from scarcity but from three features: (i) sulfur supply depends on the throughput of oil and gas processing rather than on sulfur demand, (ii) sulfur is concentrated in a few exporting regions, and (iii) it moves along a small number of maritime routes.

Structural trends add to this exposure. Refinery closures and lower refinery runs in Europe reduced liquid sulfur availability and forced some sulfur burners in the Benelux region to shut down as early as 2025 [48]. Demand from metal leaching is growing rapidly: sulfuric acid demand from Indonesia's high-pressure acid leaching of nickel ores rose from 3.5 Mt per year in 2021 to 16 Mt per year in 2025 [49], and sulfur demand for metals leaching is projected to roughly double to 24.6 Mt by 2050 [50]. Maslin et al. [9] project that global sulfuric acid demand could rise from 246 to 400 Mt by 2040, while decarbonization reduces by-product sulfur supply, leading to an annual shortfall of 100–320 Mt depending on the pace of decarbonization. This is a long-term scenario. For the near term, CRU estimated a deficit of about 1.9 Mt of sulfur in 2025 and expects the market to remain in deficit until 2028 [45]. The sulfur and sulfuric acid markets were therefore already tight before 2026. Sulfur prices rose sharply in 2025, partly because exports from Kazakhstan and Turkmenistan declined [51], and European acid producers faced rising sulfur costs [52]. OCP's financial statements for 2025 document this tightening. The Middle East sulfur price rose from about 165 USD/t FOB at the beginning of 2025 to almost 520 USD/t in December. Supply in the fourth quarter was about 1.0 Mt lower because Russian volumes were missing and plants in the Middle East had unplanned maintenance, and stocks in Kazakhstan, Turkmenistan and Iran that could otherwise have filled the gap were exhausted. OCP's average sulfur purchase price more than doubled from 113 USD/t CFR in 2024 to 229 USD/t CFR in 2025 [53]. In February 2026, before the closure of the Strait of Hormuz, sulfuric acid prices in Italy reached a record level that analysts attributed to a product shortage across Europe [51].

3.3. Evidence from 2025 to 2026

The events of 2025–2026 provide a real-world test for the argument made here. Three disruptions overlapped. In November 2025, Russia banned exports of technical sulfur to stabilize supply to its domestic fertilizer industry, after drone strikes in September 2025 had damaged the Astrakhan and Orenburg gas processing plants. The ban was introduced by government resolution on 1 November 2025 and has since been extended three times, most recently to 31 December 2026 [54–58]. In September 2026, Russia also restricted exports

of sulfuric acid until the end of the year and now permits them only with government approval [59]. On 28 February 2026, the outbreak of war in the Middle East closed the Strait of Hormuz to most commercial shipping [23]. Apart from a brief, partial resumption between mid-June and mid-July, the strait remained effectively closed in mid-September 2026 [60]. On 10 April 2026, it was reported that China had instructed producers to halt exports of smelter acid from May, after China had exported 4.65 Mt in 2025 [61,62]. We could not locate the official notice. According to SunSirs, the Ministry of Commerce and the General Administration of Customs suspended the export clearance of industrial and smelter sulfuric acid from 1 May to the end of 2026, and customs data show acid exports of 0.78 Mt in January–June 2026, against 2.19 Mt a year earlier, with only 980 t in June [63]. A chronology of the events, distinguishing announcements, implementation, observed trade effects and forecasts, is given in Table S6 of the Supplementary Materials.

The effects on sulfur were immediate. Global sulfur exports fell by 33% in the first half of 2026, and shipments from the Gulf states fell by 41–50% [60]. Sulfur prices reached all-time highs: 815–820 USD/t free on board (FOB) Middle East and 1200 USD/t cost and freight (CFR) Brazil at the end of May 2026 [23], and more than 1000 USD/t at Vancouver in August 2026, compared with less than 100 USD/t in January 2024 [24]. Average sulfuric acid prices in the second quarter of 2026 were 2.3 to 2.8 times the first-quarter level, at about 276 USD/t in the United States, 290 USD/t in Germany and 403 USD/t in Brazil [32]. The difference between European and US acid prices, by contrast, has fluctuated and even reversed [32]. According to the International Energy Agency (IEA), sulfuric acid prices doubled from 144 USD/t in February 2026 to 283 USD/t in April 2026, and the price of purified phosphoric acid, a precursor of the battery cathode material lithium iron phosphate (LFP), rose by about 50% [34].

The effect on phosphate production followed. With about 0.4 t of sulfur per tonne of DAP, the sulfur input accounted for less than 7% of the US DAP price in early 2024 (sulfur below 100 USD, DAP 600–700 USD per short ton) but for about 49% in August 2026 (sulfur about 1040 USD, DAP about 850 USD per short ton) (Vancouver spot sulfur and Corn Belt DAP, calculated from Paulson et al. [24]). This is an illustrative indicator of price exposure, the ratio of the estimated value of the sulfur consumed to the DAP price, and not a producer cost share. It overstates the cost pressure on producers that buy sulfur under quarterly contracts or hold inventories. Mosaic, for example, reported an average consumed sulfur price of 466 USD per long ton for its Brazilian operations in the first quarter of 2026, and its US sulfur contracts for the third quarter settled at 705 USD per long ton, both well below spot [30,31]. At the third-quarter contract price of 705 USD per long ton, about 629 USD per short ton, the same calculation gives about 30% instead of 49%. The Moroccan producer OCP had secured sulfur stocks ahead of the price increase [64]. The ratio therefore shows the direction and approximate size of the price exposure, not industry-wide manufacturing margins. Producers responded with curtailments (Table 3). Table 3 separates the reasons stated by the companies from other factors documented in the same period. Mosaic first idled single superphosphate production at two Brazilian plants in December 2025, citing the sharp increase in sulfur prices [65]. In April 2026 it announced the idling of its Araxá complex and of mining at Patrocínio, to reduce costs and redeploy capital [66]. In May 2026 it withdrew its phosphate production guidance, stating that sulfur had hit record prices because of limited availability, and began partial curtailments in Louisiana and Florida [67]. In July it announced further reductions in the United States and Brazil because of curtailed raw material supply availability. According to Argus, the company stated that sulfur inventories were declining, and it told S&P Global that it had adjusted its Brazilian production amid reduced global supply and rising sulfur prices [68,69]. It tied the duration of the restrictions to the reopening of international

shipping routes [69]. In its results for the third quarter, Mosaic stated that it had aligned phosphate production with the availability of affordable sulfur [70], and its quarterly report named constrained raw material availability and limited customer credit availability in Brazil as reasons for lower production [71]. In early November 2026, Mosaic reported that spot sulfur prices had begun to fall but were still too high to restart curtailed production, and it expected global phosphate supply to remain constrained into 2027 [72]. According to a source at the company, the Egyptian Financial & Industrial Co. began maintenance at its three granular superphosphate plants on 21 May 2026 because of high sulfur costs [23]. The shortage was not confined to fertilizer production. Copper producers that extract the metal by sulfuric acid leaching, about one fifth of world copper output, competed for the same acid. In Chile, the spot price of sulfuric acid doubled to about 380 USD/t between late February and mid-April 2026, and analysts expect high prices to divert acid from fertilizer production to mining [33]. In this competition, phosphate fertilizer producers, with their low margins, are the weaker buyers. Integration from rock to fertilizer did not protect producers that import their sulfur. In the first half of 2026, the revenue of the Moroccan OCP Group fell by 7.3% and its earnings before interest, taxes, depreciation and amortization (EBITDA) by 28.5% year-on-year, and the group reported a net loss attributable to its shareholders of 2.84 billion Moroccan dirhams (MAD) [73]. According to OCP, sulfur prices roughly tripled in this period, while fertilizer prices rose by only about 20%. OCP shifted its exports toward triple superphosphate, whose share of its fertilizer export volumes rose from 26% to 35% [74]. Triple superphosphate requires no ammonia and less sulfuric acid per tonne of P_2O_5 than ammonium phosphates, because part of its phosphorus comes from rock that is digested with phosphoric acid. OCP named higher ammonia prices and weaker import demand in major markets alongside sulfur [64]. By its own comparison, Ma'aden, which has access to sulfur and ammonia produced in Saudi Arabia, kept the highest EBITDA margin among the major producers in the first half of 2026 (33%) [75].

Table 3. Production curtailments and adjustments in 2025–2026: reasons stated by the companies and other documented factors.

Producer and Action	Date	Reason Stated by the Company	Other Factors Documented	Source
Mosaic: SSP production idled at Fospar and Araxá, Brazil	December 2025, extended January 2026	Sharp increase in sulfur prices.	Before the Hormuz closure, with the Russian sulfur export ban in force.	[54,65]
Mosaic: Araxá complex idled and offered for sale, mining at Patrocínio idled, about 1 Mt per year less phosphate production	8 April 2026	Reduce costs and redeploy capital.	Limited effect on adjusted EBITDA expected by the company given elevated sulfur prices.	[66]
Mosaic: phosphate production guidance withdrawn, partial curtailments in Louisiana and Florida, Brazil scaled back	May 2026	Sulfur at record prices because of limited availability.	Production and logistics disruptions for ammonia also named.	[67]
Mosaic: further reductions at four US plants and in Brazil	July 2026	Curtailed raw material supply availability. Declining sulfur inventories, reduced global supply and rising sulfur prices (statements reported by Argus and S&P Global).	Duration tied by the company to the reopening of international shipping routes.	[68,69]

Table 3. *Cont.*

Producer and Action	Date	Reason Stated by the Company	Other Factors Documented	Source
Mosaic Fertilizantes: lower production	Q3 2026	Constrained raw material availability. Production aligned with the availability of affordable sulfur.	Limited customer credit availability in Brazil.	[70,71]
EFIC, Egypt: maintenance at three granular SSP plants	From 21 May 2026	High sulfur costs (company source).	None reported.	[23]
OCP, Morocco: product mix shifted to TSP, maintenance brought forward	First half of 2026	Limited availability and exceptionally high price of sulfur.	Higher ammonia prices, lower import demand in India, Europe and Africa.	[64]

Reasons are given as stated by the companies or, where indicated, by trade press. The table does not quantify the contribution of each factor. SSP = single superphosphate, TSP = triple superphosphate.

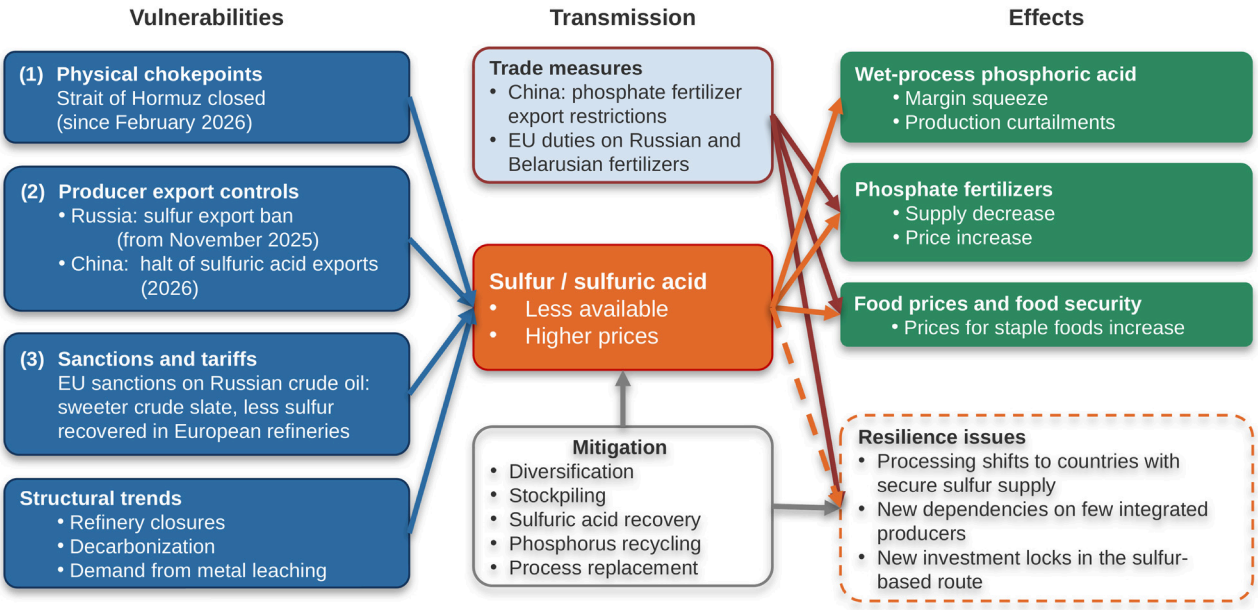
These observations support our central argument for the producers documented here. Phosphate rock remained available throughout, while Mosaic also curtailed phosphate-rock mining operations in Brazil in the same period in which it reported constrained raw material availability [66,68]. At the same time, the market partially absorbed the shock. According to IFPRI, global phosphate fertilizer exports fell by only 9% in the first half of 2026, as non-Gulf exporters increased shipments, and phosphate fertilizer prices rose by 25–30% after the closure [60]. OCP put the contraction of traded volumes at about 22% [64]. Sulfur did not halt phosphate production globally. For wet-process producers that depend on imported sulfur, however, it was the input whose price and availability the companies themselves cited most often when curtailing output (Table 3). Other factors, notably ammonia costs, weaker import demand and, in Brazil, limited customer credit, contributed as well. Public data do not allow these factors to be separated quantitatively, and we do not claim that sulfur was the sole cause.

At the time of writing (early November 2026), the strait remained closed to most commercial shipping. Iran let vessels from selected countries, including China, India, Iraq and Qatar, pass, in part against transit fees, and stated that the strait would remain closed to others until the United States accepted its conditions [76,77]. Middle Eastern sulfur contract prices for October 2026 eased by 45–70 USD/t, to 820–890 USD/t FOB [29], but remained almost twice their level of November 2025, when sulfur was quoted at 455–460 USD/t FOB Middle East [52]. A United Nations (UN) mechanism that would allow up to five fertilizer vessels per day to pass the strait has been prepared but not yet activated. In presenting it, the responsible UN Under-Secretary-General pointed out that the strait had carried nearly half of seaborne sulfur before the war [78]. Governments have also begun to treat phosphate supply as an emergency: in June 2026, the United States suspended countervailing duties on Moroccan phosphate fertilizers for up to eight months, citing a supply emergency caused by conflicts in fertilizer-producing regions and trade actions by major producing countries [79,80].

4. Disruption Channels: Chokepoints, Export Controls and Sanctions

The 2026 episode shows that sulfur supply can be disrupted through several channels that differ in cause, duration and policy response (Figure 5). Treating them separately avoids attributing outcomes to the wrong cause. Trade measures on finished fertilizers, such as export restrictions or import duties, bypass the sulfur channel and act directly on fertilizer supply and prices. Structural trends such as refinery closures and decarbonization (Section 3.2) add to the pressure on sulfur supply, and the mitigation options discussed

in Section 5 act on the sulfur bottleneck and on the resilience issues that persistently high sulfur prices may create (Section 4.4).



Blue: disruption channels originating from geopolitics and market developments. Solid orange: transmission via sulfur and sulfuric acid. Dark red: trade measures on finished fertilizers act directly on fertilizer supply and prices, bypassing the sulfur channel. Dashed orange: possible longer-term effects if high sulfur prices persist. Grey: mitigation options that act on the sulfur bottleneck and on resilience.

Figure 5. Channels through which sulfur supply disruptions are transmitted to phosphate fertilizer markets.

4.1. Physical Chokepoints

The closure of the Strait of Hormuz is a physical disruption: Gulf sulfur was produced but could not be shipped. Nearly half of global sulfur trade, almost half of urea exports and more than 20% of traded phosphate fertilizers originate in countries exposed to this route [47]. Early policy and media attention focused on nitrogen fertilizers, whose prices rose fastest: urea climbed above 850 USD/t in April 2026, 80% above its February level [81]. Three factors explain why nitrogen reacted first. First, the Gulf region normally supplies about one third to 40% of globally traded urea [82,83], so the closure removed finished product directly, and an estimated 2.6 Mt of urea exports were suspended within two months [82]. Second, the closure coincided with the main purchasing and application season for nitrogen fertilizers in the Northern Hemisphere. Third, China restricted fertilizer exports at the same time, removing the usual supplier of last resort [13]. Higher energy costs played a smaller role than in 2022: natural gas and ammonia prices rose less sharply than after the outbreak of war in Ukraine [82]. The nitrogen shock was also comparatively short-lived. After Northern Hemisphere planting ended and China relaxed its urea export restrictions, urea fell back to about 410 USD/t by late August 2026 [84]. Phosphate followed a different path, because the shock reached it through sulfur. Sulfur prices kept rising through August 2026 [24], and Arita et al. [83] note that sulfur-related tightness keeps phosphate prices high for longer, so that buyers who delay purchases are not rewarded as they are for nitrogen. The consequences of the chokepoint for phosphate therefore became visible later and persisted longer. A chokepoint disruption affects all importers regardless of their political alignment, and its duration depends on military and diplomatic developments rather than on market signals.

4.2. Producer Export Controls

Export restrictions by producing countries protect domestic supply at the expense of importers. Russia's sulfur export ban explicitly aims to secure feedstock for its own phosphate fertilizer industry [55]. China's halt of sulfuric acid exports and its restrictions on phosphate fertilizer exports serve the same purpose [13,61]. With sulfur supplies tight, Chinese phosphate fertilizer production has been focused on the domestic market. Exports, 5.3 Mt in 2025, fell to almost nothing in 2026, and Argus expects only a partial recovery, to about 2 Mt, in 2027 [85]. Such measures shift scarcity onto importing countries and tend to be introduced precisely when markets are already tight, as in 2008 [12]. They also favor integrated producers that control sulfur, phosphate rock and processing within one jurisdiction. China's halt of sulfuric acid exports also affected metal producers abroad. Chile, which obtained 37% of its sulfuric acid imports from China in 2025, and the copper producers of Zambia and the Democratic Republic of the Congo are particularly exposed [33,62]. Zambia restricts sulfuric acid exports to protect its domestic industry, and First Quantum began selling surplus acid from its Kansanshi smelter [86]. Even in Europe, which has substantial domestic acid production, the import price of sulfuric acid rose by 42% between January and September 2026 [87].

4.3. Sanctions and Tariffs

Sanctions and tariffs are a third, deliberate channel. Since 2022, the EU has progressively restricted imports of Russian energy. In January 2026, it adopted a regulation to phase out Russian gas imports, with a full ban on liquefied natural gas (LNG) from the beginning of 2027 and on pipeline gas from autumn 2027 [88]. Sanctions on Russian crude oil have made the crude slate of European refineries sweeter and have thus contributed to lower domestic sulfur recovery [48]. For fertilizers, the EU introduced additional duties on Russian and Belarusian products from July 2025, rising for nitrogen fertilizers from 40 to 45 EUR/t to 430 EUR/t by 2028 [89]. In May 2026, the EU additionally suspended its import duties on certain nitrogen fertilizers for one year, with imports from Russia and Belarus excluded [90]. Nevertheless, Russian fertilizer exports to the EU rose by 5% year-on-year in the first nine months of 2025 [91], and Russia already supplied about 30% of EU urea imports in 2024 [92]. Europe's dependence on imported nitrogen fertilizers increased its exposure to the 2026 shock, but it did not cause the urea price spike, which occurred on world markets and affected all importers (Section 4.1).

We do not assess whether these measures achieve their primary strategic aims. The narrower point is that energy sanctions also act on the sulfur supply of the sanctioning economy, a side effect that is rarely considered when such measures are designed. Unlike chokepoints, sanctions are a policy choice whose interactions with raw material dependencies can be assessed in advance.

4.4. Possible Structural Consequences

If high sulfur prices persist, the economics of phosphoric acid production will favor locations that combine phosphate rock with domestic sulfur or with secure sulfur supply. Such shifts could increase global supply but also create new dependencies on a small number of integrated producers. Before the war, much of the new sulfur supply from the Middle East was expected to serve new phosphate capacity in Saudi Arabia and Morocco [41]. Integration therefore favors producers in oil- and gas-producing countries, while importers such as Morocco remain exposed to maritime chokepoints. At the same time, new investment continues to lock in the sulfur-based route even in countries without domestic sulfur: Jordan Phosphate Mines Company, for example, signed a contract in February 2026, through its subsidiary Indian-Jordanian Chemicals Company, for a 900,000 t/a sulfuric acid plant at

Shidiya to expand phosphoric acid capacity from 330,000 to 550,000 t/a [93]. In China, high sulfur prices have already changed the relative costs of the two routes to purified phosphoric acid. The wet process consumes nearly 0.5 t of sulfur per tonne of acid, so the rise in the Chinese sulfur price from about 4000 to 6800 Chinese yuan (CNY) per tonne added more than 1400 CNY/t to its cost. In August 2025, wet-process acid was still cheaper than thermal acid made from elemental phosphorus, at about 6500 against 6900 CNY/t. By April 2026, the order had reversed, at 8450 against 8250 CNY/t. Shanghai Metals Market expects the share of thermal acid in the phosphoric acid supplied to new-energy applications such as LFP to rise from less than 5% to 10–15% within three to five years, and Hubei Xingfa Chemicals Group plans to expand its thermal acid capacity from 150,000 to 225,000 t/a in 2026 [94]. The thermal route avoids sulfur but depends on electricity and coke (Section 5.3). Such a shift therefore replaces one input dependency with another rather than removing it. Whether a lasting relocation of processing capacity occurs is an open empirical question that should be monitored rather than assumed.

5. Resilience Options and Process Replacement

5.1. Resilience Within the Wet Process

Several measures can reduce the vulnerability of the wet process without changing its chemistry:

- Diversifying sulfur sources and logistics routes and using long-term contracts, including supply from outside chokepoint-exposed regions, or protected transit arrangements such as the UN mechanism for fertilizer shipments through the Strait of Hormuz [78].
- Strategic stocks. Elemental sulfur is cheap to store as solid blocks, so sulfur stockpiles can buffer disruptions of a few months. The disruption of 2026 lasted longer, and even OCP, which had secured sulfur stocks, had to adjust its production [64].
- Using more smelter acid, pyrite and regenerated acid, within the limits described in Section 3.2.
- Recovering sulfur from phosphogypsum, for example by the Müller–Kühne process, which is technically proven but energy-intensive [95].
- Reducing primary demand through phosphorus recycling. Germany, for example, mandates phosphorus recovery from sewage sludge from 2029 [96], and the EU has since listed sewage sludge and the ashes from its mono-incineration as waste streams with relevant critical raw materials recovery potential [97]. The European Commission's Fertiliser Action Plan of May 2026 notes that about 70% of EU consumption of phosphate fertilizers is imported, names the supply of sulfur for phosphate fertilizer production as one channel through which the Middle East crisis affects the EU, and announces work towards a combined minimum reuse and recycling rate for phosphorus from sewage sludge and urban wastewater [98]. How readily the phosphorus in sewage sludge ash can be digested depends on its mineral phases, mainly whitlockite-type calcium phosphates, and the composition of the ashes varies considerably between plants [99,100].

These measures act at different time scales. Stocks and diversification address short disruptions, while recycling and sulfur recovery address long-term demand. None removes the dependency of the dominant route on sulfur.

5.2. Replacement Versus Substitution

A complementary strategy is process replacement. We define replacement, following our earlier Perspective [10], as producing an industrial product of the same specification, here, phosphoric acid, by a different process that does not depend on a critical input, when

that input's price or availability is highly uncertain (Figure 6). In the case of phosphoric acid, sulfuric acid is the critical input, and hydrochloric acid regenerated with electricity is one alternative. Replacement also includes changing the energy source of a process. It must be distinguished from substitution, in which a material is exchanged for another that performs the same function. Substitution changes the material that fulfills a function. Process replacement changes the manufacturing route and retains the target product.

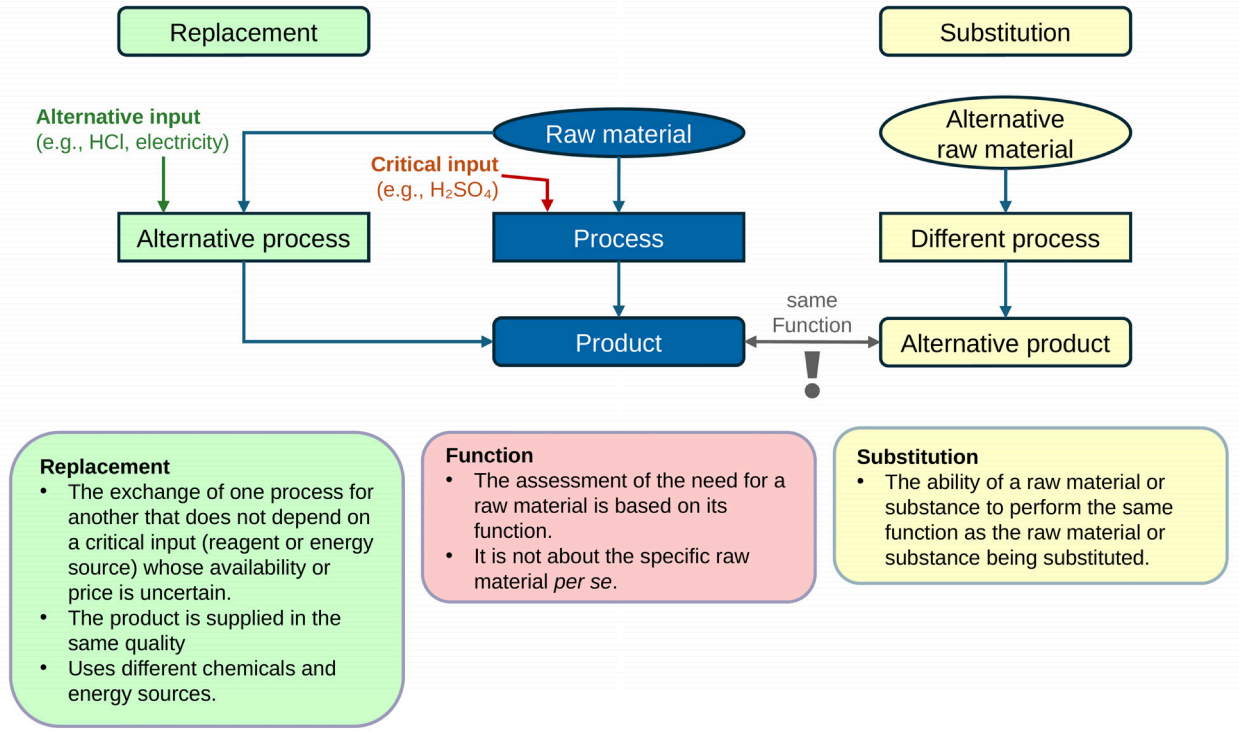


Figure 6. Replacement versus substitution, both assessed by the function of the product. Modified and adapted from [10].

For replacement to strengthen resilience rather than create new dependencies, the replacing process should, as far as possible, meet the following requirements: (a) no use of fossil feedstock; (b) zero or low waste, or marketable by-products; (c) a low CO_2 footprint; (d) low freshwater use; (e) use of renewable energy; and (f) energy and resource efficiency.

5.3. Comparison of Digestion Routes

Sulfur-free digestion of phosphate is not new. Table 4 compares the wet process with established and emerging alternatives on a common set of criteria and groups them by feedstock and product. Three observations stand out. First, most alternatives replace sulfur dependency with another input: the nitrophosphate (Odda) route uses nitric acid, which is made from ammonia and hence from natural gas [101], and the thermal and kiln routes use coke and large amounts of energy. Second, hydrochloric acid routes, established since the process of Israel Mining Industries (IMI) [102], avoid fossil feedstocks but produce calcium chloride, for which outlets are limited. The fate of this by-product is a decisive and often under-reported design criterion. Third, most recent developments originate in phosphorus recycling from sewage sludge ash, driven by regulation, and their operating experience at industrial scale is still limited. The grouping in Table 4 makes a further distinction clear. Only a few routes can replace the wet process for primary phosphate rock and still deliver phosphoric acid. The thermal process is commercial but electricity-intensive [95]. In China, it has recently become cost-competitive with the wet process for purified acid (Section 4.4).

The Improved Hard Process has reached the demonstration stage [103,104]. Among the hydrochloric acid routes, the IMI process was operated commercially in the past [102], Ecophos has been demonstrated [105], and PARFORCE has so far processed phosphate rock at laboratory scale [106]. The thermal process, the Improved Hard Process and PARFORCE were compared in more detail in our earlier Perspective [10]. The nitrophosphate route also starts from phosphate rock but yields NP/NPK fertilizers rather than phosphoric acid. The routes based on sewage sludge ash recover phosphorus from a secondary source. They reduce the demand for primary phosphate but cannot replace primary production. Because the routes differ in feedstock, product grade, recovery yield and system boundaries, and no common functional unit is available, Table 4 compares them qualitatively. Missing data are marked as evidence gaps, and the table does not support a ranking of overall performance.

Table 4. Comparison of phosphoric acid and phosphate digestion routes on common criteria, grouped into primary routes from phosphate rock and recycling routes from secondary feedstocks.

Route	Digestion Agent (Fossil Link)	Feedstock	Main Product	Calcium by-Product and Outlet	Energy	Status and Scale (Source)
A. Primary routes: phosphoric acid from phosphate rock						
Wet process (dihydrate/hemi-hydrate)	H_2SO_4, ≈2.7 t/t P_2O_5, sulfur mainly from oil and gas	Phosphate rock	Merchant-grade acid (52–54% P_2O_5)	Phosphogypsum, ≈5 t/t P_2O_5, mostly stacked.	120–180 kWh electricity and 0.5–2.2 t steam per t P_2O_5 (phosphoric acid plant only). Steam largely from sulfur burning. The sulfuric acid plant recovers 5.2–5.8 GJ/t H_2SO_4 as steam [38].	Dominant route, plants up to Mt/a [11,35].
Thermal (electric furnace)	None, coke and silica as reductant and flux	Phosphate rock	P_4 → high-purity thermal acid	Calcium silicate slag.	Very high electricity demand.	Commercial, mainly for P_4 and high-purity products [95].
Improved Hard Process (kiln)	None, carbon reductant in rotary kiln	Low-grade phosphate rock	Phosphoric and superphosphoric acid	Calcium silicate pellets.	Fuel-intensive high-temperature kiln.	Demonstration [103,104].
HCl route with solvent extraction (IMI)	HCl	Phosphate rock	Purified phosphoric acid	$CaCl_2$ brine, limited outlets, disposal needed.	Depends on HCl source.	Commercial in the past, limited by HCl cost and $CaCl_2$ outlet [102].
Ecophos (Prayon)	HCl, incl. by-product HCl; optional H_2SO_4 module regenerates HCl from $CaCl_2$	Low- to high-grade rock, secondary materials	Feed-grade DCP, phosphoric acid	$CaCl_2$ (de-icing, drilling) or, with the H_2SO_4 module, gypsum, marketed according to the supplier.	n.r.	Ecophos insolvent in 2020; IP and Varna (Bulgaria) demonstration plant acquired by Prayon; no operating commercial plant reported [105,107].
PARFORCE (phosphate rock)	HCl, regenerated from NaCl by bipolar electrodialysis (chloride loop not completely closed, net HCl demand not reported for phosphate rock)	Phosphate rock, magmatic and sedimentary	Phosphoric acid	$Ca(OH)_2$, intended for building materials (quality data not published), Fe/Al chloride reused in wastewater treatment.	n.r. for phosphate rock.	Laboratory, kg scale, electricity not HCl as cost driver [106].

Table 4. *Cont.*

Route	Digestion Agent (Fossil Link)	Feedstock	Main Product	Calcium by-Product and Outlet	Energy	Status and Scale (Source)
B. Primary route without phosphoric acid						
Nitrophosphate (Odda)	HNO_3 (from NH_3, i.e., natural gas)	Phosphate rock	NP/NPK fertilizers, not merchant acid	$Ca(NO_3)_2$ → calcium ammonium nitrate (marketed).	Coupled to NH_3 synthesis.	Commercial [101].
C. Recycling routes: secondary feedstocks (sewage sludge ash and other secondary phosphates)						
TetraPhos	H_3PO_4 (recycled) + H_2SO_4 for Ca removal	Sewage sludge ash (SSA)	Technical-grade phosphoric acid	Gypsum.	n.r.	Full-scale plant, Hamburg (~22,000 t SSA/a): trial operation since 2021 [108,109].
Ash2Phos	HCl	SSA	Calcium phosphate (RevoCaP)	Fe/Al products and sand recovered; chloride-rich process wastewater (also high in Ca), max. 161,600 m^3/a, discharged into the Saale River after heavy-metal removal; further chloride reduction may be required [110].	n.r.	First full-scale plant (38,000 t SSA/a), permitted 2024, under construction since 2025, Schkopau [108,110,111].
PARFORCE (secondary feedstocks)	HCl, regenerated from NaCl by bipolar electrodialysis (chloride loop not completely closed, chloride lost with the solid residue, net demand 21.0 kg HCl/kg P for SSA)	SSA, struvite, Ca phosphates (pilot, ton scale)	Phosphoric acid (75 wt%)	$Ca(OH)_2$, intended for building materials (quality data not published), Fe/Al chloride reused in wastewater treatment.	Electricity 0.7 (struvite) to 26.5 (SSA) kWh/kg P, heat 3.1–11.5 kWh/kg P (HCl digestion), from feedstock to 75 wt% acid incl. HCl/NaOH regeneration (SSA: 11.6 and 5.0 MWh/t P_2O_5).	Demonstration: 1 t/d (Freiberg, 2017), Pilot: 1000 t SSA/a (Bottrop, opened 2024, in operation since 2025), operated by PhosRec Phosphor-Recycling GmbH [112–115].

n.r. = not reported in the public sources consulted. Such entries are evidence gaps. Energy figures are not directly comparable across routes because feedstocks, system boundaries, product grades and recovery yields differ, and no common functional unit is available. Where sources permit, the system boundary is stated in the table. Phosphorus recovery is reported for PARFORCE only (>80% of the P in SSA, 99% for DCP [112]). SSA = sewage sludge ash, DCP = dicalcium phosphate.

5.4. Closing the By-Product Loops

Table 4 shows that, once sulfuric acid is replaced, the decisive question for both resilience and environmental performance is what happens to the calcium. In the wet process, it leaves as phosphogypsum, about 5 t per tonne of P_2O_5, most of which is stacked [35]. Phosphogypsum need not remain a waste: it is not yet processed industrially in the EU, but it could replace the flue-gas desulfurization gypsum that the phase-out of coal-fired power removes from the market, provided that inexpensive ways are found to sort and purify it [116]. Such processes are not yet available at industrial scale, but phosphogypsum purification and utilization are the subject of intensive research [117,118]. Hydrochloric acid routes avoid both sulfur and gypsum but produce calcium chloride [102]. Digesting fluorapatite yields at least 2.6 t of anhydrous calcium chloride per tonne of P_2O_5, so a single plant producing 1 Mt of P_2O_5 per year would generate about 2.6 Mt of calcium chloride

annually. Two different reference figures must be distinguished here. World production, i.e., the quantity manufactured, was about 4.6 Mt in 2022, although the sources do not state the mass basis [119,120]. The world market volume, i.e., the quantity actually sold to users, is estimated at about 3.8 Mt (dry basis) in 2024 [121]. Our figure and the market volume both refer to anhydrous (dry) calcium chloride. A single plant of this size would thus produce more than half of current world production, corresponding to about two thirds of the world market volume. Growth is slow: world production is expected to grow by 3–4% per year [119], and demand in the United States (1.05 Mt in 2024), part of the largest regional market, North America, is projected to grow by only 0.6% per year until 2034 [121]. Outlets such as de-icing and drilling fluids, to which the supplier of the Ecophos process refers [107], cannot absorb such volumes. Moreover, de-icing and dust control are the lowest-priced applications, at about USD 240 per tonne, and de-icing demand fluctuates with winter weather [121]. At the scale of phosphoric acid production, calcium chloride is therefore effectively a waste stream. At the first full-scale Ash2Phos plant in Schkopau, the chloride-rich process wastewater, which also contains high concentrations of calcium, is to be discharged into the Saale River after removal of heavy metals. The licensing authority expects the chloride concentration in the river to rise by up to 17 mg/L at mean low flow, classifies this as significant with respect to the deterioration ban for the water body, and has reserved the right to require additional chloride reduction [110].

Electrochemical regeneration offers a way to avoid calcium chloride as a by-product. In the PARFORCE process, developed at the Institute of Chemical Technology of Freiberg University of Mining and Technology (see Conflicts of Interest), calcium is precipitated as hydrated lime with sodium hydroxide, and the remaining sodium chloride solution is split by bipolar membrane electrodialysis into hydrochloric acid and sodium hydroxide, both of which return to the process [106,112]. The net inputs are phosphate feedstock, electricity, heat and make-up hydrochloric acid and a small amount of sodium hydroxide, and the calcium leaves as hydrated lime, about 1.7 t per tonne of P_2O_5 from fluorapatite. World lime production is about 420 Mt per year [122], but market size alone does not show that the product can be sold. Saleability depends on purity, moisture, contaminants carried over from the feedstock, such as heavy metals or radionuclides, transport costs and local demand, the same criteria that apply to calcium chloride and phosphogypsum. No quality data for the hydrated lime have been published yet. Calcium thus leaves the process as a product, but the chloride loop is not completely closed. Chloride is lost with the solid digestion residue and, for sewage sludge ash, with the iron and aluminum chloride solution that is reused in wastewater treatment. The published key figures for sewage sludge ash, derived from the demonstration plant in Freiberg (1 t/d, 2017), list a net demand of 21.0 kg HCl and 0.3 kg NaOH per kg of recovered phosphorus [112]. Hydrochloric acid therefore has to be made up continuously. The quantity of acid regenerated per kilogram of phosphorus has not been published, so the degree of closure cannot yet be quantified. Corresponding figures for phosphate rock have not been published. The process concept is described in the patent [106] and the key figures in [112], while the operator of the pilot plant has published first operating results but has not yet published sufficiently detailed energy or reagent-consumption data [113–115]. The price of this regeneration is energy: for sewage sludge ash, about 26.5 kWh of electricity and up to 11.5 kWh of heat per kg of recovered phosphorus, or 11.6 and 5.0 MWh (about 42 and 18 GJ) per tonne of P_2O_5, have been reported [112], whereas an integrated wet-process complex is a net energy exporter: its sulfuric acid plant can recover about 5.4 GJ per tonne of H_2SO_4 as steam, or roughly 14–15 GJ per tonne of P_2O_5, more than the phosphoric acid plant requires [35,38] (Section 3.1). On energy alone, the wet process is clearly superior. Within the reported system boundaries, integrated wet-process sulfuric acid production can export steam, whereas the published

PARFORCE values show a net demand of 0.7–26.5 kWh of electricity and 3.1–11.5 kWh of heat per kg P for HCl digestion, depending on the feedstock, with the highest values for sewage sludge ash [112]. Comparable PARFORCE data for phosphate rock have not been published. The case for sulfur-free routes rests on supply security and on the fate of calcium, not on energy efficiency, and such routes are attractive only where low-cost renewable electricity is available. Phosphate rock of magmatic and sedimentary origin has so far been processed at kilogram scale in the laboratory [106], the operator of the pilot plant in Bottrop, PhosRec Phosphor-Recycling GmbH, a company founded by five public water associations in North Rhine-Westphalia, has reported first operating results, but not comprehensive energy or reagent-consumption data [114,115], and investment costs are available only in indexed form [112]. The EU is preparing a universal restriction of per- and polyfluoroalkyl substances (PFAS) under REACH: the Risk Assessment Committee of the European Chemicals Agency adopted its opinion in March 2026, and the final opinion of the Socio-Economic Analysis Committee is expected by the end of 2026, after which the European Commission will propose the restriction [123,124]. The ion-exchange and bipolar membranes used are non-fluorinated, so this restriction would not affect them.

5.5. What Process Replacement Can and Cannot Do

Process replacement is not a short-term remedy. No sulfur-free route currently operates at a scale that could offset a disruption such as that of 2026, and scaling up any new process from demonstration to world scale takes a decade or more. In the short term, resilience depends on stocks, diversification and trade policy (Section 5.1). Replacement is a medium- to long-term option, most attractive where three conditions coincide: (i) access to phosphate feedstock (primary or secondary), (ii) access to low-cost renewable electricity, and (iii) regulatory or market drivers, such as the German phosphorus recovery mandate or high and volatile sulfur prices. Regions in North Africa and the Middle East that combine large phosphate deposits with high solar potential meet the first two conditions. Independent techno-economic and life-cycle comparisons of the routes in Table 4 under common assumptions are needed before policy can prioritize among them.

6. Conclusions and Policy Implications

Phosphate rock is not facing imminent geological scarcity, but the wet process, and with it most of the phosphorus supply chain, depends critically on sulfur. Phosphate fertilizers account for roughly half of world sulfuric acid consumption, sulfur is predominantly recovered as a by-product of oil and gas processing concentrated in a few exporting regions, and the 2026 disruptions showed that a sulfur shock can translate into production curtailments at wet-process producers that depend on traded sulfur, while phosphate rock remains available. The closure of the Strait of Hormuz did not create this bottleneck but exposed and amplified a shortage that had been building for some time. In this sense, and for the wet process that dominates production, sulfur, not phosphorus, is the hidden bottleneck of phosphoric acid production. Rock-related risks, such as declining ore grades and the concentration of reserves and processing capacity, remain and should be assessed alongside it. For sustainable development, this dependency creates a conflict between goals that has received little attention. The decarbonization pursued under Goal 13 (climate action) reduces the supply of by-product sulfur, while the food security sought under Goal 2 (zero hunger) depends on it. Sulfur-free digestion routes, phosphorus recovery from secondary sources and the use of phosphogypsum can ease this conflict, provided that their energy demand and by-product outlets are documented (Section 5). They contribute to Goal 12 (responsible consumption and production), phosphorus recovery from sewage

sludge ash also to Goal 6 (clean water and sanitation), and the development of new process routes to Goal 9 (industry, innovation and infrastructure).

Four implications follow:

- Criticality assessments of phosphorus should be route-specific. The sulfur (and sulfuric acid) dependency of the dominant wet process should be assessed explicitly, alongside the supply of phosphate rock and elemental phosphorus.
- Sulfur trade flows, stocks and chokepoint exposure should be monitored as part of food security risk assessments, together with the established focus on nitrogen fertilizers and natural gas.
- Sanctions, tariffs and export controls should be assessed for their effects on by-product supply chains, such as sulfur from oil and gas processing, before they are introduced.
- Demonstration of sulfur-free digestion routes should be supported in a way that allows transparent benchmarking of energy demand, by-product outlets and costs under common assumptions.

Viewed as an opportunity rather than a setback, the current situation invites the development of processes that strengthen supply security while improving resource efficiency and reducing environmental impact, and so serve several Sustainable Development Goals at once.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su182312172/s1, File S1: Data, sources and calculations for Figures 1, 2 and 4 and for the key calculations in the text, and a chronology of the events of 2025–2026 (Table S6) and the reaction enthalpy of sulfuric acid production (Table S7) (Microsoft Word document). File S2: The same data, with the key calculations as live formulas and with the charts of Figures 1, 2 and 4 (Microsoft Excel workbook). Reference [125] is cited in the Supplementary Materials.

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Conflicts of Interest: M.B. is a co-inventor of the PARFORCE process [106] and holds a 15% equity stake in PARFORCE Engineering & Consulting GmbH (Freiberg, Germany), a spin-off of Freiberg University of Mining and Technology. The company co-owns PTC-PARFORCE Technology Cooperation GmbH, which designed and built the PARFORCE pilot plant in Bottrop (Germany). The Bottrop plant was funded by the German Federal Ministry of Education and Research (BMBF) within the AMPHORE joint project [113]. It is owned and operated by PhosRec Phosphor-Recycling GmbH, a company founded by the Ruhrverband, Emschergenossenschaft, Lippeverband, Wupperverband and Linksniederrheinische Entwässerungs-Genossenschaft (LINEG), and is located on the site of the

Emschergenossenschaft sewage treatment plant [114]. Neither M.B. nor PARFORCE Engineering & Consulting GmbH holds a stake in PhosRec Phosphor-Recycling GmbH. To limit the influence of this interest, PARFORCE is assessed on the same criteria as all other routes (Table 4), it is discussed as one example in Section 5.4 together with its limitations, and operating data from the plant operator are cited where available. The description of PARFORCE in this manuscript is based exclusively on published sources. No unpublished company data were used. Unpublished operating data from the pilot plant in Bottrop belong to PhosRec Phosphor-Recycling GmbH and are not available to the authors. The other authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CFR	Cost and freight
CRM	Critical raw material
DAP	Diammonium phosphate
DCP	Dicalcium phosphate
CNY	Chinese yuan
EBITDA	Earnings before interest, taxes, depreciation and amortization
EU	European Union
FOB	Free on board
IEA	International Energy Agency
IHP	Improved Hard Process
IMI	Israel Mining Industries
LFP	Lithium iron phosphate
LNG	Liquefied natural gas
MAD	Moroccan dirham
MAP	Monoammonium phosphate
NPK	Nitrogen–phosphorus–potassium
SSA	Sewage sludge ash
TSP	Triple superphosphate
UN	United Nations
WCP	Wet chemical process

References

1. European Union. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials. Official Journal of the European Union 2024, L 2024/1252, 3 May 2024. Available online: http://data.europa.eu/eli/reg/2024/1252/oj (accessed on 22 November 2026).
2. European Commission. *Study on the Critical Raw Materials for the EU 2023—Final Report*; Publications Office of the European Union: Luxembourg, 2023.
3. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects 2024: Summary of Results*; United Nations: New York, NY, USA, 2024.
4. Popkin, B.M.; Adair, L.S.; Ng, S.W. Global Nutrition Transition and the Pandemic of Obesity in Developing Countries. *Nutr. Rev.* **2012**, *70*, 3–21. [CrossRef] [PubMed]
5. United Nations General Assembly. *Transforming Our World: The 2030 Agenda for Sustainable Development*; Resolution A/RES/70/1; United Nations: New York, NY, USA, 2015.
6. Cordell, D.; Drangert, J.-O.; White, S. The Story of Phosphorus: Global Food Security and Food for Thought. *Glob. Environ. Change* **2009**, *19*, 292–305. [CrossRef]
7. Scholz, R.W.; Wellmer, F.-W.; Mew, M.; Steiner, G. The Dynamics of Increasing Mineral Resources and Improving Resource Efficiency: Prospects for Mid- and Long-Term Security of Phosphorus Supply. *Resour. Conserv. Recycl.* **2025**, *213*, 107993. [CrossRef]
8. Raddant, M.; Bertau, M.; Steiner, G. Advancing the Analysis of Resilience of Global Phosphate Flows. *Resources* **2025**, *14*, 151. [CrossRef]
9. Maslin, M.; Van Heerde, L.; Day, S. Sulfur: A Potential Resource Crisis That Could Stifle Green Technology and Threaten Food Security as the World Decarbonises. *Geogr. J.* **2022**, *188*, 498–505. [CrossRef]
10. Bertau, M.; Wellmer, F.-W.; Scholz, R.W.; Mew, M.; Zenk, L.; Aubel, I.; Fröhlich, P.; Raddant, M.; Steiner, G. The Future of Phosphoric Acid Production—Why We Have to Leave Trodden Paths. *ChemSusChem* **2025**, *18*, e202401155. [CrossRef] [PubMed]

11. Jasinski, S.M. Phosphate Rock. In *Mineral Commodity Summaries 2026*; U.S. Geological Survey: Reston, VA, USA, 2026; pp. 142–143.
12. Khabarov, N.; Obersteiner, M. Global Phosphorus Fertilizer Market and National Policies: A Case Study Revisiting the 2008 Price Peak. *Front. Nutr.* **2017**, *4*, 22. [CrossRef] [PubMed]
13. Fertilizer Daily. China Phosphate Export Restrictions Extended Through August 2026, Russia Quotas. 29 July 2026. Available online: https://www.fertilizerdaily.com/20260729-china-phosphate-export-restrictions-august-2026-russia-quotas/ (accessed on 22 November 2026).
14. Mew, M.; Steiner, G.; Haneklaus, N.; Geissler, B. Phosphate Price Peaks and Negotiations—Part 2: The 2008 Peak and Implications for the Future. *Resour. Policy* **2023**, *83*, 103588. [CrossRef]
15. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2010 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2010.
16. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2014 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2014.
17. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2015 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2015.
18. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2017 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2017.
19. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2018 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2018.
20. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2021 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2021.
21. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2025 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2025.
22. U.S. Geological Survey. Sulfur. In *Mineral Commodity Summaries 2026 (Salient Statistics: Average Unit Value of Elemental Sulfur, f.o.b. Mine/Plant)*; U.S. Geological Survey: Reston, VA, USA, 2026.
23. Silveira Lima, M.; Velarde, L.; S&P Global Energy. High Sulfur Prices Squeeze Fertilizer Margins, Spur Production Cutbacks. 29 May 2026. Available online: https://www.spglobal.com/energy/en/news-research/latest-news/agriculture/052926-high-sulfur-prices-squeeze-fertilizer-margins-spur-production-cutbacks (accessed on 22 November 2026).
24. Paulson, N.; Schnitkey, G.; Zulauf, C.; Dhakal, A.; Farmdoc Daily. Sulfur and Increasing Phosphate Fertilizer Prices. 25 August 2026. Available online: https://farmdocdaily.illinois.edu/2026/08/sulfur-and-increasing-phosphate-fertilizer-prices.html (accessed on 22 November 2026).
25. World Bank. Commodity Price Data (The Pink Sheet), October 2026. 2 October 2026. Available online: https://thedocs.worldbank.org/en/doc/74e8be41ceb20fa0da750cda2f6b9e4e-0050012026/related/CMO-Pink-Sheet-October-2026.pdf (accessed on 22 November 2026).
26. Indexmundi. Triple Superphosphate Monthly Price (World Bank Data). Available online: https://www.indexmundi.com/commodities/?commodity=triple-superphosphate&months=240 (accessed on 22 November 2026).
27. U.S. Energy Information Administration (EIA). Europe Brent Spot Price FOB, Annual. Available online: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rbrte&f=a (accessed on 22 November 2026).
28. U.S. Energy Information Administration (EIA). Europe Brent Spot Price FOB, Monthly. Available online: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rbrte&f=m (accessed on 22 November 2026).
29. Shanghai Metals Market (SMM). Middle East October Sulfur Contract Prices Announced. 8 October 2026. Available online: https://news.metal.com/newscontent/104145450-smm-flash-middle-east-october-sulfur-contract-prices-announced (accessed on 22 November 2026).
30. The Mosaic Company. The Mosaic Company Reports Second Quarter 2026 Results. Exhibit 99.1. August 2026. Available online: https://s1.q4cdn.com/823038994/files/doc_financials/2026/q2/Press-Release-Q2-2026-Exhibit-99-1-Publish.pdf (accessed on 22 November 2026).
31. The Mosaic Company. *Form 10-Q for the Quarterly Period Ended 31 March 2026*; U.S. Securities and Exchange Commission: Washington, DC, USA, 2026. Available online: https://www.sec.gov/Archives/edgar/data/0001285785/000128578526000067/mos-20260331.htm (accessed on 22 November 2026).
32. ChemAnalyst. Sulphuric Acid Prices, Trend, Chart and Forecast. Available online: https://www.chemanalyst.com/Pricing-data/sulphuric-acid-70 (accessed on 22 November 2026).
33. Keen, K.; S&P Global Energy. No Quick Sulfuric Acid Fix for Chilean Copper Sector: Analysts. 21 April 2026. Available online: https://www.spglobal.com/energy/en/news-research/latest-news/metals/042126-no-quick-sulfuric-acid-fix-for-chilean-copper-sector-analysts (accessed on 22 November 2026).

34. International Energy Agency (IEA). *Global Critical Minerals Outlook 2026*; Revised Version, July 2026; IEA: Paris, France, 2026; pp. 28, 53. Available online: https://iea.blob.core.windows.net/assets/19c60aa0-ee07-4a20-a138-33c967ac5008/GlobalCriticalMineralsOutlook2026.pdf (accessed on 22 November 2026).
35. European Fertilizer Manufacturers' Association (EFMA). *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry. Booklet No. 4 of 8: Production of Phosphoric Acid*; EFMA: Brussels, Belgium, 2000. Available online: https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Booklet_4_final.pdf (accessed on 22 November 2026).
36. Shang, D.; Geissler, B.; Mew, M.; Satalkina, L.; Zenk, L.; Tulsidas, H.; Barker, L.; El-Yahyaoui, A.; Hussein, A.; Taha, M.; et al. Unconventional Uranium in China's Phosphate Rock: Review and Outlook. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110740. [CrossRef]
37. Belboom, S.; Szöcs, C.; Léonard, A. Environmental Impacts of Phosphoric Acid Production Using Di-Hemihydrate Process: A Belgian Case Study. *J. Clean. Prod.* **2015**, *108*, 978–986. [CrossRef]
38. European Commission. *Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals—Ammonia, Acids and Fertilisers*; European Commission, Joint Research Centre: Seville, Spain, 2007; pp. 195–198. Available online: https://bureau-industrial-transformation.jrc.ec.europa.eu/sites/default/files/2022-03/LVIC-AAF.pdf (accessed on 22 November 2026).
39. OCP Group. *Sustainability Report 2025: Integrated Report*; OCP: Casablanca, Morocco, 2026; pp. 116–118. Available online: https://www.ocpgroup.ma/fr/investors/results-reports-presentations (accessed on 22 November 2026).
40. Saloum, S.H. Sulfur. In *Mineral Commodity Summaries 2026*; U.S. Geological Survey: Reston, VA, USA, 2026; pp. 182–183.
41. S&P Global Commodity Insights. *Sulfur—Chemical Economics Handbook (Abstract)*; S&P Global Inc.: New York, NY, USA, 2024. Available online: https://www.spglobal.com/commodityinsights/en/ci/products/sulfur-chemical-economics-handbook.html (accessed on 22 November 2026).
42. CRU International. *Sulphuric Acid Supply Study; Report Prepared for the Queensland Government, Public Version*; CRU Reference ST2627-23; CRU Consulting: North Sydney, Australia, 2024; pp. 10, 45. Available online: https://statedevelopment.qld.gov.au/__data/assets/pdf_file/0018/94500/sulphuric-acid-supply-study.pdf (accessed on 22 November 2026).
43. King, M.J.; Davenport, W.G.; Moats, M.S. *Sulfuric Acid Manufacture: Analysis, Control and Optimization*, 2nd ed.; Elsevier: Oxford, UK, 2013.
44. S&P Global Commodity Insights. *Sulfuric Acid—Chemical Economics Handbook (Report Summary)*; S&P Global Inc.: New York, New York, USA, 2023. Available online: https://www.spglobal.com/content/dam/spglobal/ci/en/documents/products/pdf/CI_0325_Global_CEH_Sulfuric_Acid_Abstract.pdf (accessed on 22 November 2026).
45. CRU. The Sulphur Market in Deficit. Sulphur 2026, 422 (January–February). Available online: https://www.bcinsight.crugroup.com/2026/01/28/the-sulphur-market-in-deficit/ (accessed on 22 November 2026).
46. Chambers, S. War Turns Sulphur Market Toxic in Acid Supply Shock (Based on Data from Ursa Shipbrokers). Splash247, 23 April 2026. Available online: https://splash247.com/war-turns-sulphur-market-toxic-in-acid-supply-shock/ (accessed on 22 November 2026).
47. The Fertilizer Institute (TFI). Fertilizer and the Middle East Conflict. March 2026. Available online: https://www.tfi.org/wp-content/uploads/2026/03/Fertilizer-and-the-Middle-East-Conflict-2.pdf (accessed on 22 November 2026).
48. Argus Media. EU Sulphur Shortage Persists, Limiting Sul Acid Output. 1 February 2025. Available online: https://www.argusmedia.com/en/news-and-insights/latest-market-news/2643425-eu-sulphur-shortage-persists-limiting-sul-acid-output (accessed on 22 November 2026).
49. CRU Group. CRU Launches Indonesia Acid Price as Nickel Sector Lifts Demand. 28 May 2026. Available online: https://www.crugroup.com/en/communities/thought-leadership/2026/CRU-launches-Indonesia-acid-price-as-nickel-sector-lifts-demand/ (accessed on 22 November 2026).
50. S&P Global Commodity Insights. Metals Leaching Expected to Increasingly Drive Sulfur Demand Growth Through 2050. 7 March 2024. Available online: https://www.spglobal.com/commodity-insights/en/news-research/latest-news/agriculture/030724-metals-leaching-expected-to-increasingly-drive-sulfur-demand-growth-through-2050 (accessed on 22 November 2026).
51. Bidoia, L.; PricePedia. Sulphuric Acid: Product Scarcity and Cost Increases Drive Current High Prices. 6 February 2026. Available online: https://www.pricepedia.it/en/magazine/article/2026/02/06/sulphuric-acid-product-scarcity-and-cost-increases-drive-current-high-prices/ (accessed on 22 November 2026).
52. Velarde, L.; S&P Global Energy. Rising Sulfur Costs Create Affordability Crisis for European Acid Producers. 18 November 2025. Available online: https://www.spglobal.com/energy/en/news-research/latest-news/fertilizers/111825-rising-sulfur-costs-create-affordability-crisis-for-european-acid-producers (accessed on 22 November 2026).
53. OCP S.A. *États Financiers au 31 Décembre 2025 [Financial Statements as of 31 December 2025]*; Note 4.2; OCP: Casablanca, Morocco, 2026; pp. 22–23. Available online: https://www.ocpgroup.ma/fr/investors/results-reports-presentations (accessed on 22 November 2026). (In French)

54. Sulphur Ban Extended. Sulphur (BCInsight), 28 January 2026. Available online: https://www.bcinsight.crugroup.com/2026/01/28/sulphur-ban-extended (accessed on 22 November 2026).
55. Interfax. Russia Extends Sulfur Export Ban Through End of 2026. 26 June 2026. Available online: https://interfax.com/newsroom/top-stories/118234/ (accessed on 22 November 2026).
56. Government of the Russian Federation. Government Introduces a Temporary Ban on Exports of Technical Sulphur, a Critical Raw Material for Fertiliser Production; Resolution No. 1730 of 1 November 2025. 2 November 2025. Available online: http://government.ru/en/docs/56821/ (accessed on 22 November 2026).
57. Global Trade Alert. Russia: Temporary Ban on Export of Certain Types of Sulphur (4 November 2025 to 31 December 2026). State Act 95109, Updated July 2026. Available online: https://globaltradealert.org/state-act/95109-russia-temporary-ban-on-export-of-certain-types-of-sulfur-4-november-to-31-december-2025/ (accessed on 22 November 2026).
58. Interfax. Russian Govt Extends Ban on Exporting Sulfur Until 30 June 2026. 31 March 2026. Available online: https://www.interfax.com/newsroom/top-stories/116882/ (accessed on 22 November 2026).
59. Interfax. Russia Bans Sulfuric Acid Exports Until End of Year to Ensure Sufficient Supplies for Mineral Fertilizer Producers, Industry. 14 September 2026. Available online: https://interfax.com/newsroom/top-stories/119121/ (accessed on 22 November 2026).
60. Glauber, J.; Arita, S.; IFPRI Blog. How Are Fertilizer Markets Coping with the Continued Closure of the Strait of Hormuz? 18 September 2026. Available online: https://www.ifpri.org/blog/how-are-fertilizer-markets-coping-with-the-continued-closure-of-the-strait-of-hormuz/ (accessed on 22 November 2026).
61. Exiger. China Halts Sulphuric Acid Exports as War Squeezes Global Supply. 16 April 2026. Available online: https://www.exiger.com/perspectives/china-halts-sulphuric-acid-exports-as-war-squeezes-global-supply/ (accessed on 22 November 2026).
62. Bloomberg News; MINING.COM. China to Ban Sulfuric Acid Exports as Iran War Hits Supply. 10 April 2026. Available online: https://www.mining.com/web/china-moves-to-ban-sulfuric-acid-exports-as-iran-war-hits-supply/ (accessed on 22 November 2026).
63. SunSirs. China's Sulfur Imports Plummet and Sulfuric Acid Exports Nearly Halt in First Half of 2026 (Based on China Customs Statistics). 23 July 2026. Available online: https://www.sunsirs.com/uk/detail_news-34681.html (accessed on 22 November 2026).
64. OCP S.A. OCP Publie ses Résultats à Fin Juin 2026. Press Release, 29 September 2026. Available online: https://www.ocpgroup.ma/fr/investors/results-reports-presentations (accessed on 22 November 2026). (In French)
65. The Mosaic Company. Mosaic Announces Extension of Phosphate Production Curtailments in Brazil. Press Release. 21 January 2026. Available online: https://investors.mosaicco.com/press-releases/news-details/2026/Mosaic-Announces-Extension-of-Phosphate-Production-Curtailments-in-Brazil/default.aspx (accessed on 22 November 2026).
66. The Mosaic Company. Mosaic Announces Idling of Araxá and Patrocínio Facilities and Pursuit of Sale of Araxá Assets. Press Release. 8 April 2026. Available online: https://www.accessnewswire.com/newsroom/en/food-and-beverage-products/mosaic-announces-idling-of-arax%C3%A1-and-patroc%C3%ADnio-facilities-and-pursuit-o-1155814 (accessed on 22 November 2026).
67. The Mosaic Company. The Mosaic Company Reports First Quarter 2026 Results. Exhibit 99.1 to Form 8-K. 11 May 2026. Available online: https://www.sec.gov/Archives/edgar/data/0001285785/000128578526000063/pressreleaseq12026-ex991.htm (accessed on 22 November 2026).
68. Zavala, T.; Argus Media. Mosaic to Further Curtail US, Brazil Phosphate Output. 8 July 2026. Available online: https://www.argusmedia.com/en/news-and-insights/latest-market-news/2849723-mosaic-to-further-curtail-us-brazil-phosphate-output (accessed on 22 November 2026).
69. S&P Global Energy. Mosaic Cuts Brazil Phosphate Output amid Tight Sulfur Supply, Rising Costs. 8 July 2026. Available online: https://www.spglobal.com/energy/en/news-research/latest-news/agriculture/070826-mosaic-cuts-brazil-phosphate-output-amid-tight-sulfur-supply-rising-costs (accessed on 22 November 2026).
70. The Mosaic Company. The Mosaic Company Reports Third Quarter 2026 Results. Press Release. 3 November 2026. Available online: https://investors.mosaicco.com/financials/quarterly-results (accessed on 22 November 2026).
71. The Mosaic Company. *Form 10-Q for the Quarterly Period Ended 30 September 2026*; U.S. Securities and Exchange Commission: Washington, DC, USA, 2026. Available online: https://www.sec.gov/Archives/edgar/data/0001285785/000128578526000147/mos-20260930.htm (accessed on 22 November 2026).
72. The Mosaic Company. Q3 2026 Earnings Call Transcript. The Motley Fool. 4 November 2026. Available online: https://www.fool.com/earnings/call-transcripts/2026/11/04/mosaic-mos-q3-2026-earnings-call-transcript/ (accessed on 22 November 2026).
73. Finances News Hebdo. Le Groupe OCP Publie ses Résultats à Fin Juin 2026 et Souligne la Solidité de sa Marge d'EBITDA. 29 September 2026. Available online: https://fnh.ma/article/actualites-marocaines/ocp-premier-semestre-2026 (accessed on 22 November 2026). (In French)
74. Naim, F.; Morocco World News. OCP Holds EBITDA Margin at 28% Despite Global Phosphate Market Shock. 29 September 2026. Available online: https://www.moroccoworldnews.com/2026/09/340166/ocp-holds-ebitda-margin-at-28-despite-global-phosphate-market-shock/ (accessed on 22 November 2026).

75. Challenge. L'OCP Affiche sa Résilience dans des Conditions de Marché Difficiles. 29 September 2026. Available online: https://www.challenge.ma/locp-affiche-sa-resilience-dans-des-conditions-de-marche-difficiles-324851/ (accessed on 22 November 2026). (In French)
76. Adler, N.; Al Jazeera. Why Is Iran Exempting India, China, Qatar, Iraq from Hormuz Restrictions? 6 November 2026. Available online: https://www.aljazeera.com/news/2026/11/6/why-is-iran-exempting-india-china-qatar-iraq-from-hormuz-restrictions (accessed on 22 November 2026).
77. Bernama-IRNA; The Star. 'No Backing Down': Strait of Hormuz Will Stay Shut Until US Accepts Its Terms, Says Iran. 7 November 2026. Available online: https://www.thestar.com.my/aseanplus/aseanplus-news/2026/11/07/039no-backing-down039-strait-of-hormuz-will-stay-shut-until-us-accepts-its-terms-says-iran (accessed on 22 November 2026).
78. Reuters. Failure to Activate Hormuz Fertilizer Plan Could Trigger Food Crisis, UN Official Says. Reproduced by American Journal of Transportation (AJOT). 14 October 2026. Available online: https://www.ajot.com/news/failure-to-activate-hormuz-fertilizer-plan-could-trigger-food-crisis-un-official-says (accessed on 22 November 2026).
79. The President of the United States. Proclamation 11038 of 29 June 2026: Declaration of Emergency and Authorization for Temporary Duty-Free Importation of Phosphate Fertilizer from Morocco. Fed. Regist. 2026, FR Doc. 2026-13588. 2 July 2026. Available online: https://www.federalregister.gov/documents/2026/07/02/2026-13588/declaration-of-emergency-and-authorization-for-temporary-duty-free-importation-of-phosphate (accessed on 22 November 2026).
80. S&P Global Energy. Trump Suspends Import Duties on Moroccan Fertilizer for Eight Months to Ease Supply. 30 June 2026. Available online: https://www.spglobal.com/energy/en/news-research/latest-news/agriculture/063026-trump-suspends-import-duties-on-moroccan-fertilizer-for-eight-months-to-ease-supply (accessed on 22 November 2026).
81. Baffes, J.; Temaj, K.; World Bank Data Blog. Fertilizer Prices Surge as Strait of Hormuz Disruptions Tighten Supplies. 14 May 2026. Available online: https://blogs.worldbank.org/en/opendata/fertilizer-prices-surge-as-strait-of-hormuz-disruptions-tighten- (accessed on 22 November 2026).
82. Agricultural Market Information System (AMIS). Market Monitor. May 2026. Available online: https://www.foodsecurityportal.org/sites/default/files/2026-05/AMIS_Market_Monitor_May_2026.pdf (accessed on 22 November 2026).
83. Arita, S.; Wang, M.; Kim, J.; Chakravorty, R.; Steinbach, S.; Farmdoc Daily. Strait of Hormuz Disruption Scenarios and Fertilizer Purchasing Risks for U.S. Crop Producers. 29 April 2026. Available online: https://farmdocdaily.illinois.edu/2026/04/strait-of-hormuz-disruption-scenarios-and-fertilizer-purchasing-risks-for-u-s-crop-producers.html (accessed on 22 November 2026).
84. Fertilizer Daily. Urea Price at $409 in August 2026 as Hormuz Risk Eases and China Relaxes Exports. 30 August 2026. Available online: https://www.fertilizerdaily.com/20260830-urea-price-409-august-2026-hormuz-china/ (accessed on 22 November 2026).
85. Clarksen, K.; Fertilizer Daily. China Phosphate Exports Collapse to Near Zero in 2026 as Sulfur Squeeze Bites, Argus Sees 2mt Rebound. 15 October 2026. Available online: https://www.fertilizerdaily.com/20261015-china-phosphate-exports-2026-sulfur-argus/ (accessed on 22 November 2026).
86. Ecofin Agency. First Quantum Becomes Acid Supplier as Hormuz Disruptions Tighten Supply in Zambia. 1 May 2026. Available online: https://www.ecofinagency.com/news-industry/0105-55181-first-quantum-becomes-acid-supplier-as-hormuz-disruptions-tighten-supply-in-zambia (accessed on 22 November 2026).
87. Lobasso, D.V.; PricePedia. Sulphuric Acid: The Suspension of Chinese Exports Tightens an Already Fragile Market. 5 October 2026. Available online: https://www.pricepedia.it/en/magazine/article/2026/10/05/sulphuric-acid-the-suspension-of-chinese-exports-tightens-an-already-fragile-market/ (accessed on 22 November 2026).
88. Enerdata; Daily Energy News. EU Formally Adopts Ban on Russian Pipeline Gas and LNG Imports. January 2026. Available online: https://www.enerdata.net/publications/daily-energy-news/eu-formally-adopts-ban-russian-pipeline-gas-and-lng-imports.html (accessed on 22 November 2026).
89. European Union. Regulation (EU) 2025/1227 of the European Parliament and of the Council of 17 June 2025 on the Modification of Customs Duties Applicable to Imports of Certain Goods Originating in or Exported Directly or Indirectly from the Russian Federation and the Republic of Belarus. Official Journal of the European Union 2025, L 2025/1227, 20 June 2025. Available online: http://data.europa.eu/eli/reg/2025/1227/oj (accessed on 22 November 2026).
90. Baker McKenzie; Global Import Blog. EU: One-Year Suspension of Customs Duties on Certain Fertilisers. 28 May 2026. Available online: https://globalimportblog.bakermckenzie.com/2026/05/28/eu-one-year-suspension-of-customs-duties-on-certain-fertilisers/ (accessed on 22 November 2026).
91. Ukrainska Pravda. Russia Increases Fertiliser Exports to EU despite Higher Tariffs. 15 November 2025. Available online: https://www.pravda.com.ua/eng/news/2025/11/15/8007478 (accessed on 22 November 2026).
92. Fertilizers Europe. Russian Fertilizer Imports: A Call to Action. 2024. Available online: https://www.fertilizerseurope.com/wp-content/uploads/2025/01/Tiffanie_STEPHANI_Event_MEP_Hetman_20241120_FINAL-002.pdf (accessed on 22 November 2026).
93. Jordan News Agency (Petra). JPMC Subsidiary Signs $193 Million Deal to Build Sulfuric Acid Plant in Maan. 11 February 2026. Available online: https://pt1.petra.gov.jo/en/news/jpmc-subsidiary-signs-193-million-deal-to-build-sulfuric-acid-plant-in-maan (accessed on 22 November 2026).

94. Yang, Z.; Shanghai Metals Market (SMM). Thermal Phosphoric Acid Will Accelerate Its Displacement of Purified Wet-Process Acid in the New Energy Sector [SMM Analysis]. 8 April 2026. Available online: https://news.smm.cn/news/103846326 (accessed on 22 November 2026). (In Chinese)
95. Becker, P. *Phosphates and Phosphoric Acid: Raw Materials, Technology, and Economics of the Wet Process*, 2nd ed.; Marcel Dekker: New York, NY, USA, 1989.
96. Bundesgesetzblatt. *Verordnung über die Verwertung von Klärschlamm, Klärschlammgemisch und Klärschlammkompost (Klärschlammverordnung—AbfKlärV)*; Bundesgesetzblatt: Bonn, Germany, 2017; Volume I, p. 3465.
97. European Union. Commission Implementing Regulation (EU) 2026/1116 of 26 May 2026 Listing the Products, Components and Waste Streams Considered as Having a Relevant Critical Raw Materials Recovery Potential under Regulation (EU) 2024/1252. Official Journal of the European Union 2026, L 2026/1116, 27 May 2026. Available online: http://data.europa.eu/eli/reg_impl/2026/1116/oj (accessed on 22 November 2026).
98. European Commission. *Fertiliser Action Plan: Partnership for Ensuring the Availability, Affordability and Strategic Autonomy in Home-Grown EU Fertilisers*; COM(2026) 310 Final; European Commission: Strasbourg, France, 2026. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52026DC0310 (accessed on 22 November 2026).
99. Krüger, O.; Grabner, A.; Adam, C. Complete Survey of German Sewage Sludge Ash. *Environ. Sci. Technol.* **2014**, *48*, 11811–11818. [CrossRef] [PubMed]
100. Herzel, H.; Krüger, O.; Hermann, L.; Adam, C. Sewage Sludge Ash—A Promising Secondary Phosphorus Source for Fertilizer Production. *Sci. Total Environ.* **2016**, *542*, 1136–1143. [CrossRef] [PubMed]
101. Hussain, I. The Operating Experience of Nitrophosphate Plant. *Procedia Eng.* **2012**, *46*, 172–177. [CrossRef]
102. Habashi, F.; Awadalla, F.T.; Yao, X.-B. The Hydrochloric Acid Route for Phosphate Rock. *J. Chem. Technol. Biotechnol.* **1987**, *38*, 115–126. [CrossRef]
103. Walters, M.D. A Technical Review of the Improved Hard Process. In *Paper P1102, Presented at the Fertiliser Association of India International Technical Conference, New Delhi, India, April 2011*; KEMWorks Technology: Lakeland, FL, USA, 2011. Available online: https://kemworks.com/a-technical-review-of-the-improved-hard-process/ (accessed on 22 November 2026).
104. World Fertilizer. JDC's IHP Technology Successfully Produces High Quality Super Phosphoric Acid. 7 August 2018. Available online: https://www.worldfertilizer.com/phosphates/07082018/jdcs-ihp-technology-successfully-produces-high-quality-super-phosphoric-acid/ (accessed on 22 November 2026).
105. World Fertilizer. Prayon Acquires Parts of Ecophos Assets. 7 May 2020. Available online: https://www.worldfertilizer.com/phosphates/07052020/prayon-acquires-parts-of-ecophos-assets/ (accessed on 22 November 2026).
106. Bertau, M.; Fuhrland, M.; Fröhlich, P.; Greb, V.-G.; Martin, G. Verfahren zur Herstellung von Phosphorsäure aus Phosphorhaltigen Primär- und Sekundärrohstoffen. European Patent EP 3266742 B1, 23 October 2019.
107. Prayon. DCP Feed—Ecophos Process. Available online: https://prayon.com/en/processes/dcp-ecophos (accessed on 22 November 2026).
108. Bund/Länder-Arbeitsgemeinschaft Abfall (LAGA). *Ressourcenschonung Durch Phosphor-Rückgewinnung—4. Bericht der LAGA Ad-hoc-AG an die Umweltministerkonferenz*; LAGA: Bremen, Germany, 2024. Available online: https://www.laga-online.de/documents/bericht-laga-ag-phosphor-stand-2024_1747031775.pdf (accessed on 22 November 2026).
109. Lorenz-Meyer, A. Wer Schon 2029 Liefern Kann. ZfK—Zeitung für kommunale Wirtschaft. 8 July 2026. Available online: https://www.zfk.de/wasser-abwasser/wer-schon-2029-liefern-kann (accessed on 22 November 2026).
110. Landesverwaltungsamt Sachsen-Anhalt. *Genehmigungsbescheid nach § 4 Bundes-Immissionsschutzgesetz (BImSchG): Errichtung und Betrieb Einer Anlage zur Gewinnung von Phosphor aus Aschen (38.000 t Asche pro Jahr) am Standort Schkopau, Phosphorgewinnung Schkopau (PGS) GmbH*; Az. 402.4.2-44008/22/18; Landesverwaltungsamt Sachsen-Anhalt: Halle (Saale), Germany, 2024; pp. 4–6, 42–43, 49–50. Available online: https://lvwa.sachsen-anhalt.de/fileadmin/Bibliothek/Politik_und_Verwaltung/LVWA/LVwA/Dokumente/3_wirtschaft_kultur_verbrschutz_bau/309/4_landwirtschaftumwelt/402/bekanntmachungen/2024_10/22_18__4_15.08.24-1.pdf (accessed on 22 November 2026).
111. Smart Water Magazine. Germany Breaks Ground on First Full-Scale Phosphorus Recovery Plant. 2025. Available online: https://smartwatermagazine.com/news/smart-water-magazine/germany-breaks-ground-first-full-scale-phosphorus-recovery-plant (accessed on 22 November 2026).
112. Fröhlich, P.; Eschment, J.; Martin, G.; Lohmeier, R.; Bertau, M. The PARFORCE-Technology (Germany). In *Phosphorus: Polluter and Resource of the Future—Removal and Recovery from Wastewater*; Schaum, C., Ed.; IWA Publishing: London, UK, 2018; pp. 417–424. [CrossRef] [PubMed]
113. Ruhrverband. Phosphorus Recycling from Sewage Sludge Ash: Demonstration Plant Is in Operation. Press Release. 21 March 2025. Available online: https://ruhrverband.de/en/press/press-releases/detail/phosphor-recycling-aus-klaerschlammasche-demonstrationsanlage-ist-in-betrieb (accessed on 22 November 2026).
114. Ruhrverband. Project AMPHORE. Available online: https://ruhrverband.de/en/sustainability/research-projects/current-projects/amphore (accessed on 22 November 2026).

115. Le, H.; Montag, D.; Blöhse, D.; Evers, H. Phosphorrückgewinnung im großtechnischen Maßstab: Erste Betriebsergebnisse aus dem Projekt AMPHORE. In *59. Essener Tagung für Wasserwirtschaft "Resiliente Wasserwirtschaft"*; Wintgens, T., Ed.; Gewässerschutz, Wasser, Abwasser; Gesellschaft zur Förderung des Instituts für Siedlungswasserwirtschaft an der RWTH Aachen e.V.: Aachen, Germany, 2026; Volume 261, pp. 55/1–55/15.
116. Haneklaus, N.; Barbossa, S.; Basallote, M.D.; Bertau, M.; Bilal, E.; Chajduk, E.; Chernysh, Y.; Chubur, V.; Cruz, J.; Dziarczykowski, K.; et al. Closing the Upcoming EU Gypsum Gap with Phosphogypsum. *Resour. Conserv. Recycl.* **2022**, *182*, 106328. [CrossRef]
117. Chernysh, Y.; Yakhnenko, O.; Chubur, V.; Roubík, H. Phosphogypsum Recycling: A Review of Environmental Issues, Current Trends, and Prospects. *Appl. Sci.* **2021**, *11*, 1575. [CrossRef]
118. Bilal, E.; Bellefqih, H.; Bourgier, V.; Mazouz, H.; Dumitraş, D.-G.; Bard, F.; Laborde, M.; Caspar, J.P.; Guilhot, B.; Iatan, E.-L.; et al. Phosphogypsum Circular Economy Considerations: A Critical Review from More than 65 Storage Sites Worldwide. *J. Clean. Prod.* **2023**, *414*, 137561. [CrossRef]
119. Merchant Research & Consulting. Calcium Chloride: A Versatile Inorganic Salt in a Changing Market Landscape. 24 August 2023. Available online: https://mcgroup.co.uk/news/20230824/calcium-chloride-a-versatile-inorganic-salt-in-a-changing-market-landscape.html (accessed on 22 November 2026).
120. Statista Research Department. Market Volume of Calcium Chloride Worldwide from 2015 to 2022, with a Forecast for 2023 to 2030. 5 July 2023. Available online: https://www.statista.com/statistics/1245251/calcium-chloride-market-volume-worldwide/ (accessed on 22 November 2026).
121. Fluor Corporation; Miocene, Inc.; Escalante Geological Services, LLC; Geomega, Inc. *Pre-Feasibility Study & Technical Report Summary, Fort Cady Project, California*; Prepared for 5E Advanced Materials, Inc.; Exhibit 96.1 Filed with the U.S. Securities and Exchange Commission; Section 16.3 (Market Study Based on Kline & Company); U.S. Securities and Exchange Commission (SEC): Washington, DC, USA, 2025; pp. 95–96. Available online: https://www.sec.gov/Archives/edgar/data/1888654/000119312525174941/d932700dex961.htm (accessed on 22 November 2026).
122. MacGregor, J.R. Lime. In *Mineral Commodity Summaries 2026*; U.S. Geological Survey: Reston, VA, USA, 2026.
123. European Chemicals Agency (ECHA). ECHA's Risk Assessment Committee Adopts Its Opinion on PFAS Restriction Proposal. Press Release. 3 March 2026. Available online: https://echa.europa.eu/-/echa-s-risk-assessment-committee-adopts-its-opinion-on-pfas-restriction-proposal (accessed on 22 November 2026).
124. CMS. Support for EU-Wide PFAS Restriction with Targeted Derogations: What Happens Next? 8 April 2026. Available online: https://cms.law/en/gbr/legal-updates/support-for-eu-wide-pfas-restriction-with-targeted-derogations-what-happens-next (accessed on 22 November 2026).
125. Wagman, D.D.; Evans, W.H.; Parker, V.B.; Schumm, R.H.; Halow, I.; Bailey, S.M.; Churney, K.L.; Nuttall, R.L. The NBS Tables of Chemical Thermodynamic Properties: Selected Values for Inorganic and C_1 and C_2 Organic Substances in SI Units. *J. Phys. Chem. Ref. Data* **1982**, *11*, 2-1–2-392.

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