Supplementary Material

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

M. Bertau, S.T. Shutters, G. Steiner

This document lists every value plotted in Figures 1, 2 and 4 of the manuscript, together with the source and edition each value is taken from, and it documents the key calculations given in the text. Nothing here is new data. It is the content of the figures and calculations in tabular form, so that a reader can reproduce them. Numbers in square brackets refer to the reference list of the manuscript. The same data, with the key calculations as live formulas, are provided in the Excel workbook (Supplementary File S2).

A note on sources and editions

Most quantities are taken from the Mineral Commodity Summaries (MCS) of the United States Geological Survey (USGS). USGS revises its figures between editions, sometimes considerably. Every value is therefore attributed to the specific edition it is taken from, and the most recent edition is used wherever a value has been revised. Sulfur prices before 2026 are average unit values of elemental sulfur, f.o.b. mine or plant, in the United States. They are not spot quotations, and they are not directly comparable with the 2026 quotations in Table S3 and in Table 1 of the manuscript, which are listed separately and are not plotted for this reason.

Table S1. Phosphate rock mine production and reserves by country, in thousand tonnes (kt) gross weight, from the MCS 2026 [11]. These are the data behind Figure 1a (reserves) and Figure 1b (mine production).

Country	Production 2024 (kt)	Production 2025e (kt)	Share 2025 (%)	Reserves (Mt)	Share of reserves (%)
Morocco	35,300	36,000	14.4	50,000	68.5
China	105,000	110,000	44.0	3,400	4.7
Egypt	5,300	5,500	2.2	2,800	3.8
Tunisia	3,280	3,300	1.3	2,500	3.4
Russia	14,400	14,000	5.6	2,400	3.3
Algeria	2,000	2,000	0.8	2,200	3.0
Brazil	5,300	5,000	2.0	1,600	2.2
South Africa	2,220	2,200	0.9	1,500	2.1
United States	19,400	20,000	8.0	1,000	1.4
Saudi Arabia	10,000	10,000	4.0	1,000	1.4
Finland	974	980	0.4	1,000	1.4
Jordan	11,500	12,000	4.8	820	1.1
Australia	2,500	2,500	1.0	800	1.1
Kazakhstan	1,700	1,900	0.8	260	0.4
Syria	800	800	0.3	250	0.3
Peru	4,800	4,800	1.9	210	0.3
Uzbekistan	950	950	0.4	100	0.1
Turkey	1,220	1,200	0.5	71	0.1
Israel	2,380	2,400	1.0	60	0.1
Senegal	2,800	2,800	1.1	50	0.1
India	1,700	1,500	0.6	31	<0.1

Country	Production 2024 (kt)	Production 2025e (kt)	Share 2025 (%)	Reserves (Mt)	Share of reserves (%)
Vietnam	3,000	3,000	1.2	30	<0.1
Togo	1,560	1,600	0.6	30	<0.1
Mexico	365	450	0.2	30	<0.1
Other countries	769	770	0.3	800	1.1
World (rounded)	**239,000**	**250,000**	**100.0**	**73,000**	**100.0**

a) Figure 1a shows the seven countries with the largest reserves (Morocco, China, Egypt, Tunisia, Russia, Algeria, Brazil) and Figure 1b the seven largest producers in 2025 (China, Morocco, United States, Russia, Jordan, Saudi Arabia, Egypt). In both panels, "Other" is the world total minus the listed countries, i.e., 8.1 billion tonnes of reserves and 42 million tonnes of production. The shares in the category labels refer to the rounded world totals given by USGS.

b) The reserves of Australia are 800,000 kt. In the PDF of the MCS 2026, footnote 5 runs into this number, so that it can be misread as 5,800,000 kt. Only 800,000 kt is consistent with the world total.

c) Dividing world reserves by 2025 mine production gives a static reserve lifetime of 292 years, which the manuscript rounds to about 290 years. This is a static ratio, not a forecast.

Table S2. Annual prices of triple superphosphate (TSP), elemental sulfur and Brent crude oil, 2006–2025. These are the series plotted in Figure 2a (TSP and sulfur) and Figure 2b (Brent).

Year	TSP (USD/t)	Months	Sulfur (USD/t)	Sulfur, USGS edition	Brent (USD/bbl)
2006	202.7	5	32.85	MCS 2010	65.16
2007	339.1	12	36.29	MCS 2010	72.44
2008	879.4	12	262.32	MCS 2010	96.94
2009	257.4	12	1.73	MCS 2014	61.74
2010	381.9	12	70.16	MCS 2015	79.61
2011	538.3	12	159.88	MCS 2015	111.26
2012	462.0	12	123.54	MCS 2017	111.63
2013	380.8	12	68.71	MCS 2018	108.56
2014	382.0	12	80.07	MCS 2018	98.97
2015	377.6	12	87.62	MCS 2018	52.32
2016	290.3	12	37.88	MCS 2021	43.64
2017	283.2	12	46.39	MCS 2021	54.13
2018	346.7	12	81.16	MCS 2021	71.34
2019	294.5	12	51.08	MCS 2021	64.30
2020	265.0	12	24.90	MCS 2025	41.96
2021	538.2	12	90.40	MCS 2026	70.86
2022	716.1	12	177.80	MCS 2026	100.93
2023	480.2	12	58.90	MCS 2026	82.49
2024	474.6	12	46.42	MCS 2026	80.52
2025	577.6	12	180.00	MCS 2026 (est.)	69.14

a) TSP is the annual average of the monthly World Bank price series (triple superphosphate, bulk, spot), retrieved via Indexmundi [26]. The column "Months" gives the number of monthly values averaged. For 2006, only August to December are available.

b) Sulfur is the average unit value of elemental sulfur, f.o.b. mine or plant, in the United States, from the USGS edition named in the next column [15–22,40]. The 2025 value is a USGS estimate.

c) Brent is the annual average of the Europe Brent spot price FOB published by the U.S. Energy Information Administration (EIA) [27,28].

Table S3. Values for 2026. They are quotations or partial-year averages and not annual averages, and they are therefore not plotted in Figure 2. The full set of 2026 price quotations by market is given in Table 1 of the manuscript.

Quantity	Period	Value	Unit	Source
TSP, quarterly average	Q1 2026	541.2	USD/t	World Bank Pink Sheet, October 2026 [25]
TSP, quarterly average	Q2 2026	702.4	USD/t	World Bank Pink Sheet, October 2026 [25]
TSP, quarterly average	Q3 2026	704.6	USD/t	World Bank Pink Sheet, October 2026 [25]
Brent, monthly average	January 2026	66.60	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	February 2026	70.89	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	March 2026	103.13	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	April 2026	117.29	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	May 2026	107.14	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	June 2026	85.40	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	July 2026	83.76	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	August 2026	91.08	USD/bbl	EIA, monthly series [27,28]
Brent, monthly average	September 2026	114.16	USD/bbl	EIA, monthly series [27,28]
Brent, average July–September	Q3 2026	96.3	USD/bbl	calculated from the three months above
Sulfur spot, Middle East FOB	end of May 2026 (midpoint of 815–820)	817.5	USD/t	S&P Global, 29 May 2026 [23]
Sulfur spot, Vancouver	August 2026	1,040.0	USD/short ton	farmdoc daily, 25 August 2026 [24]

a) The TSP average for July–September 2026 (Q3, 704.6 USD/t) is the value compared with the 2025 annual average in the manuscript (note c). The Brent average for July–September 2026 is given for reference.

b) The Middle East quotation is the midpoint of the range of 815–820 USD/t FOB reported for the end of May 2026.

c) The rise of TSP from the 2025 annual average (Table S2) to the Q3 2026 average is the increase of about 22% stated in the manuscript (704.6 / 577.6 = 1.22).

Table S4. Sources of global sulfuric acid production in 2022, after the Sulphuric Acid Supply Study of CRU International, public version, pp. 10 and 45 [42]. These are the data behind Figure 4.

Production route	Share (%)	Mt H_2SO_4 stated by CRU	Mt H_2SO_4 (share × total)
Sulfur burning	60	172.0	171.0
Smelter off-gas	30	86.3	85.5
Pyrite roasting	6	17.8	17.1
Spent-acid recycling	2	—	5.7
Other processes	2	—	5.7
Total	**100**	**285**	**285.0**

a) CRU states tonnages only for sulfur burning, smelter acid and pyrite roasting. The last column applies the stated shares to the total of 285 Mt and is shown for orientation only.

b) According to CRU, about 95% of the elemental sulfur burned is recovered from oil refining and natural-gas processing, and about 90% of global sulfuric acid production depends on by-products of other industries.

Table S5. Key calculations stated in the manuscript. Molar masses: $Ca_5(PO_4)_3F$ 504.30, P_2O_5 141.94, H_2SO_4 98.08, $CaSO_4 \cdot 2H_2O$ 172.17, $CaCl_2$ 110.98, $Ca(OH)_2$ 74.09 and S 32.06 g/mol.

Quantity	Result	Unit	Basis
Sulfuric acid demand, stoichiometric	2.30	t/t P_2O_5	Equation (1): 5 H_2SO_4 per $Ca_5(PO_4)_3F$, which yields 1.5 P_2O_5
Phosphogypsum (dihydrate), stoichiometric minimum	4.04	t/t P_2O_5	5 $CaSO_4 \cdot 2H_2O$ per $Ca_5(PO_4)_3F$
Sulfur use in practice	0.87	t S/t P_2O_5	0.4 t S per t DAP, DAP contains 46% P_2O_5 [23,24]
Sulfuric acid use in practice (indirect estimate)	2.66	t/t P_2O_5	Previous row × 98.08/32.06
Excess over stoichiometry	15	%	Practical / stoichiometric sulfuric acid demand
Sulfuric acid from sulfur	3.06	t/t S	1 mol S yields 1 mol H_2SO_4 (100%)
Calcium chloride from HCl digestion	2.61	t/t P_2O_5	5 $CaCl_2$ per $Ca_5(PO_4)_3F$
Hydrated lime after regeneration (PARFORCE)	1.74	t/t P_2O_5	5 $Ca(OH)_2$ per $Ca_5(PO_4)_3F$
$CaCl_2$ from a plant of 1 Mt P_2O_5/a	2.6	Mt/a	1 Mt P_2O_5/a × 2.61 t $CaCl_2$/t P_2O_5
$CaCl_2$ from a plant of 1 Mt P_2O_5/a, share of world production 2022 (4.58 Mt, mass basis not stated in the source)	57	%	Merchant Research & Consulting [119]
$CaCl_2$ from a plant of 1 Mt P_2O_5/a, share of world market volume 2024 (3.825 Mt, dry basis)	68	%	Fort Cady pre-feasibility study [121], Section 16.3
Static lifetime of phosphate rock reserves	292	years	73,000 Mt reserves / 250 Mt mine production 2025e (Table S1)
Sulfur value / DAP price, early 2024 (upper bound)	6.7	%	0.4 t S per t DAP, sulfur below 100 USD, DAP 600–700 USD per short ton, the lower DAP price gives the upper bound [24]
Sulfur value / DAP price, August 2026	48.9	%	0.4 t S per t DAP, sulfur about 1,040 USD, DAP about 850 USD per short ton [24]
Conversion factor P → P_2O_5	2.291	kg P_2O_5/kg P	141.94 / (2 × 30.974)
PARFORCE, sewage sludge ash: electricity 26.5 kWh/kg P	11.57	MWh/t P_2O_5	[112], Table 26.1, divided by the conversion factor
PARFORCE, sewage sludge ash: heat 11.5 kWh/kg P	5.02	MWh/t P_2O_5	[112], Table 26.1, divided by the conversion factor

a) The stoichiometric values assume ideal fluorapatite. Real phosphate rock contains carbonate, fluoride excess and impurities, which is why practical sulfuric acid consumption is about 2.7 t per t P_2O_5 and phosphogypsum generation about 5 t per t P_2O_5. [35].

b) The sulfur-to-DAP ratio compares quoted prices. It is an illustrative indicator of price exposure and not a producer cost share. It overstates the cost pressure on producers that buy sulfur under quarterly contracts or hold inventories. At the US contract price for the third quarter of 2026, 705 USD per long ton or about 629 USD per short ton, the same calculation gives 0.4 × 629 / 850 = 30% instead of 49% (Section 3.3 of the manuscript).

c) An energy demand per kilogram of phosphorus is divided by the conversion factor of 2.29 to express it per kilogram of P_2O_5, because one kilogram of phosphorus corresponds to 2.29 kg of P_2O_5.

d) Table 26.1 of [112] also lists a net demand of 21.0 kg HCl and 0.3 kg NaOH per kg P for sewage sludge ash. Chloride is lost with the solid digestion residue and with the iron and aluminum chloride solution that is reused in wastewater treatment, so the chloride loop is not completely closed. The quantity of acid regenerated per kilogram of phosphorus has not been published.

Table S6. Chronology of the events of 2025–2026 discussed in Section 3.3 of the manuscript. The column Type distinguishes announcements, implemented measures, observed market and trade effects, and forecasts. Numbers in square brackets refer to the reference list of the manuscript.

Date	Event	Type	Source
1 November 2025	Russia introduces a temporary ban on exports of technical sulfur by Government Resolution No. 1730, after drone strikes in September 2025 had damaged the Astrakhan and Orenburg gas processing plants.	Implementation	[56,57]
Fourth quarter of 2025	Sulfur supply about 1.0 Mt lower because Russian volumes are missing and plants in the Middle East have unplanned maintenance. Stocks in Kazakhstan, Turkmenistan and Iran are exhausted. The Middle East price reaches almost 520 USD/t FOB in December.	Market effect	[53]
December 2025	Mosaic idles single superphosphate production at two Brazilian plants, citing the sharp increase in sulfur prices.	Implementation (company)	[65]
28 January 2026	Extension of the Russian sulfur export ban reported.	Implementation	[54]
February 2026	Sulfuric acid prices in Italy reach a record level, attributed by analysts to a product shortage across Europe.	Market effect	[51]
28 February 2026	Outbreak of war in the Middle East closes the Strait of Hormuz to most commercial shipping.	Physical disruption	[23]
Late February to mid-April 2026	Spot price of sulfuric acid in Chile doubles to about 380 USD/t.	Market effect	[33]
31 March 2026	Russia extends the sulfur export ban to 30 June 2026 (Decree No. 350).	Implementation	[58]
8 April 2026	Mosaic announces the idling of its Araxá complex, which it intends to sell, and of mining at Patrocínio, reducing its annual phosphate production in Brazil by about 1 Mt. Stated reason: to reduce costs and redeploy capital. The company expects a limited effect on adjusted EBITDA given elevated sulfur prices.	Implementation (company)	[66]
10 April 2026	Reported instruction to Chinese producers to halt exports of smelter acid from May 2026.	Announcement (reported)	[61]
1 May 2026	Suspension of export clearance for industrial and smelter sulfuric acid until the end of 2026, announced jointly by the Ministry of Commerce and the General Administration of Customs according to SunSirs. The official notice could not be located.	Implementation (reported)	[63]
May 2026	Mosaic withdraws its phosphate production guidance, citing record sulfur prices due to limited availability, and begins partial curtailments in Louisiana and Florida.	Implementation (company)	[67]
21 May 2026	The Egyptian Financial & Industrial Co. begins maintenance at its three granular superphosphate plants because of high sulfur costs, according to a source at the company.	Implementation (company, reported)	[23]
End of May 2026	Sulfur spot prices of 815–820 USD/t FOB Middle East and 1,200 USD/t CFR Brazil.	Market effect	[23]
26 June 2026	Russia extends the sulfur export ban to 31 December 2026.	Implementation	[55]

Date	Event	Type	Source
29 June 2026	The United States suspends countervailing duties on Moroccan phosphate fertilizers for up to eight months (Proclamation 11038), citing a supply emergency. Sulfur is not mentioned.	Implementation (policy response)	[79,80]
January–June 2026	Chinese sulfuric acid exports of 0.78 Mt, against 2.19 Mt a year earlier (customs data).	Trade effect	[63]
January–June 2026	Global phosphate fertilizer exports 9% lower year-on-year according to IFPRI. OCP puts the contraction of traded volumes at about 22%.	Trade effect	[60,64]
July 2026	Mosaic announces further production reductions in the United States and Brazil, citing curtailed raw material supply availability. According to Argus, the company stated that sulfur inventories were declining. It told S&P Global that it adjusted Brazilian production amid reduced global supply and rising sulfur prices.	Implementation (company)	[68,69]
August 2026	Vancouver sulfur spot price about 1,040 USD per short ton.	Market effect	[24]
12 September 2026	Russia restricts exports of sulfuric acid until 31 December 2026. Exports require government approval.	Implementation	[59]
29 September 2026	OCP reports its results for the first half of 2026: revenue −7.3%, EBITDA −28.5%, net loss attributable to shareholders of 2.84 billion MAD.	Financial effect	[64,73]
Third quarter of 2026	Mosaic states that it aligned phosphate production with the availability of affordable sulfur and names constrained raw material availability and limited customer credit availability in Brazil as reasons for lower production.	Company disclosure	[70,71]
Early November 2026	Mosaic: spot sulfur prices falling but still too high to restart curtailed production. Global phosphate supply expected to remain constrained into 2027.	Company statement and forecast	[72]
2026	CRU estimates a sulfur deficit of about 1.9 Mt for 2025 and expects the market to remain in deficit until 2028.	Forecast	[45]

a) Entries marked as reported rest on trade press or news agency reports and could not be verified against an official document. The Chinese suspension of sulfuric acid exports is the main example. SunSirs attributes it to a joint announcement by the Ministry of Commerce and the General Administration of Customs, which we could not locate. Its effect is visible in the customs data.

b) Company reasons are given as stated by the companies. Interpretations by trade press are not attributed to the companies (Table 3 of the manuscript).

Table S7. Reaction enthalpy of sulfuric acid production from elemental sulfur under standard conditions (298.15 K). The heat released explains the steam export of sulfur-burning plants discussed in Section 3.1 of the manuscript. Negative values denote heat released.

Step	Reaction	ΔH° (kJ/mol)	GJ per t H_2SO_4
Combustion of sulfur	$S(s) + O_2(g) \rightarrow SO_2(g)$	−296.8	−3.03
Oxidation of SO_2 (contact stage)	$SO_2(g) + ½\ O_2(g) \rightarrow SO_3(g)$	−98.9	−1.01
Absorption of SO_3	$SO_3(g) + H_2O(l) \rightarrow H_2SO_4(l)$	−132.4	−1.35
Total	**$S(s) + 1½\ O_2(g) + H_2O(l) \rightarrow H_2SO_4(l)$**	**−528.2**	**−5.39**

a) Standard enthalpies of formation from the NBS tables (Wagman et al. [125]): $SO_2(g)$ −296.83, $SO_3(g)$ −395.72, $H_2O(l)$ −285.83 and $H_2SO_4(l)$ −813.99 kJ/mol. The total equals $\Delta fH°(H_2SO_4, l) - \Delta fH°(H_2O, l)$. One tonne of H_2SO_4 corresponds to 10,196 mol (M = 98.08 g/mol).

b) The combustion of sulfur alone releases 9.26 GJ per tonne of sulfur. One tonne of H_2SO_4 contains 0.327 t of sulfur, so combustion contributes 3.03 GJ per tonne of acid, or 56% of the total. The oxidation of SO_2 and the absorption of SO_3 provide the remaining 44%.

c) For a plant producing 1,000 t/d of H_2SO_4, the heat released corresponds to about 5,400 GJ per day, or a thermal power of about 62 MW. Per tonne of P_2O_5, it corresponds to about 12.4 GJ at the stoichiometric demand of 2.30 t H_2SO_4 and to about 14.5 GJ at the indirect estimate of 2.7 t H_2SO_4 (Table S5).

d) Comparison with the EU BREF document [38]: its energy balance for a sulfur-burning double-contact plant of 1,000 t/d (100% H_2SO_4, 11% v/v SO_2) gives 3.1–3.4 GJ per tonne of H_2SO_4 recoverable as high-pressure steam and 2.1–2.4 GJ as low-pressure steam (Table 4.17 of [38]), together 5.2–5.8 GJ. The text of [38] gives an export of about 6 GJ per tonne for a modern plant (Section 4.4.15). These values lie close to, and at their upper end slightly above, the standard reaction enthalpy. The BREF does not state the reference state of its balance. Compression work of the main air blower, which ends up as heat in the process gas, may account for part of the difference. The standard reaction enthalpy of about 5.4 GJ per tonne is therefore the more conservative figure.