Supporting Information

Table S1: Leading Phosphate Ore Reserves

Country	Deposits Types	Phosphate Minerals	Gangue Minerals	Reserves (Million Tons)
China	Sedimentary, Igneous, Metamorphic, Guano	Collophane, fluorapatite, francolite, monazite	Dolomite, quartz, clay, calcite, goethite, chlorite, zircon	3200
Morocco	Marine sedimentary	Apatite	Quartz, dolomite, calcite, aluminum silicate minerals	50000
United Sates	Sedimentary, Igneous, Metamorphic, Guano	Francolite, monazite, wavellite, crandallite	Quartz, dolomite, calcite, magnetite, aluminum silicate minerals, goethite, ankerite	1000
Russia	Marine sedimentary, Igneous	Fluorapatite, hydroxylapatite, francolite, monazite	Magnetite, ilmenite, titanium magnetite, baddeleyite, forsterite, calcite, phlogopite, mica, titanium augite, pyrite	600
Jordan	Marine sedimentary	-	-	1000
Saudi Arabia	Marine sedimentary	-	-	1400
Vietnam	Sedimentary, Metamorphic, Guano	Apatite	-	30
Brazil	Igneous, Guano	Fluorapatite, francolite, collophane, dahllite, monazite-(Ce), phoscorite, metavariscite, strengite, variscite	Calcite, magnetite, quartz, aluminum silicate minerals, pyrite, ankerite, flfluorite, barite, quartz, carbonate	1700
Egypt	Marine sedimentary	Collophane, francolite, dahllite, wavellite, manganapatite	Pyrite, quartz, calcite, dolomite, goethite, chlorite, zircon, montmorillonite, gypsum, glauconite	1300
Peru	Marine sedimentary	Fluorapatite	Carbonates, diatomite	210
Israel	Marine sedimentary	-	-	62
Tunisia	Marine sedimentary	-	-	100
Australia	Sedimentary, Metamorphic, Igneous, Guano	Fluorapatite, collophane, monazite, wavellite, dufrenite, millisite, churchite, xenotime, flflorencite, goyazite	Calcite, dolomite, quartz, hematite, goethite, quartz, Aluminum silicate minerals	1200
Syria	Sedimentary	-	-	1800
South Africa	Igneous, Marine sedimentary	Fluorapatite, francolite, collophane, dahllite, monazite-(Ce), phoscorite, metavariscite, strengite, variscite	Calcite, magnetite, quartz, aluminium silicate minerals, pyrite, ankerite, flfluorite, barite, quartz, carbonate, anatase, Au, Mn, aegirine, amphibole, pyroxene, arfvedsonite, vermiculite, serpentine, carbonatite minerals enriched in copper and iron	1400

Table S2: Abundant Phosphate Minerals and their Occurrence

Name	Types	Formula	Occurrence
Apatite	Chlorapatite	$Ca_5(PO_4)3Cl$	Igneous rocks, Metamorphic rocks
	Hydroxylapatite	$Ca_5(PO_4)_3OH$	Igneous rocks, Metamorphic rocks, Sedimentary rocks
	Dahllite or Carbonate-hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH,O)$	Metamorphic rocks, Sedimentary rocks

	Fluorapatite	$Ca_5(PO_4)_3F$	Igneous rocks, Metamorphic rocks, Sedimentary rocks
	Francolite or Carbonate-flfluorapatite	$Ca_5(PO_4,CO_3)_3(F,O)$	Metamorphic rocks, Sedimentary rocks
Monazite	Monazite-(Ce)	$CePO_4$	Igneous rocks, Metamorphic rocks, Sedimentary rocks
Xenotime	Xenotime-(Y)	YPO_4	Igneous rocks, Metamorphic rocks
Vivianite		$Fe_3(PO_4)_2{\cdot}8(H_2O)$	Igneous rocks, Metamorphic rocks, Sedimentary rocks
Variscite		$AlPO_4{\cdot}2(H_2O)$	Metamorphic rocks, Sedimentary rocks
Wavellite		$Al_3(PO_4)_2(OH,F)_3{\cdot}5(H_2O)$	Metamorphic rocks, Sedimentary rocks
Monetite		$CaHPO_4$	Igneous rocks, Sedimentary rocks
Whitlockite		$Ca_9Mg\ (PO_4)_6(HPO_4)$	Metamorphic rocks, Sedimentary rocks
Brushite		$Ca(HPO_4){\cdot}2H_2O$	Sedimentary rocks
Struvite		$(NH_4)Mg(PO_4){\cdot}6H_2O$	Sedimentary rocks
Variscite		$Al(PO_4){\cdot}2H_2O$	Metamorphic rocks, Sedimentary rocks

Table S3: Beneficiation of Phosphate Rock with Different Technologies

Methods	Feed (% P_2O_5)	Concentration (% P_2O_5)	Advantages	Limits	Recovery (%)
Flotation	12-24	21-38	1) Widely used for low-grade sedimentary phosphate ore 2) Applicable for igneous phosphate 3) Effective for free minerals 4) Tests optimization (dosage, duration) 5) Diversity of flotation type (reverse, direct, double reverse, reverse-direct, double reverse)	1) Use of chemical reagents 2) High water consumption 3) Demands technical skills for use 4) High carbonate content of sedimentary phosphate ore 5) Presence of high carbonate and siliceous contents	65-95
Attrition Scrubbing and Desliming	12-23	13-29	1) Separation based on particle size 2) Provides suitable size for processing 3) Recovery of fine particles 4) Widely used as pre-concentration process	1) Mineral encapsulate in the gangue 2) Presence of humid and clay material 3) Moderate energy consumption	34-73
Electrostatic Separation	18-25	30-36	1) Eco-friendly 2) Separation on three products: conductive, non-conductive, and mixed	1) Complex separation system 2) Requires technical skills for use 3) High-cost investment and rarely used	65-85
Magnetic Separation	7-27	30-38	1) Eco-friendly 2) Easy to manipulate 3) Separation based on magnetic susceptibility 4) Applicable for igneous phosphate 5) Recommended for high-MgO phosphate 6) Adjustable process (low or high intensity)	1) Moderately used 2) Medium liberation degree 3) High capital cost 4) Separator intensities depend on the material (dry/ humid)	55-80
Gravity Separation	9-25	27-31	1) Separation based on grain density 2) Low-cost investment 3) Easier manipulation Eco-friendly 4) Depends on liberation degree 5) Good process for pre-concentration	1) Presence of fine and clay fraction 2) Difference in density between minerals must be > 1 g/cm3 3) Not applicable to all minerals 4) Requires determination of concentration criteria 5) Requires classification process 6) High water consumption	52-98

Calcinations	9-24	19-33	1) Very low water consumption 2) Complete elimination of carbonates 3) Recommended in areas with cheap energy 4) Concentrate suitable for phosphoric acid production 5) Applicable for sedimentary phosphate ore with high carbonate content and organic matter	1) High thermal energy consumption 2) Phosphate concentrate with low reactivity requires high capital costs 3) Insufficient quality of calcined product 4) Time-consuming 5) Not applicable for igneous rock and sedimentary rock with siliceous gangue 6) Changes surface properties of phosphate minerals	60-98