Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Engineering Sulfate Stability for Metal Recovery from Bauxite Residue: A Critical Review of Selective Sulfation, Roasting, Water Leaching, and Process Integration

Antonio Clareti Pereira, PhD
PhD in Chemical Engineering
Federal University of Minas Gerais (UFMG))
Belo Horizonte, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Bauxite residue is simultaneously a high-volume alkaline industrial residue and a polymetallic secondary resource containing iron, aluminum, titanium, scandium, rare earth elements, gallium, vanadium, and other potentially valuable constituents. This critical narrative/process-engineering review evaluates selective sulfation as a strategy for separating target metals from the dominant Fe–Al matrix by exploiting sequential differences in sulfate formation, thermal stability, aqueous solubility, and downstream separability. The review distinguishes sulfuric-acid leaching, acid baking, sulfate-salt roasting, and sulfation–roasting–water-leaching routes mechanistically, and explicitly separates maximum extraction from maximum process selectivity. The decisive design variable is an operational thermochemical window in which undesired Fe- and, where achievable, Al-bearing sulfates are destabilized or rendered poorly leachable while Sc/REE-bearing sulfates remain recoverable by water leaching. Mineralogical association, sulfur dosage, heating rate, residence time, bed thickness, atmosphere, gas composition, cooling history, and leaching conditions jointly control this window. The review follows the process through impurity removal, solvent extraction, ion exchange, precipitation, sulfur and water recycling, residue valorization, reactor engineering, technology readiness, techno-economic analysis, and prospective life-cycle assessment. An author-developed five-level selectivity framework—formation, thermal, solubility, separation, and process selectivity—is used to normalize route comparison. The central conclusion is that selective sulfation should be designed as an integrated closed-loop separation system, with sulfur efficiency, Fe/Al rejection, product quality, off-gas control, residue usability, and scale-up robustness treated as co-equal design objectives.

Keywords: bauxite residue; red mud; selective sulfation; scandium; rare earth elements; water leaching

Highlights

• Defines selectivity as a five-level sequence from sulfate formation to flowsheet performance.
• Distinguishes acid baking, sulfate-salt roasting, and sulfation–roasting–water leaching.

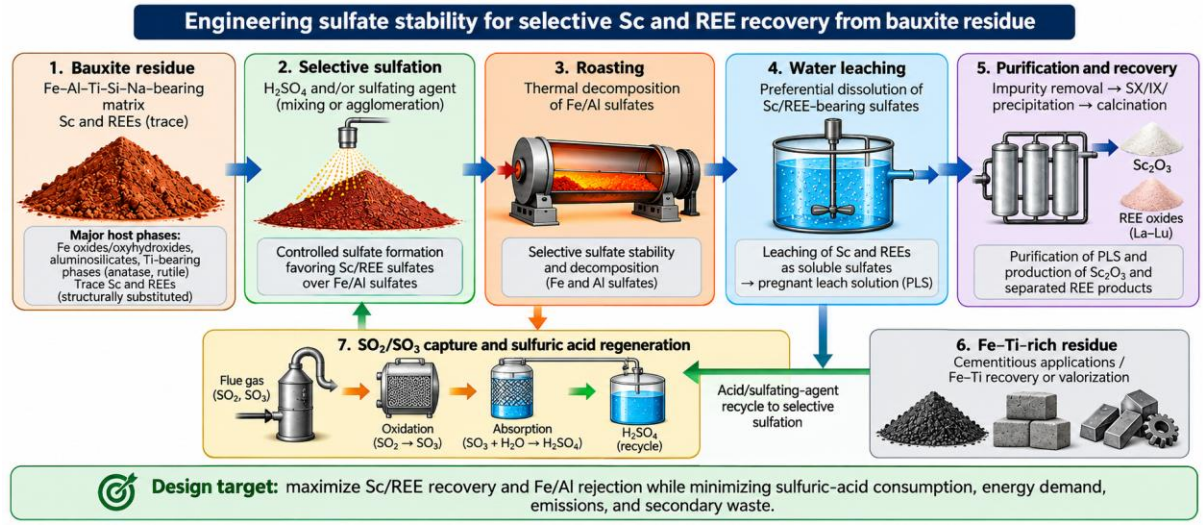


Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

• Identifies the Fe/Al sulfate-decomposition window as the central thermochemical control.
• Links recovery and selectivity to sulfur recycle, residue value, TEA/LCA, and industrial readiness.

Graphical abstract



1. Introduction

1.1. Bauxite residue as a coupled waste-management and resource-recovery problem

Bauxite residue (BR), commonly termed red mud, is generated during alumina production and is characterized by high alkalinity, fine particle size, heterogeneous mineralogy, and a major-element inventory dominated by Fe, Al, Si, Ti, Na, and Ca. Its management problem is therefore not only one of volume, storage stability, and alkalinity, but also one of resource inefficiency: the residue can contain Sc, REEs, Ga, V, and other elements whose value is diluted by the dominant Fe–Al matrix. The literature has consequently evolved from disposal-oriented studies toward integrated valorization concepts that combine metal recovery, alkali control, construction-material production, and circular use of process residues (Agrawal & Dhawan, 2021b; Borra et al., 2016a; Evans, 2016; Gomes et al., 2016b; International Aluminium Institute, 2022a, 2022b; Khairul et al., 2019; Klauber et al., 2011; Liu et al., 2014; Liu & Naidu, 2014; Power et al., 2011; Silveira et al., 2021; Song et al., 2026; Svobodova-Sedlackova et al., 2024; Swain et al., 2022; Wang et al., 2021, 2023; Zhang et al., 2026).

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

1.2. Why selective sulfation?

Direct acid leaching can mobilize target metals, but stronger acidity often increases Fe and Al dissolution, generating impurity-rich pregnant leach solutions (PLS), higher neutralization demand, larger precipitate volumes, and more difficult downstream separation. Selective sulfation changes the separation logic. Rather than requiring the leachant to discriminate perfectly among mineral phases, the solid is first converted into a population of sulfates and sulfate-derived phases, and the subsequent thermal program destroys or immobilizes unwanted sulfate species before water leaching. In the benchmark sulfation–roasting–leaching study, approximately 60% of Sc and more than 90% of the other REEs were recovered while Fe dissolution remained below 1% under selected conditions, illustrating that thermal differentiation of sulfate stability can outperform purely concentration-driven acid leaching in selectivity (Borra et al., 2015, 2016b, 2017; Davris et al., 2016; Ding et al., 2018; Meng et al., 2020; Zhang et al., 2016b; Zhu et al., 2015).

1.3. Critical question, scope, and structure of this review

The central question addressed here is: how can sulfate formation, thermal stability, decomposition, and aqueous solubility be engineered to selectively recover critical metals from bauxite residue while minimizing Fe/Al dissolution, sulfur consumption, gaseous emissions, and secondary-waste generation? To answer this question, this review uses an author-developed five-level framework in which selectivity is treated as a sequence of coupled filters: formation selectivity, thermal selectivity, solubility selectivity, separation selectivity, and process selectivity. The framework is a conceptual synthesis rather than a standardized external classification. It prevents the common error of ranking routes only by target-metal extraction while ignoring co-dissolution, reagent intensity, downstream burden, residue quality, and industrial robustness.

The review's architecture is summarized in the graphical abstract and developed in Tables 1–8 and Figures 1–7. Table 1 defines the review and normalization framework; Table 2 links feed mineralogy to sulfation response; Table 3 compares sulfating agents; Table 4

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

summarizes phase transformations; Table 5 compares water-leaching variables; Table 6 maps element deportment; Table 7 evaluates downstream purification options; and Table 8 assesses industrial readiness. Figure 1 links mineral hosts to reaction response, Figure 2 defines the conceptual sulfate-stability window, Figure 3 distinguishes sulfur-based process configurations, Figure 4 tracks phase transformation with temperature, Figure 5 connects PLS purification to final products, Figure 6 presents a closed-loop integrated flowsheet, and Figure 7 reframes route selection as a recovery–selectivity–chemical-burden–readiness problem.

2. Review methodology and critical assessment framework

2.1. Literature discovery and selection

The literature corpus was assembled as a critical narrative/process-engineering review rather than as a retrospective systematic review. Literature discovery was conducted primarily through Google Scholar using iterative Boolean combinations of the terms “bauxite residue” OR “red mud” with “selective sulfation,” “sulfation roasting,” “acid baking,” “water leaching,” “scandium,” “rare earth elements,” “sulfate decomposition,” “sulfur recycle,” “off-gas,” “solvent extraction,” “ion exchange,” “precipitation,” “residue valorization,” “techno-economic analysis,” “life-cycle assessment,” “pilot,” and “scale-up.” Backward and forward citation chaining from directly relevant studies was used to identify foundational work, and publisher or DOI landing pages were used to verify bibliographic metadata. Searches emphasized English-language peer-reviewed journal literature, with traceable institutional or technical sources retained when they provided industrial context. The final bibliographic audit for this revision was completed on 7 October 2026. Inclusion required relevance to BR mineralogy, critical-metal recovery, sulfur-based processing, downstream separation, recycle, scale-up, or sustainability; preprints, duplicate records, non-traceable items, and sources lacking process relevance were excluded. Duplicate handling was performed bibliographically by title, authorship, year, and DOI. The final manuscript retains 145 references. No PRISMA-style screening counts are reconstructed because such counts were not recorded prospectively during the original narrative-review workflow.



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

2.2. Evidence scope and directness classification

The evidence base covers feed characterization, mineral deportment, direct and indirect sulfation routes, acid baking, roasting, water leaching, Sc/REE purification, iron and aluminum recovery, dealkalization, residue valorization, scale-up, TEA, LCA, and technology readiness. Evidence is tagged conceptually at four levels: (i) Direct BR evidence, where the feed or PLS is derived from bauxite residue; (ii) Analogous metallurgical evidence, where the same mechanism or unit operation is demonstrated in another ferruginous or sulfate-bearing system; (iii) General engineering evidence, covering transferable reactor, filtration, gas-cleaning, separation, TEA, or LCA principles; and (iv) Prospective/conceptual evidence, used for author-developed integration, readiness, or future-system interpretation. Analogous and general evidence is used to inform mechanism or engineering plausibility, not as direct validation of a BR flowsheet. Because cross-study extraction values are not directly comparable when feed composition, acid dosage, thermal history, and liquid-to-solid ratio differ, reported recoveries are interpreted within their experimental context rather than treated as a homogeneous dataset (Adrianto et al., 2021; Bergerson et al., 2020; Buyle et al., 2021; Cucurachi et al., 2018; Davris et al., 2021; Filippousi et al., 2025; Georgiades et al., 2025; Joyce & Björklund, 2019; Joyce et al., 2018; Moni et al., 2020; Narayanan et al., 2018a, 2019; Thonemann et al., 2020).

2.3. Normalized indicators for critical comparison

A critical comparison requires more than the percentage of Sc or REE extracted. At a minimum, a study should report target extraction, Fe and Al co-extraction separately, sulfur or sulfating-agent consumption, energy demand for drying and roasting, water use, PLS impurity load, solid–liquid separation behavior, off-gas composition, and residue characteristics. The following author-developed metrics are recommended for transparent cross-study reporting; ratios should always be accompanied by their component values because a target/Fe ratio becomes numerically unstable as Fe extraction approaches zero.

$$E_i\ (\%) = 100 \times m_i,PLS / m_i,feed$$

$$S_t/Fe = E_t / EFe$$

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

$$C_i\ (\%) = 100 \times (\Sigma\ m_{i,out}) / m_{i,feed}$$

$$fS,recycle = S_{recycled} / S_{total,recovered}\ ;\quad fS,loss = S_{lost} / S_{fresh,in}\ ;\quad CS\ (\%) = 100 \times (\Sigma\ S_{out}) / (\Sigma\ S_{in})$$

where E_i is the extraction of element i to the primary PLS; S_i/Fe is the target-to-iron extraction selectivity ratio; C_i is elemental mass-balance closure; fS,recycle is the sulfur recycle fraction; fS,loss is the sulfur-loss fraction; and CS is total sulfur closure. Target-metal closure should include, as applicable, roasted solid, primary PLS, wash liquors, final residue, downstream precipitates/products, raffinate, and purge streams. Sulfur reporting should distinguish fresh sulfur input (mol S kg^{-1} dry BR and/or kg H_2SO_4 t^{-1} dry BR), sulfur intensity per unit of recovered or saleable target product, sulfur retained in process liquors and solids, sulfur recycled, and net sulfur loss. These quantities should not be used interchangeably.

The review framework therefore separates evidence by scale, function, and directness. Laboratory studies establish mechanisms and operating windows; pilot and semi-industrial studies test heat and mass transfer, residence-time distribution, solids handling, gas management, corrosion, and solid–liquid separation; TEA and LCA test whether the flowsheet merely transfers burdens among acid consumption, roasting energy, neutralization, water use, and residue management. Prospective LCA is especially important because conventional retrospective inventories can misrepresent emerging technologies whose industrial energy integration, recycling loops, and product-substitution credits have not yet been demonstrated (Bergerson et al., 2020; Buyle et al., 2021; Cucurachi et al., 2018; Filippousi et al., 2025; Georgiades et al., 2025; Joyce & Björklund, 2019; Joyce et al., 2018; Moni et al., 2020; Thonemann et al., 2020).

Table 1 summarizes the critical-review framework, evidence levels, and normalized performance indicators.

Table 1. *Critical-review framework, evidence levels, and normalized performance indicators.*

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Feed	Origin, chemistry, mineralogy, particle/agglomerate size	Target-metal deportment by element/host	Controls reaction accessibility and unavoidable impurity coupling
Sulfation	Agent, dosage, mixing, moisture	mol fresh S kg^{-1} dry BR; kg H_2SO_4 t^{-1} dry BR	High dosage can increase recovery but also Fe/Al sulfate formation and Ca/Na sulfur sinks
Roasting	T, time, heating rate, atmosphere, gas composition, bed depth, cooling history	Operational selectivity window; phase-verified decomposition	Must differentiate sulfate retention/decomposition rather than maximize conversion
Leaching	Water T, L/S, time, agitation, pH, particle/agglomerate size	E_t, EFe, EAl and S_t/Fe reported together	Tests whether thermal selectivity survives in solution without excessive dilution
Downstream	PLS composition, impurity ratios, purification sequence	Extraction × purification recovery; final purity/specification	Separates dissolved metal from saleable product performance
Scale-up	reactor, heat/mass transfer, RTD, corrosion, off-gas, solids handling	readiness category + throughput basis	Separates laboratory chemistry from industrial operability
Sustainability	energy, water, emissions, residue fate	TEA/LCA with recycle and uncertainty scenarios	Identifies burden shifting and the value of integration
Balances	PLS, wash liquors, residue, products, raffinate, purge	C_i and total sulfur closure CS	Requires explicit elemental and sulfur closure rather than extraction alone
Evidence directness	Direct BR; analogous metallurgy; general engineering; prospective/conceptual	evidence tag attached to mechanism/technology claim	Prevents adjacent-process evidence from being interpreted as direct BR validation

Note. Author-developed critical-assessment framework based on the literature cited in this section. Normalized ratios are intended as reporting aids and should be accompanied by the underlying extraction, mass-balance, sulfur-balance, and product-quality data.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Table 1 makes explicit that the relevant unit of comparison is the whole selective-separation function, not the roasting yield in isolation. A route that leaches slightly less Sc can still be superior if it produces a cleaner PLS, consumes less sulfur, allows high sulfate recycle, and generates a residue suitable for further valorization.

3. Bauxite residue mineralogy and element deportment

3.1. Mineralogical variability and reaction accessibility

The selective-sulfation window begins with mineralogy. BR is not a uniform Fe_2O_3–Al_2O_3 mixture, but a multiphase assemblage produced by bauxite mineralogy and Bayer-process chemistry. Hematite, goethite, or Fe-substituted phases coexist with residual gibbsite/boehmite, hydrogarnet, desilication products (DSP), anatase/rutile, perovskite-type phases, sodium-bearing phases, calcium phases, and poorly crystalline material. The fine particle size and aggregation state can favor reaction kinetics while simultaneously complicating mixing, filtration, and heat transfer (Alam et al., 2018; Alkan et al., 2018; Gräfe et al., 2011; Khairul et al., 2019; Power et al., 2011; Wang & Liu, 2012; Xue et al., 2016; Zeng et al., 2022).

3.2. Scandium and REE hosts

Scandium commonly does not occur as a discrete, easily liberated mineral. Instead, it may be structurally or surface-associated with Fe-bearing and other phases, meaning that selective recovery requires enough chemical disruption to release Sc without fully mobilizing the bulk matrix. This is the core mineralogical paradox: Fe association can make matrix destabilization necessary for Sc exposure, while excessive Fe sulfation increases impurity transfer to the PLS. REEs can occur in multiple hosts and may respond differently from Sc, so a single extraction percentage cannot represent the behavior of the entire critical-metal inventory (Abhilash et al., 2021; Borra et al., 2016a, 2016b; Davris et al., 2021; Kiskira et al., 2021, 2023; Marin Rivera et al., 2019; Narayanan et al., 2018a; Reid et al., 2017; Shoppert et

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

al., 2022a, 2022b; Vakilchap et al., 2016; Van Wyk et al., 2024; Zhang et al., 2016b; Zhu et al., 2015).

3.3. Consequences for pretreatment and route selection

Dealkalization, reductive treatment, fusion, microwave treatment, and selective iron recovery can modify both acid demand and the subsequent sulfate-forming mineral assemblage. Such pretreatments can be useful when they simplify the matrix or recover a major-value stream, but they can also add energy demand and create new phases whose sulfation behavior differs from untreated BR. Consequently, pretreatment should be justified by its effect on the total flowsheet rather than by an isolated improvement in one extraction stage (Agrawal & Dhawan, 2021b; Alkan et al., 2017; Archambo & Kawatra, 2021; Borra et al., 2016a; Cardenia et al., 2019; Guo et al., 2013; Habibi et al., 2021; Jiang et al., 2021; Kong et al., 2022; Kong et al., 2023; Li et al., 2021; Liu et al., 2021; Liu et al., 2026; Lyu et al., 2021; Pilla et al., 2025; Yang et al., 2025b; Yang et al., 2015; Yuan et al., 2020; Zhang et al., 2011b; Zhang et al., 2025; Zhao et al., 2024; Zhou et al., 2023).

Table 2 summarizes the mineralogical controls and their expected consequences, and Figure 1 illustrates the coupling between mineral hosts and sulfate selectivity.

Table 2. *Representative mineralogical controls on selective sulfation of bauxite residue.*

Fe oxides / Fe-bearing hosts	major matrix; possible Sc association	readily consumes acid; Fe sulfate should subsequently decompose	retain Fe in residue while releasing target metals
Al phases / hydrogarnet / DSP	major acid consumer	Al sulfate formation may persist into water leach	limit Al co-extraction or remove early downstream

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Ti phases	often refractory	may remain in residue or partly transform	retain/concentrate Ti-rich solid where possible
Ca-bearing phases	forms $CaSO_4$ readily	locks sulfate and may influence porosity	control sulfur sink and residue quality
Na-bearing phases	highly reactive	forms soluble sodium sulfate	recover/recycle sulfate-bearing liquor where feasible
Sc/REE hosts	dilute and heterogeneous	must form water-leachable sulfate species within thermal window	maximize target transfer to PLS with low Fe/Al

Note. Conceptual synthesis based on the mineralogical and recovery studies cited in Sections 1 and 3; behavior varies with residue source and process conditions.

Table 2 shows why feed characterization cannot be separated from flowsheet design. The same roasting temperature may be selective for one BR but suboptimal for another if Fe/Al host phases, Ca content, or the degree of desilication-product formation change acid consumption and sulfate stability.

Figure 1 illustrates the relationship between mineral hosts and sulfate selectivity.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

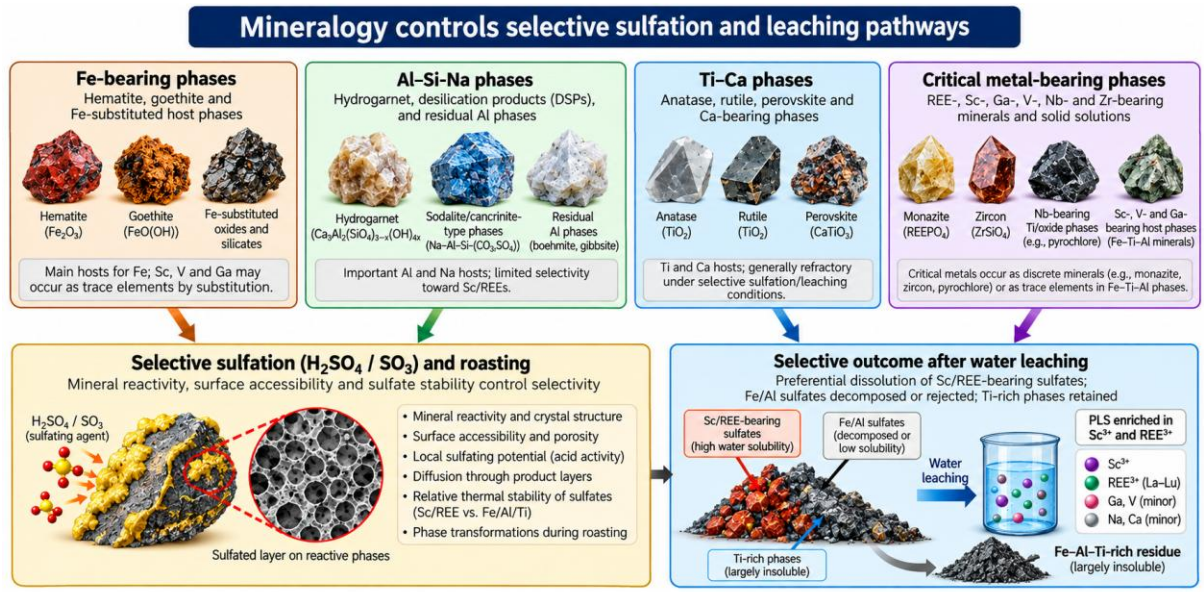


Figure 1. Mineral hosts of major and critical elements and their expected influence on selective sulfation.

Note. Conceptual synthesis developed by the author based on the mineralogical relationships discussed in this review.

As illustrated in Figure 1, mineralogy affects both the probability that a target element is exposed to sulfation and the amount of sulfur consumed by competing matrix reactions. Selectivity is therefore partly predetermined before the furnace by the distribution of target metals among Fe-, Al-, Ti-, and amorphous phases.

4. Thermodynamics and fundamental chemistry of selective sulfation

4.1. Sulfate formation as a chemical-potential problem

Selective sulfation is governed by coupled acid–base, gas–solid, and thermal equilibria. For a generic oxide MO, reaction with sulfuric acid or an SO_3-bearing gas can form sulfate species whose stability depends on temperature, oxygen potential, sulfur chemical potential, hydration state, and cation identity. The engineering objective is not complete sulfation of every element; it is to produce target-metal sulfates while creating a later thermal opportunity to destabilize unwanted Fe- and Al-bearing sulfates. This makes the sulfate-decomposition

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

sequence as important as sulfate formation (Borra et al., 2016b, 2017; Meng et al., 2020; Pereira, 2026j, 2026k, 2026l; Pereira et al., 2025).

4.2. Differential thermal stability and the origin of selectivity

The benchmark mechanism transforms reactive oxides to sulfates, followed by controlled roasting that destabilizes Fe(III) sulfate and, under sufficiently severe conditions, Al-bearing sulfates while retaining Sc/REE-bearing sulfate species in a water-leachable form. Published work reports different decomposition intervals for Ti-, Fe-, Al-, Sc-, and REE-bearing sulfate systems, but exact transitions are phase-, atmosphere-, heating-rate-, residence-time-, and analytical-criterion-specific. The scientifically defensible conclusion is therefore an operational selectivity window rather than a universal decomposition temperature (Borra et al., 2016b, 2017; Meng et al., 2020; Zhang et al., 2016b; Zhu et al., 2015).

4.3. Gas-phase sulfur chemistry and mechanistic verification

Sulfur-bearing off-gas should not be represented as a fixed decomposition product. The relative amounts of SO_2, SO_3, H_2SO_4 vapor/acid mist, H_2O, and other species depend on oxygen potential, temperature, gas residence time, equilibrium constraints, decomposition pathway, catalytic surfaces, and gas-cleaning conditions. Accordingly, sulfur balances should measure or bound the relevant gaseous species rather than assume a universal SO_2/SO_3 split. Where thermodynamic modeling is performed, the database, species set, activity assumptions, pressure, and gas composition should be reported explicitly. Mechanistic phase assignments also require more than an extraction change or a single TG–DSC event: quantitative XRD should be combined, where necessary, with evolved-gas analysis, SEM–EDS, Raman/FTIR/XPS or other spectroscopy, and element-resolved leaching response. A thermal event alone is insufficient proof of a specific sulfate decomposition reaction.

Figure 2 presents the author-developed qualitative stability concept. To avoid pseudo-quantitative interpretation, the revised figure removes the arbitrary 0–1 stability scale and

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

universal temperature axis; it uses thermal-severity categories instead of calculated equilibrium values.

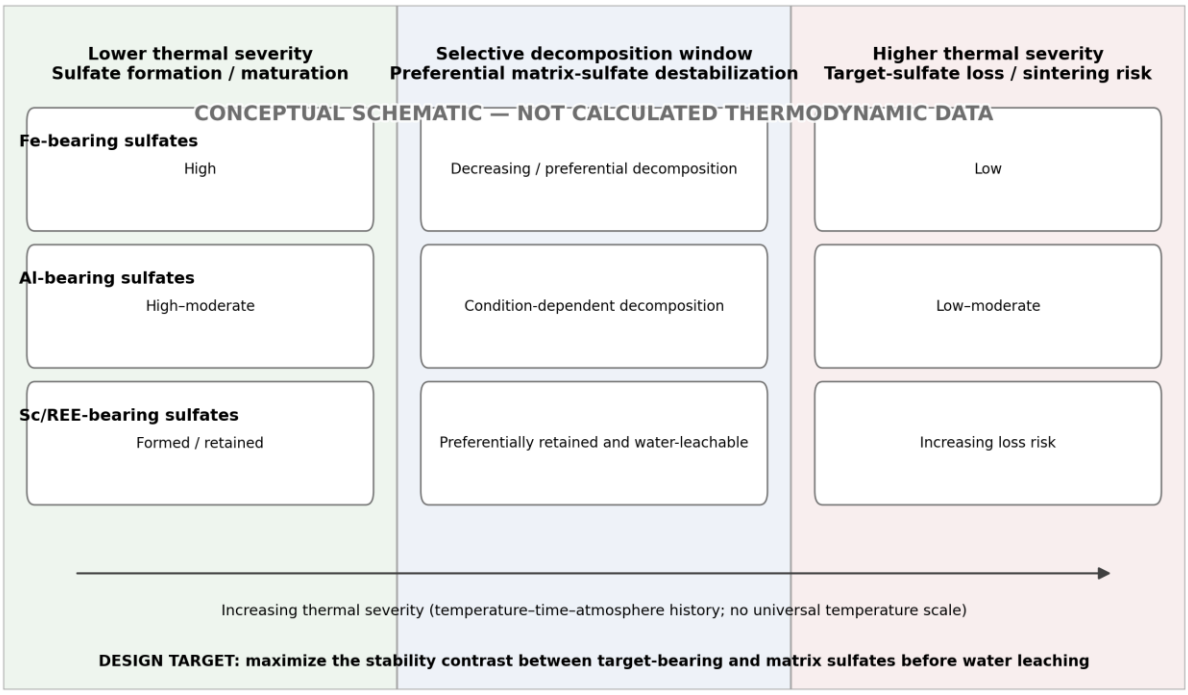


Figure 2. Qualitative sulfate-stability framework controlling selective sulfation of bauxite residue.
Note. Author-developed conceptual schematic—not calculated thermodynamic data. Thermal-severity regions are qualitative and depend on phase identity, atmosphere, heating rate, residence time, sulfur activity, bed conditions, and analytical criterion; they are not universal equilibrium-temperature boundaries.

Figure 2 clarifies why both under-roasting and over-roasting are problematic. At low temperature, target sulfates may be preserved, but Fe and Al sulfates can also remain soluble, increasing impurity dissolution. At excessive temperature or residence time, target sulfates may decompose or become less accessible, while sintering can reduce leachability. The optimum is therefore a separation window, not simply the temperature that maximizes sulfate formation.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

5. Sulfating agents and sulfation strategies

5.1. Concentrated sulfuric acid

Concentrated H_2SO_4 remains the most direct sulfating agent because it provides high sulfate activity and intimate liquid-solid contact. Its strengths are mechanistic simplicity and the ability to convert multiple oxides before roasting. Its weaknesses are corrosivity, mixing difficulty with fine alkaline solids, high local exothermicity, acid consumption by Ca/Na/Al phases, and the need to control residual free acid and sulfur-containing off-gas. The acid-to-residue ratio therefore controls both target conversion and the amount of undesired Fe/Al sulfate available to survive into leaching (Anawati & Azimi, 2019; Borra et al., 2017; Borra et al., 2016a; Davris et al., 2016; Ding et al., 2018; Reid et al., 2017).

5.2. Ammonium sulfate and other sulfate salts

Ammonium sulfate roasting offers a different reaction environment because sulfate is supplied in a salt phase rather than as concentrated free acid. Meng et al. demonstrated selective Sc extraction using ammonium sulfate roasting and leaching, showing that sulfate-salt routes can create useful selectivity without reproducing the exact chemistry of concentrated-acid impregnation (Meng et al., 2020). The advantage is potentially easier solids handling and modified reaction stoichiometry; the disadvantages include ammonium-containing off-gas or decomposition products, reagent recovery requirements, and possible Al co-extraction. Ferric sulfate, ammonium bisulfate, persulfates, and mixed agents are conceptually attractive because they alter sulfate activity, redox behavior, or oxygen availability, but they should be compared on sulfur efficiency and recycle potential rather than only extraction.

5.3. Recycled sulfur-bearing streams

A process-level strategy is to treat sulfate not as a once-through reagent but as a circulating species. Sulfate-rich raffinate, captured SO_2/SO_3, $MgSO_4$-bearing streams, or regenerated sulfuric acid can become internal reagents if impurity buildup is controlled. This shifts the design objective from minimum fresh-acid dosage to maximum sulfur utilization per

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

unit of saleable product and makes gas cleaning, evaporation, crystallization, and acid regeneration part of the separation circuit. The sulfur-recycle concept is supported here by analogous metallurgical and general engineering evidence and should not be interpreted as a fully demonstrated closed BR loop (Pereira, 2026e, 2026m, 2026n).

Table 3 summarizes the comparison.

Table 3. *Comparison of sulfating-agent strategies for bauxite-residue processing.*

Concentrated H_2SO_4	impregnation + drying/roasting	high sulfate activity; established mechanism	corrosion; acid sinks; off-gas burden	target recovery / Fe+Al co-extraction at fixed acid/BR
$(NH_4)_2SO_4$	salt roasting	dry handling; alternative sulfate chemistry	NH_x/S-containing gas management; Al co-extraction	Sc recovery per mol sulfate added
Bisulfate / mixed salts	acidic salt reaction	high reactivity at lower free-acid fraction	complex recycle and impurity buildup	net sulfur loss per cycle
Oxidizing sulfate/persulfate concepts	sulfation with oxidative promotion	may enhance reaction of refractory hosts	cost and decomposition chemistry	incremental selectivity vs oxidant demand
Recycled sulfate/acid	closed-loop reagent supply	lower fresh-reagent demand	requires purge and impurity control	fresh S consumption per kg product

Note. Prepared by the author from the sulfation and sulfur-recycling literature cited in this review.

Table 3 emphasizes selecting a sulfating agent with the recycle loop in mind. A reagent that performs well in a single batch but cannot be recovered, scrubbed, or regenerated economically may be inferior to a slightly less reactive agent embedded in an efficient closed loop.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

6. Sulfation, acid baking, and roasting process configurations

6.1. Terminological and mechanistic distinctions

Direct sulfuric-acid leaching, acid baking followed by water leaching, sulfation followed by roasting and water leaching, and sulfate-salt roasting are often grouped together because they all use sulfur-bearing chemistry. They are not mechanistically equivalent. Direct leaching relies primarily on solution chemistry and dissolution kinetics. Acid baking converts solids in a concentrated acid environment before water washing. Selective sulfation–roasting introduces an explicit thermal decomposition stage intended to destroy undesired sulfates. Sulfate-salt roasting depends on solid-state or molten-salt reactions and may involve different gas-phase species. These distinctions matter because the source of selectivity changes from one route to another (Anawati & Azimi, 2019; Borra et al., 2017; Borra et al., 2016a; Davris et al., 2016; Meng et al., 2020; Shoppert et al., 2022a).

Figure 3 classifies these routes by the dominant separation mechanism.

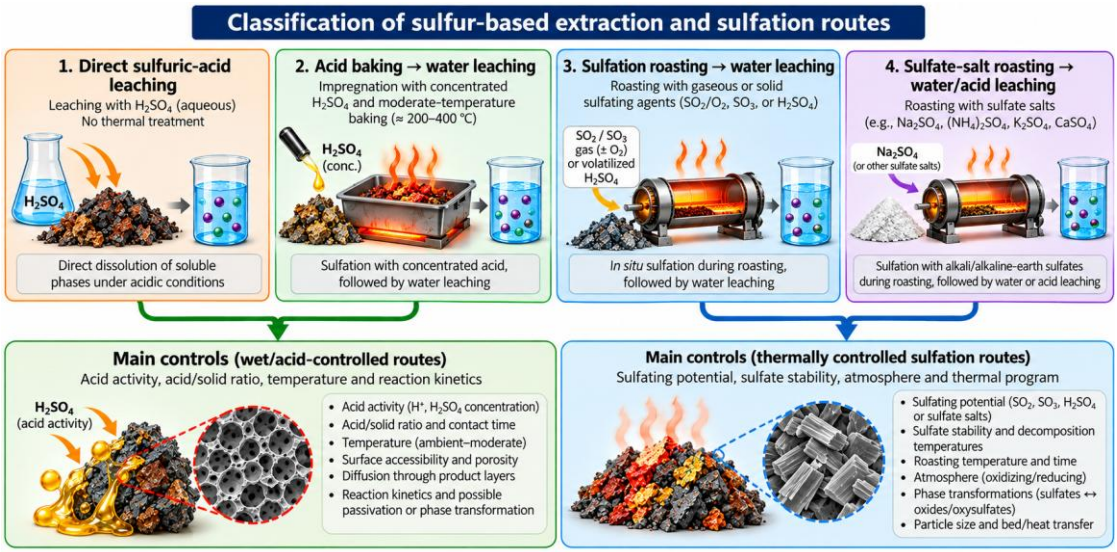


Figure 3. Classification of sulfur-based processing routes for bauxite residue.
Note. Conceptual classification developed by the author; process labels are separated by dominant chemical and thermal control.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Figure 3 prevents a common interpretive error: similar final operations—such as water leaching—do not imply identical upstream chemistry. Accordingly, the same metric should not be applied uncritically across all sulfur-based routes. Direct leaching should be judged primarily on solution impurity load, whereas sulfation–roasting should also be judged on the efficiency of thermal sulfate differentiation.

7. Roasting temperature, time, and phase transformation

7.1. Thermal program and non-monotonic selectivity

Roasting temperature and time create a non-monotonic response. Lower thermal severity can preserve a larger fraction of target sulfates, but it can also preserve Fe and Al sulfates. Higher thermal severity can improve Fe rejection by decomposition, but beyond the selective window it can destroy target sulfates, induce sintering, or generate less soluble phases. Residence time interacts with temperature because decomposition, diffusion, gas evolution, and solid-state recrystallization proceed at different rates. Heating rate determines how long the material resides in transitional regions and can therefore change the balance between sulfate formation and decomposition (Borra et al., 2016b, 2017; Meng et al., 2020; Pereira, 2026j, 2026l).

7.2. Reactor-scale heat and mass transfer

Laboratory crucibles often provide short diffusion distances and relatively uniform temperature. Industrial beds introduce radial and axial thermal gradients, gas boundary layers, variable residence-time distributions, and possible agglomeration of acid-treated fines. Bed thickness, solids holdup, and gas flow influence removal and interconversion of H_2O, SO_2, SO_3, and acid vapor/mist; local gas composition can in turn shift sulfate equilibria. Cooling history can also affect hydration, agglomeration, and the phase state presented to water leaching. These couplings explain why a laboratory ‘optimum roasting temperature’ cannot be transferred directly to a furnace without validating the complete time–temperature–gas history.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

7.3. Phase identification and evidence quality

XRD is essential for identifying crystalline sulfates and oxides, but it can underrepresent poorly crystalline and transient species. TG–DSC can locate thermal events, and evolved-gas analysis can identify associated sulfur-bearing gases; neither technique alone proves a unique phase transformation. SEM–EDS reveals spatial reaction heterogeneity and agglomeration, while Raman, FTIR, XPS, and synchrotron methods can strengthen phase and oxidation-state assignments when diffraction is ambiguous. A robust mechanistic study should therefore link quantitative phase analysis, thermal analysis, gas evolution, complementary spectroscopy where justified, and element-resolved leaching response. Phase transformations should not be inferred from extraction percentage alone.

Table 4 summarizes representative phase transformations, and Figure 4 illustrates them.

Table 4. *Reported and expected phase transformations during selective sulfation and roasting.*

Impregnation/drying	oxide/hydroxide → sulfate or acid sulfate	creates leachable target precursor	nonuniform acid distribution; excess free acid
Low/intermediate T	dehydration + sulfate maturation	improves reaction completion	Fe/Al sulfates remain fully leachable
Selective decomposition window	Fe sulfate → Fe oxide + S-bearing gas; partial Al-sulfate decay	suppresses Fe/Al in PLS	target sulfate decomposition begins
High-T extension	further sulfate decomposition / recrystallization	may improve matrix rejection	loss of Sc/REE leachability; sintering
Cooling/conditioning	stabilization of roasted product	prepares water-leach feed	rehydration or agglomeration affects kinetics

Note. Conceptual synthesis from sulfation–roasting studies; exact phase assemblages depend on feed mineralogy and atmosphere.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

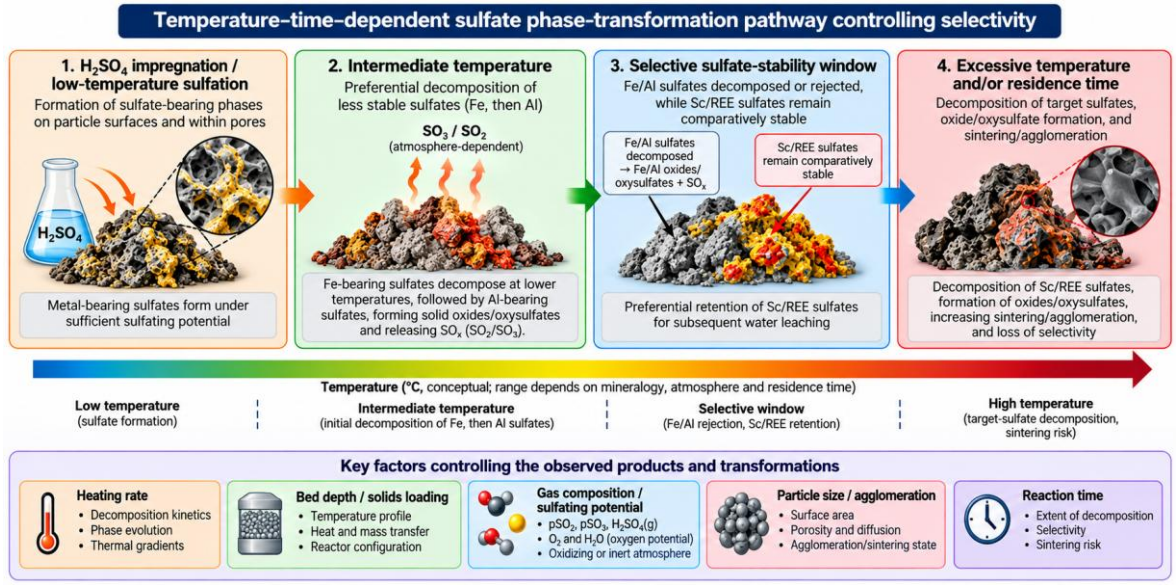


Figure 4. Temperature-dependent phase-transformation pathway during selective sulfation roasting.
Note. Conceptual synthesis developed by the author based on the roasting mechanisms discussed in this review.

Table 4 and Figure 4 together show that selective roasting is a sequence of reactions rather than a single-temperature treatment. This supports reporting full thermal histories—heating rate, hold time, bed depth, gas composition, and cooling procedure—when comparing studies.

8. Water leaching after selective sulfation

8.1. Why water leaching is chemically strategic

Water leaching is not merely a low-cost washing step. It is the operation that tests whether the upstream thermal program created a useful solubility contrast. Ideally, Sc/REE sulfates dissolve rapidly while decomposed Fe-bearing phases and much of the Al/Ti matrix remain in the solid. If the roasted product still contains soluble Fe or Al sulfate, the water-leach stage reveals that thermal selectivity was incomplete. Conversely, low target recovery after clean Fe rejection may indicate over-roasting, target sulfate decomposition, or diffusion limitations.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

8.2. Operating variables

Leaching temperature, liquid-to-solid ratio (L/S), residence time, agitation intensity, particle/agglomerate size, initial sulfate concentration, and PLS pH affect dissolution and reprecipitation. These variables should be reported quantitatively, including water-leach temperature, L/S, contact time, agitation conditions, and particle or agglomerate-size range where relevant. Higher temperature can accelerate dissolution, but the benefit may be offset by hydrolysis or secondary precipitation during cooling and pH drift. High L/S can reduce solution saturation and improve washing while producing an unattractively dilute PLS. Counter-current or staged washing is therefore an engineering option for reducing water demand and soluble-metal loss, but it is not a universal requirement.

8.3. Reprecipitation, filtration, and PLS quality

Target-metal closure should include roasted solid, primary PLS, wash liquors, final residue, and downstream precipitates/products; raffinate and purge streams should be included when the balance extends through purification and recycle. Apparent extraction losses can arise from incomplete washing, adsorption on Fe-rich solids, hydrolysis, or coprecipitation during pH change. Because BR is extremely fine, solid–liquid separation is a scale-up variable rather than a secondary laboratory detail. Where applicable, studies should report settling rate, filtration flux, specific cake resistance, cake moisture, wash efficiency, slurry rheology, and particle-size evolution. These quantitative metrics are needed to connect batch extraction with continuous clarification and filtration performance (Alam et al., 2018; Pereira, 2026c, 2026h; Zeng et al., 2022).

Table 5 summarizes the principal water-leaching controls.

Table 5. *Water-leaching variables and their influence after selective sulfation.*

Temperature	report quantitatively; controls dissolution kinetics	hydrolysis/reprecipitation during cooling or pH drift	heat integration with roasted-solid cooling

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

L/S ratio	report quantitatively; controls saturation and PLS concentration	high L/S dilutes PLS and raises water/evaporation burden	counter-current/staged washing may reduce water demand
Residence time	report quantitatively; controls approach to dissolution plateau	long contact may promote secondary reactions	tank volume and throughput
Agitation	report speed/power or mixing regime where possible	attrition can create finer solids	power demand and settler/filter load
Particle/agglomerate size	controls internal diffusion and wash accessibility	large acid-baked agglomerates may leach incompletely	milling versus permeability/filtration trade-off
PLS sulfate/pH	controls speciation and downstream compatibility	reprecipitation or impurity solubilization	SX/IX/precipitation and recycle compatibility
Washing	wash stages, wash-water volume, wash efficiency	target loss or excessive dilution if poorly controlled	include wash liquor in metal and sulfur balances
Solid–liquid separation	settling rate, filtration flux, cake resistance, cake moisture, rheology	fine-particle carryover and low throughput	scale equipment from quantitative separation data

Note. Prepared by the author as a process interpretation of the water-leaching literature discussed in this review.

Table 5 demonstrates that the water-leach stage should be designed simultaneously for extraction, PLS concentration, and solid-liquid separation. The highest extraction at very high L/S can be an unattractive industrial result if it creates an excessively dilute PLS and large evaporation duty.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

9. Element deportment and the origin of selectivity

9.1. Scandium and rare earth elements

Sc and REEs are the principal target metals in many selective-sulfation studies, but their deportment should be evaluated individually. Sc commonly exhibits stronger coupling to Fe-bearing phases than many REEs, which helps explain why conditions that recover most REEs may still recover only part of Sc. Light and heavy REEs can also differ in host phase, sulfate formation, thermal behavior, and downstream separation chemistry. Future reporting should therefore provide, at minimum, Sc, the major light REEs relevant to the feed, and any relevant heavy REEs as separate extraction and mass-balance values. A single 'total REE recovery' value should not be the only critical-metal endpoint.

9.2. Iron, aluminum, titanium, calcium, sodium, and silicon

Fe is the dominant selectivity penalty because even modest fractional dissolution can overwhelm the mass of Sc/REEs in solution. Al is often the second major impurity and can consume both acid and downstream neutralization reagent. Ti is generally less soluble but may become valuable if concentrated in the final residue. Ca acts as a sulfate sink through $CaSO_4$ formation, while Na can transfer readily to the liquid phase as sulfate and thereby become part of the sulfate-recycle problem. Silicon can influence rheology, gel formation, and the physical accessibility of reacted particles. The desired process therefore routes each major element deliberately rather than treating all non-target metals as undifferentiated impurities.

Table 6 provides an element-by-element deportment map.

Table 6. *Element-by-element deportment during selective sulfation–roasting–water leaching.*

Sc	target sulfate formation	retain leachable sulfate in selected window	high extraction	PLS → selective recovery

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

REEs	target sulfate formation	comparatively stable in selected window	high extraction	PLS → separation/product
Fe	often sulfated initially	decomposition to oxide desired	very low extraction	solid residue
Al	condition-dependent sulfate formation	partial/controlled decomposition desired	low to moderate extraction	preferably solid; otherwise early impurity removal
Ti	limited/phase-dependent	often refractory after roasting	generally low	Ti-enriched residue or later recovery
Ca	$CaSO_4$ readily forms	thermally persistent over useful window	limited dissolution	solid residue / sulfate sink
Na	forms soluble sulfate	remains mobile	high transfer possible	PLS / recycle loop
Si	silicate/silicic phases	limited sulfate chemistry	mostly solid; may affect filtration	residue

Note. Conceptual deportment map; behavior is feed- and condition-dependent and should not be interpreted as a universal equilibrium rule.

The most useful feature of Table 6 is not any single row but the simultaneous destination logic. A truly selective flowsheet is one in which target metals move to the PLS, Fe/Ti-rich solids remain saleable or usable, sodium and sulfate are recycled where practical, and impurity transfer is minimized before downstream purification.

10. Pregnant leach solution purification and Sc/REE recovery

10.1. From dissolved metal to saleable product

A review that ends at ‘Sc leached’ overstates process maturity. The sulfate PLS can contain Al, Fe, Na, Ca, Mg, sulfate, and multiple minor metals, and the economics of Sc/REE recovery depend on concentration, impurity ratios, reagent compatibility, and recycle. Downstream performance should distinguish (i) extraction to PLS, (ii) purification-stage

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

recovery, (iii) overall flowsheet recovery, and (iv) final product purity and impurity specification. A high Sc recovery into an intermediate is not equivalent to production of high-purity Sc_2O_3. Candidate operations include selective precipitation, solvent extraction (SX), ion exchange (IX), chelating resins, adsorption, and combinations of these methods (Avdibegović & Binnemans, 2020; Binnemans & Jones, 2017; Gomes et al., 2016a; Meng et al., 2023; Niu & Lin, 2024a, 2024b; Padhan & Paul, 2022, 2025; Pereira, 2026c, 2026d, 2026i).

10.2. Impurity control before selective capture

Early Fe and Al removal can protect SX or resin capacity, but precipitation must avoid Sc/REE coprecipitation. pH control, hydrolysis kinetics, seeding, residence time, precipitate filterability, and washability therefore become selectivity variables. Sulfate concentration and impurity ratios can alter metal speciation and extraction equilibria. Evidence directness must also be stated: a separation system demonstrated in another sulfate or chloride matrix is a candidate downstream technology until it is validated with representative BR-derived sulfate PLS containing the relevant Al, Na, Ca, Fe, Mg, sulfate, and trace-metal inventory. Analogous hydrometallurgical literature is used here to identify mechanisms and design options, not to claim automatic validation for BR.

Figure 5 shows the downstream sequence, and Table 7 compares it.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

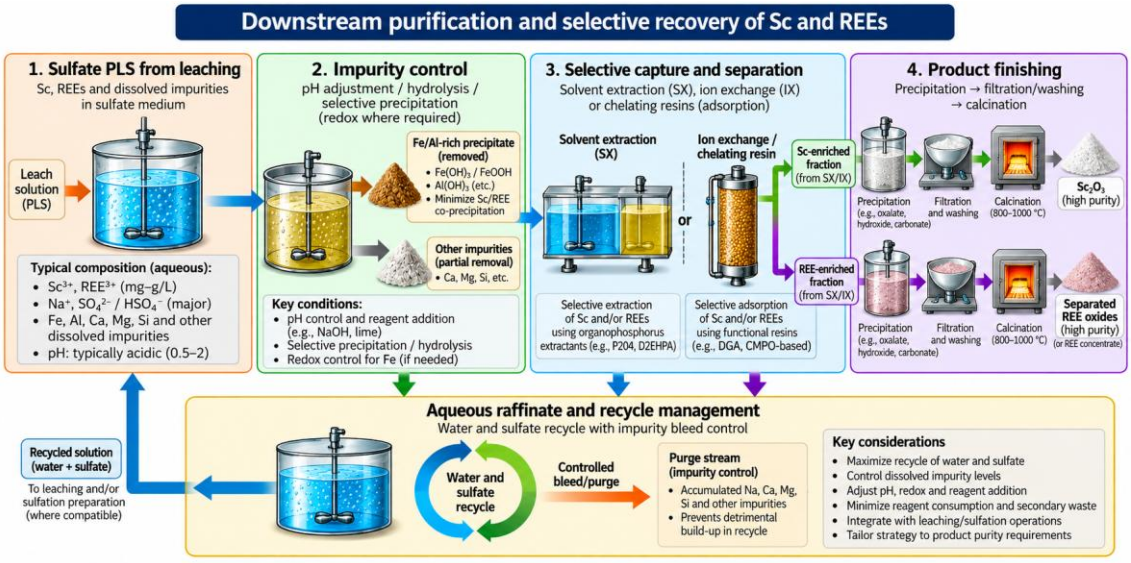


Figure 5. Selective sulfation–water leaching followed by impurity removal and Sc/REE recovery.

Note. Conceptual synthesis developed by the author based on downstream separation technologies discussed in this review.

Table 7. *Downstream technologies for purification of sulfate leachates generated from bauxite residue.*

Selective precipitation	bulk Fe/Al or product precipitation	simple equipment; concentration step	coprecipitation and fine solids	pH control + filterability
Solvent extraction	high selectivity and concentration	scalable staged separation	organic loss, phase disengagement, acidity sensitivity	scrubbing/stripping + raffinate recycle
Ion exchange	polishing or selective capture	compact; useful at low concentration	resin fouling and competing ions	regeneration chemistry
Chelating resin	high-affinity target capture	improved selectivity vs conventional IX	capacity and elution trade-off	pretreatment of PLS
Adsorption / hybrid sorbents	polishing or niche separation	potentially low solvent use	scale and regeneration uncertainty	solid handling and eluent recycle

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Crystallization / product precipitation	final product recovery	direct product formation	purity controlled by co-precipitation	upstream impurity control

Note. Evidence is graded by directness. 'Direct BR' indicates testing on bauxite residue or a BR-derived liquor; 'analogous' indicates transfer from another metallurgical matrix; and 'candidate' indicates that representative BR sulfate-PLS validation is still required. Selective precipitation and IX have direct BR precedents in parts of the literature, whereas several SX, chelating-resin, adsorption, and crystallization examples are matrix-dependent or adjacent evidence. Technology performance remains composition-specific, and no technology demonstrated elsewhere is treated as automatically validated for BR sulfate PLS.

Figure 5 and Table 7 show that sulfate management links the front end and the downstream circuit. The raffinate is not automatically waste: it can be a source of water and sulfate for recycle, provided that Na, Ca, Mg, and trace impurities do not accumulate beyond process limits.

11. Integrated flowsheets, sulfur recycling, and residue valorization

11.1. Closing the sulfur and water loops

The environmental and economic performance of selective sulfation depends strongly on sulfur closure. A complete sulfur balance should include sulfate retained in roasted solids, sulfate in the primary PLS and wash liquor, raffinate, purge, $CaSO_4$-bearing solids, Na_2SO_4-bearing streams, measured or bounded SO_2 and SO_3, acid vapor/mist, and regenerated acid where relevant. Sulfur reporting should distinguish fresh sulfur input, internal sulfur recycle, net sulfur loss, and total sulfur closure. Captured sulfur may be returned as H_2SO_4, sulfite/bisulfite, or another sulfate-bearing reagent, but the chemical form and conversion efficiency must be specified. These loops can reduce fresh-acid demand and emissions while concentrating non-volatile impurities, so recycle benefit must be evaluated together with purge demand (Pereira, 2026e, 2026m, 2026n).

Recycle should also be tested by accumulation analysis rather than by a single-cycle recycle percentage. For a dissolved impurity j, a practical purge criterion can be defined by a maximum allowable recycle concentration Cj,max set by precipitation, scaling, corrosion,

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

solvent/resin performance, product purity, or environmental constraints. Multi-cycle or steady-state simulation should quantify Na, Ca, Mg, chloride where present, trace metals, dissolved organics, and total sulfate inventory. The purge fraction should then be selected to keep each critical impurity below its process-specific limit while minimizing freshwater and fresh-reagent demand.

11.2. Residue as a co-product design variable

Selective sulfation intentionally retains a large fraction of Fe, Ti, Si, and part of Al in the solid. The post-leach residue should therefore be designed for a subsequent use rather than treated as an unavoidable waste. Opportunities include iron recovery, Ti enrichment, cementitious binders, alkali-activated materials, clinker raw meal, bricks, road materials, aggregates, and other construction products. However, chemical durability, alkalinity, sulfate content, radionuclide behavior, and trace-metal leaching must be evaluated before claiming circularity (Balomenos et al., 2024; Feng et al., 2022; Giels et al., 2023; Giels et al., 2022; Goronovski et al., 2021; Hertel & Pontikes, 2020; International Aluminium Institute, 2020; Joyce et al., 2018; Peys et al., 2022; Raj et al., 2024; Silveira et al., 2021; Singh et al., 2024; Wang et al., 2026; Xiao et al., 2022; Yang et al., 2025a; Yang et al., 2020; Zhang et al., 2021; Zhang et al., 2016a; Zhang et al., 2011a; Zhang et al., 2023; Zhou et al., 2020).

11.3. Integrated closed-loop configuration

A stronger flowsheet therefore couples dealkalization or conditioning, selective sulfation, controlled roasting, water leaching, product recovery, off-gas treatment, sulfur recycle, and residue valorization. The critical improvement over a linear laboratory flowsheet is that each recycle stream is assigned a quality specification and each solid has a defined destination. Figure 6 illustrates this architecture.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

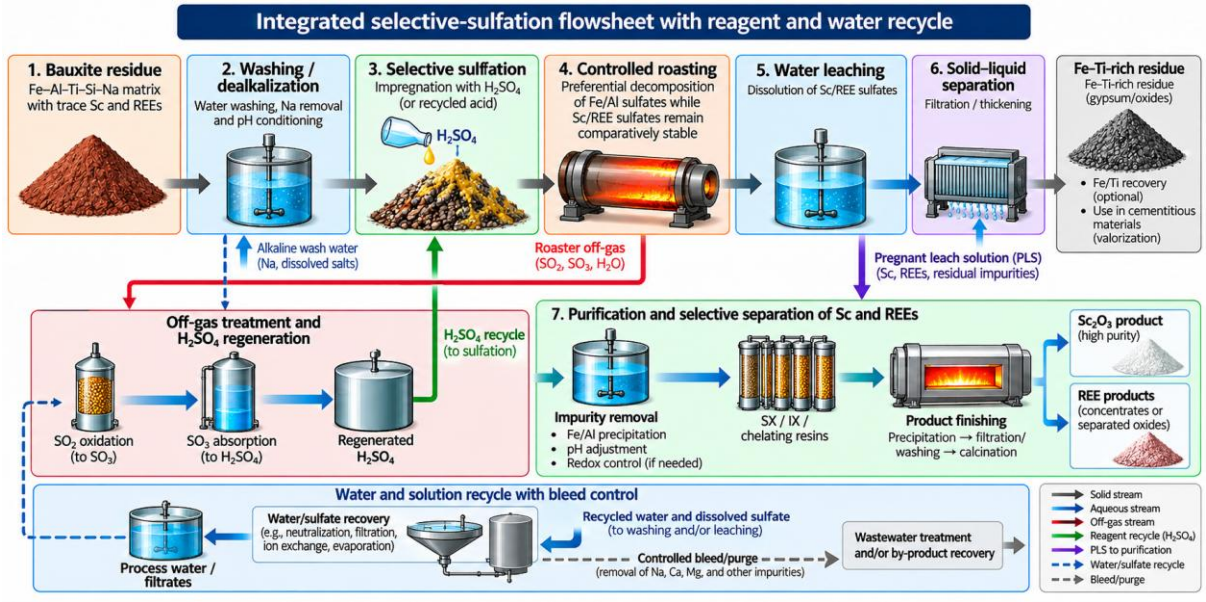


Figure 6. Closed-loop selective-sulfation flowsheet for comprehensive bauxite-residue valorization.
Note. Conceptual synthesis developed by the author from the process-integration and residue-valorization literature cited in this review.

As Figure 6 shows, sulfur capture, water recycle, and residue utilization are not end-of-pipe additions; they shift the optimal front-end operating point. For example, a lower fresh-acid dosage may be preferred if it produces a more recyclable sulfate liquor and a higher-quality Fe–Ti-rich residue, even if the first-pass Sc extraction is slightly lower.

12. Scale-up, reactor engineering, TEA, LCA, TRL, and research gaps

12.1. Reactor engineering and operability

Industrial translation requires continuous solids handling, controlled acid or salt addition, corrosion-resistant materials, predictable residence time, heat recovery, and reliable off-gas scrubbing. Rotary kilns tolerate variable solids but can suffer from ring formation and broad residence-time distributions. Fluidized beds offer strong gas-solid transfer but require control of particle size and agglomeration. Multiple-hearth or staged systems can separate drying, sulfate formation, and decomposition zones but increase equipment complexity.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Reactor selection should therefore reflect the physical behavior of acid-treated BR as much as the thermodynamic window.

12.2. Technology readiness and evidence hierarchy

Pilot evidence is still limited relative to the number of laboratory studies. Demonstrations of Sc extraction from BR at pilot scale and semi-industrial iron-roasting studies are important because they expose issues absent from small crucibles: heat-transfer validation, residence-time distribution, throughput, solids handling, corrosion, filtration, off-gas scrubbing, recycle accumulation, and product consistency (Davris et al., 2021; Yuan et al., 2020). The qualitative readiness rubric used in this review distinguishes five evidence levels: Chemistry proof (batch mechanism demonstrated); Integrated bench (coupled unit operations with representative material); Continuous pilot (continuous solids/gas/liquid handling and measured mass balances); Recycle demonstration (sustained operation with sulfur/water loops and accumulation control); and Sustained industrial operation (qualified products, stable environmental controls, and reproducible long-duration performance). These categories are an author-developed evidence hierarchy and are not formal TRL certification.

12.3. Techno-economic and life-cycle assessment

TEA should identify cost drivers rather than simply attach a metal value to recovered Sc. At minimum, results should be reported on a per-tonne-dry-BR functional basis (for example, USD t^{-1} dry BR processed), with a second functional basis per unit of saleable product when product recovery and purity are sufficiently defined (for example, USD kg^{-1} qualified Sc_2O_3 or mixed REE product). Major variables include BR transport and dewatering, acid or sulfate consumption, roasting energy, corrosion allowance, gas scrubbing, water evaporation, impurity-removal reagents, solvent/resin inventory, residue handling, and final refining. Revenue from Sc/REEs, Fe, Ti, construction products, or avoided disposal should be credited only when product specification, recoverable quantity, market absorption, and qualification requirements are explicit. Prospective LCA should state the system boundary (e.g., gate-to-gate or cradle-to-gate), functional unit, electricity/heat assumptions, sulfur and water recycle



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

assumptions, treatment of avoided burdens, and allocation method when multiple co-products are claimed. Sensitivity or uncertainty analysis is required for emerging-scale inventories, and environmental superiority should not be inferred from laboratory extraction alone (Adrianto et al., 2021; Bergerson et al., 2020; Buyle et al., 2021; Cucurachi et al., 2018; Filippousi et al., 2025; Georgiades et al., 2025; Joyce & Björklund, 2019; Joyce et al., 2018; Moni et al., 2020; Narayanan et al., 2018b, 2019; Thonemann et al., 2020).

12.4. Research gaps and decision-oriented roadmap

Five gaps are decisive. First, mineralogical characterization must be linked quantitatively to sulfate formation and element-resolved deportment. Second, studies should report complete metal and sulfur balances, including wash liquor, off-gas, recycle, and purge streams. Third, the thermal window must be validated in continuous reactors with realistic bed depths, residence-time distributions, gas composition, heat transfer, corrosion, and solids handling. Fourth, downstream purification and sulfate/water recycle must be included in integrated mass balances with accumulation and purge criteria. Fifth, TEA/LCA should be performed on flowsheets with stated functional units, system boundaries, allocation rules, product specifications, and uncertainty ranges rather than idealized laboratory inventories. Recent review literature increasingly emphasizes integrated valorization, industrial symbiosis, feed variability, and the efficiency–selectivity–sustainability trade-off, supporting a shift from isolated recovery tests to decision-oriented process design (de Souza et al., 2025; Duarte & Fourie, 2026; Liu et al., 2026; Long et al., 2026; Song et al., 2026; Soto-Montandon et al., 2025; Tanvar & Mishra, 2025; U.S. Geological Survey, 2024, 2025; Zhang et al., 2026).

Table 8 and Figure 7 summarize this transition from laboratory performance to industrial readiness.

Table 8. *Industrial-readiness comparison of selective-sulfation and adjacent bauxite-residue routes.*

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Direct acid leaching	simple flowsheet	high Fe/Al impurity load and neutralization	high acid; moderate heat	Integrated bench / limited pilot evidence (route-dependent)
Acid baking + water leach	concentrates acid reaction before leach	corrosion, mixing, bake uniformity	high acid + thermal duty	Integrated bench / limited pilot evidence
H_2SO_4 sulfation–roasting	strong thermochemical selectivity potential	bed heat transfer, SOx control, sulfate recycle	acid + roasting; recycle-sensitive	Chemistry proof with strong scale-up case; continuous pilot still needed
$(NH_4)_2SO_4$/salt roasting	alternative reagent handling	NHx/S off-gas and salt recycle	salt + roasting	Chemistry proof / integrated bench
Integrated pretreatment + sulfation	can recover Fe or reduce alkali before Sc/REE stage	flowsheet complexity and CAPEX	multiple thermal/chemical steps	Module-dependent: integrated bench to continuous pilot
Closed-loop co-product flowsheet	best circularity potential	requires simultaneous market and recycle closure	lowest fresh inputs only if loops perform	Prospective integrated system; recycle demonstration required

Note. Author-developed qualitative readiness assessment; not formal TRL certification. Readiness categories: Chemistry proof = batch mechanism demonstrated; Integrated bench = coupled operations on representative material; Continuous pilot = continuous operation with measured balances and transport/handling validation; Recycle demonstration = sustained sulfur/water recycle with accumulation and purge control; Sustained industrial operation = qualified products and stable long-duration operation. Route assignments indicate the highest evidence level supported by the cited literature, not a numerical score.

Figure 7 presents a qualitative decision map linking target-metal recovery and process selectivity with evidence directness, chemical burden, and the readiness rubric defined in Table 8. The revised figure intentionally avoids data-like bubble sizes or numerical coordinates.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

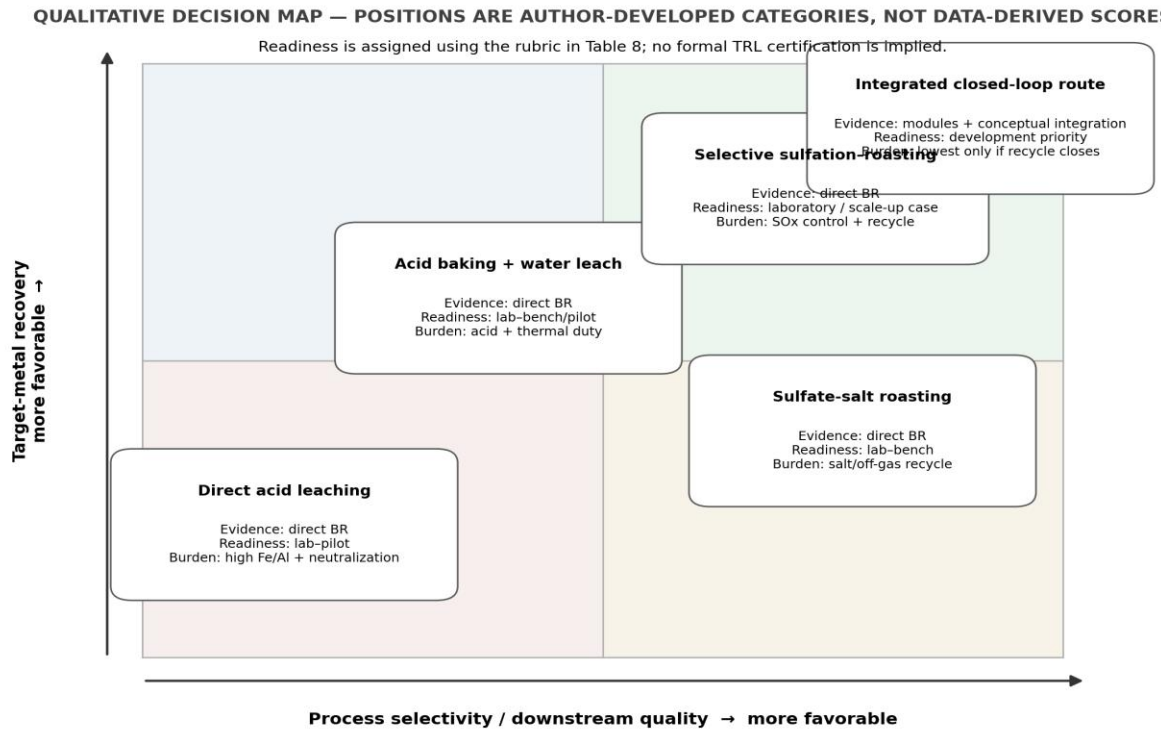


Figure 7. Qualitative recovery–selectivity–readiness decision map for selective-sulfation route selection.

Note. Author-developed conceptual schematic. Route positions are qualitative categories, not data-derived scores; no bubble size is used. Readiness labels follow the rubric in Table 8, and chemical burden is described textually rather than encoded as a pseudo-quantitative graphical variable.

Figure 7 reframes process selection without implying numerical comparability among heterogeneous studies. The desirable region combines high target-metal recovery, low Fe/Al transfer, acceptable sulfur and water intensity, qualified downstream recovery, manageable off-gas/residue burdens, and progressively stronger continuous-operation evidence. A route can therefore move toward industrial preference even with slightly lower first-pass Sc extraction if it improves PLS quality, recycle closure, residue usability, and operational robustness.

13. Conclusion

Selective sulfation of bauxite residue is best understood as the deliberate engineering of sulfate stability rather than as a variant of conventional acid leaching. The true origin of

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

selectivity is sequential. First, the target and matrix elements differ in their tendency to form sulfate species. Second, those sulfates differ in thermal stability, creating a roasting window in which Fe- and potentially Al-bearing sulfates decompose while Sc/REE sulfates remain recoverable. Third, water leaching converts that thermal contrast into solubility selectivity. Fourth, downstream purification must preserve the advantage created upstream. Finally, sulfur recycle, energy integration, residue quality, and product markets determine whether chemical selectivity becomes process selectivity.

No universal optimum temperature or reagent dosage can be assigned independently of mineralogy. Residue source, Fe/Al host phases, Ca and Na content, particle aggregation, sulfating agent, heating rate, residence time, bed thickness, atmosphere, gas composition, cooling history, and leaching conditions jointly determine the useful window. Future studies should replace single-point ‘maximum extraction’ reporting with element-resolved mass balances, complete sulfur closure, separate Fe and Al extraction, target/Fe selectivity accompanied by its component values, full thermal histories, quantitative PLS and wash characterization, solid–liquid separation metrics, and residue-quality evaluation.

The most promising development pathway is a closed-loop flowsheet in which sulfation and roasting are designed together with gas capture, water leaching, Sc/REE purification, sulfate/acid regeneration, purge control, and Fe–Ti-rich residue valorization. The principal research priority is not another isolated high laboratory extraction, but stable process selectivity under continuous operation with realistic heat and mass transfer, residence-time distribution, recycle accumulation, corrosion, solid–liquid separation, product consistency, and environmental qualification. Circularity should be claimed only when product qualification, radionuclide behavior, sulfate content, alkalinity, durability, and trace-metal leaching are demonstrated for the intended residue destination.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Declarations

Funding

This review received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. The review is based on the literature cited in the manuscript.

Author Contributions

The author performed conceptualization, methodology, literature synthesis, critical analysis, visualization, writing—original draft, and writing—review and editing.

Acknowledgments

None.

References

1. Abhilash, Hedrich, S., & Schippers, A. (2021). Distribution of scandium in red mud and extraction using Gluconobacter oxydans. Hydrometallurgy, 202, 105621. https://doi.org/10.1016/j.hydromet.2021.105621

2. Adrianto, L. R., van der Hulst, M. K., Tokaya, J. P., Arvidsson, R., Blanco, C. F., Caldeira, C., Guillén-Gonsálbez, G., Sala, S., Steubing, B., Buyle, M., Kaddoura, M., Navarre, N. H., Pedneault, J., Pizzol, M., Salieri, B., van Harmelen, T., & Hauck, M. (2021). How can LCA include prospective elements to assess emerging technologies and system transitions? The 76th LCA Discussion Forum. International Journal of Life Cycle Assessment, 26, 1541–1544. https://doi.org/10.1007/s11367-021-01934-w

3. Agrawal, S., & Dhawan, N. (2021a). A combined soda sintering and microwave reductive roasting process of bauxite residue for iron recovery. Minerals, 11(2), 222. https://doi.org/10.3390/min11020222

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

4. Agrawal, S., & Dhawan, N. (2021b). Evaluation of red mud as a polymetallic source—A review. Minerals Engineering, 171, 107084. https://doi.org/10.1016/j.mineng.2021.107084

5. Alam, S., Das, B. K., & Das, S. K. (2018). Dispersion and sedimentation characteristics of red mud. Journal of Hazardous, Toxic, and Radioactive Waste, 22(4), 04018025. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000420

6. Alkan, G., Schier, C., Gronen, L., Stopic, S., & Friedrich, B. (2018). A mineralogical assessment on residues after acidic leaching of bauxite residue (red mud) for titanium recovery. Metals, 8(6), 458. https://doi.org/10.3390/met8060458

7. Alkan, G., Xakalashe, B., Yagmurlu, B., Kaussen, F., & Friedrich, B. (2017). Conditioning of red mud for subsequent titanium and scandium recovery—A conceptual design study. World of Metallurgy – ERZMETALL, 70, 71–79. https://doi.org/10.13140/RG.2.2.21261.79847

8. Anawati, J., & Azimi, G. (2019). Recovery of scandium from Canadian bauxite residue utilizing acid baking followed by water leaching. Waste Management, 95, 549–559. https://doi.org/10.1016/j.wasman.2019.06.044

9. Archambo, M. S., & Kawatra, S. K. (2021). Utilization of bauxite residue: Recovering iron values using the iron nugget process. Mineral Processing and Extractive Metallurgy Review, 42, 222–230. https://doi.org/10.1080/08827508.2020.1715640

10. Avdibegović, D., & Binnemans, K. (2020). Separation of scandium from hydrochloric acid–ethanol leachate of bauxite residue by a supported ionic liquid phase. Industrial & Engineering Chemistry Research, 59(34), 15332–15342. https://doi.org/10.1021/acs.iecr.0c02943

11. Balomenos, E., Davris, P., Sakkas, K. M., Georgopoulos, C., & Makrigiannis, I. (2024). Bauxite residue valorisation through reductive smelting: Coproduction of pig iron and precursor for inorganic polymer fire resistant building materials. OALib Journal, 11, 1–15. https://doi.org/10.4236/oalib.1111029

12. Bergerson, J. A., Brandt, A., Cresko, J., Carbajales-Dale, M., MacLean, H. L., Matthews, H. S., McCoy, S., McManus, M., Miller, S. A., Morrow, W. R., Posen, I. D., Seager, T., Skone, T., & Sleep, S. (2020). Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity. Journal of Industrial Ecology, 24(1), 11–25. https://doi.org/10.1111/jiec.12954

13. Binnemans, K., & Jones, P. T. (2017). Solvometallurgy: An emerging branch of extractive metallurgy. Journal of Sustainable Metallurgy, 3, 570–600. https://doi.org/10.1007/s40831-017-0128-2

14. Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., & Pontikes, Y. (2015). Towards zero-waste valorisation of rare-earth-containing industrial process residues:



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

A critical review. Journal of Cleaner Production, 99, 17–38. https://doi.org/10.1016/j.jclepro.2015.02.089

15. Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: A critical review. Journal of Cleaner Production, 51, 1–22. https://doi.org/10.1016/j.jclepro.2012.12.037

16. Binnemans, K., Jones, P. T., Müller, T., & Yurramendi, L. (2018). Rare earths and the balance problem: How to deal with changing markets? Journal of Sustainable Metallurgy, 4, 126–146. https://doi.org/10.1007/s40831-018-0162-8

17. Borra, C. R., Blanpain, B., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2016a). Recovery of rare earths and other valuable metals from bauxite residue (red mud): A review. Journal of Sustainable Metallurgy, 2, 365–386. https://doi.org/10.1007/s40831-016-0068-2

18. Borra, C. R., Blanpain, B., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2016c). Smelting of bauxite residue (red mud) in view of iron and selective rare-earth recovery. Journal of Sustainable Metallurgy, 2, 28–37. https://doi.org/10.1007/s40831-015-0026-4

19. Borra, C. R., Blanpain, B., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2017). Recovery of rare earths and major metals from bauxite residue by sulfation-roasting-leaching. Journal of Sustainable Metallurgy, 3, 393–404. https://doi.org/10.1007/s40831-016-0098-9

20. Borra, C. R., Mermans, J., Blanpain, B., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2016b). Selective recovery of rare earths from bauxite residue by combination of sulfation, roasting and leaching. Minerals Engineering, 92, 151–159. https://doi.org/10.1016/j.mineng.2016.03.002

21. Borra, C. R., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2015). Leaching of rare earths from bauxite residue (red mud). Minerals Engineering, 76, 20–27. https://doi.org/10.1016/j.mineng.2015.01.005

22. Buyle, M., Maes, B., Van Passel, S., Boonen, K., Vercalsteren, A., & Audenaert, A. (2021). Ex-ante LCA of emerging carbon steel slag treatment technologies: Fast forwarding lab observations to industrial-scale production. Journal of Cleaner Production, 313, 127921. https://doi.org/10.1016/j.jclepro.2021.127921

23. Cardenia, C., Balomenos, E., & Panias, D. (2019). Iron recovery from bauxite residue through reductive roasting and wet magnetic separation. Journal of Sustainable Metallurgy, 5, 9–19. https://doi.org/10.1007/s40831-018-0181-5

24. Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of emerging technologies. Procedia CIRP, 69, 463–468. https://doi.org/10.1016/j.procir.2017.11.005

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

25. Davris, P., Balomenos, E., Nazari, G., Abrenica, G., Patkar, S., Xu, W.-Q., & Karnachoritis, Y. (2021). Viable scandium extraction from bauxite residue at pilot scale. Materials Proceedings, 5(1), 129. https://doi.org/10.3390/materproc2021005129

26. Davris, P., Balomenos, E., Panias, D., & Paspaliaris, I. (2016). Selective leaching of rare earth elements from bauxite residue using sulfuric acid. Hydrometallurgy, 164, 125–135. https://doi.org/10.1016/j.hydromet.2016.05.001

27. de Souza, P. H. C., Engvall, K., Penha, F. M., Kantarelis, E., & Nazir, S. M. (2025). Sustainable pathway towards red mud valorization through biomass thermochemical conversion and metals recovery. Bioresource Technology, 434, 132847. https://doi.org/10.1016/j.biortech.2025.132847

28. Ding, W., Bao, S., Zhang, Y., & Xiao, J. (2018). Selective leaching of scandium from red mud using a highly selective acid-leaching process. Hydrometallurgy, 175, 340–348. https://doi.org/10.1016/j.hydromet.2017.11.015

29. Duarte, J. P., & Fourie, A. (2026). Geotechnical behaviour of bauxite residue (red mud): A review of global parameter variability and chemical–mechanical interactions. Minerals, 16(8), 787. https://doi.org/10.3390/min16080787

30. Evans, K. (2016). The history, challenges, and new developments in the management and use of bauxite residue. Journal of Sustainable Metallurgy, 2, 316–331. https://doi.org/10.1007/s40831-016-0060-x

31. Feng, L., Yao, W., Zheng, K., Cui, N., & Xie, N. (2022). Synergistically using bauxite residue (red mud) and other solid wastes to manufacture eco-friendly cementitious materials. Buildings, 12(2), 117. https://doi.org/10.3390/buildings12020117

32. Filippousi, A., Samouhos, M., & Bartzas, G. (2025). Comparative life cycle assessment of management and valorization practices for bauxite residue. Earth: Environmental Sustainability, 1(1), 102–113. https://doi.org/10.53941/eesus.2025.100008

33. Georgiades, M., Özcan Kilcan, C., Giels, M., Hertel, T., Pontikes, Y., Tkaczyk, A. H., Cheeseman, C., & Myers, R. J. (2025). Ex ante life cycle assessment of bauxite residue vitrification technology. International Journal of Life Cycle Assessment, 30, 1896–1911. https://doi.org/10.1007/s11367-025-02512-0

34. Giels, M., Hertel, T., & Pontikes, Y. (2023). Transformation of bauxite residue into a reactive supplementary cementitious material. Proceedings of the 16th International Congress on the Chemistry of Cement. https://reactivproject.eu/publications/

35. Giels, M., Hertel, T., Gijbels, K., Schroeyers, W., & Pontikes, Y. (2022). High performance mortars from vitrified bauxite residue: The quest for the optimal chemistry and processing conditions. Cement and Concrete Research, 155, 106739. https://doi.org/10.1016/j.cemconres.2022.106739

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

36. Gomes, H. I., Jones, A., Rogerson, M., Burke, I. T., & Mayes, W. M. (2016a). Vanadium removal and recovery from bauxite residue leachates by ion exchange. Environmental Science & Technology, 50, 2467–2475. https://doi.org/10.1021/acs.est.5b05242

37. Gomes, H. I., Mayes, W. M., Rogerson, M., Stewart, D. I., & Burke, I. T. (2016b). Alkaline residues and the environment: A review of impacts, management practices and opportunities. Journal of Cleaner Production, 112, 3571–3582. https://doi.org/10.1016/j.jclepro.2015.09.111

38. Goronovski, A., Rivera, R. M., Van Gerven, T., & Tkaczyk, A. H. (2021). Radiological assessment of bauxite residue processing to enable zero-waste valorisation and regulatory compliance. Journal of Cleaner Production, 294, 125165. https://doi.org/10.1016/j.jclepro.2020.125165

39. Gräfe, M., Power, G., & Klauber, C. (2011). Bauxite residue issues: III. Alkalinity and associated chemistry. Hydrometallurgy, 108(1–2), 60–79. https://doi.org/10.1016/j.hydromet.2011.02.004

40. Guo, Y.-H., Gao, J.-J., Xu, H.-J., Zhao, K., & Shi, X.-F. (2013). Nuggets production by direct reduction of high iron red mud. Journal of Iron and Steel Research International, 20(5), 24–27. https://doi.org/10.1016/S1006-706X(13)60092-8

41. Habibi, H., Piruzian, D., Shakibania, S., Pourkarimi, Z., & Mokmeli, M. (2021). The effect of carbothermal reduction on the physical and chemical separation of the red mud components. Minerals Engineering, 173, 107216. https://doi.org/10.1016/j.mineng.2021.107216

42. Hertel, T., & Pontikes, Y. (2020). Geopolymers, inorganic polymers, alkali-activated materials and hybrid binders from bauxite residue (red mud)—Putting things in perspective. Journal of Cleaner Production, 258, 120610. https://doi.org/10.1016/j.jclepro.2020.120610

43. Ilkhani, Z., Vakilchap, F., Sadeghi, N., & Mohammad Mousavi, S. (2024). Base metals (Fe, Al, Ti) and rare earth elements (Ce, La, Pr) leaching from red mud through an efficient chemical-biological hybrid approach. Minerals Engineering, 208, 108603. https://doi.org/10.1016/j.mineng.2024.108603

44. Ilyas, S., Kim, H., & Srivastava, R. R. (2021). Feasibility of the bio-mobilization of rare earth elements from bauxite residual red mud. Environmental Sciences Proceedings, 6(1), 5. https://doi.org/10.3390/iecms2021-09334

45. International Aluminium Institute. (2020). Opportunities for using bauxite residue in Portland cement clinker production. https://international-aluminium.org/wp-content/uploads/2024/03/opportunities_for_use_of_bauxite_residue_in_portl.pdf

46. International Aluminium Institute. (2022a). Bauxite residue: An introduction. https://international-aluminium.org/wp-content/uploads/2022/09/Bauxite-Residue_Final_ENG-1.pdf



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

47. International Aluminium Institute. (2022b). Sustainable bauxite residue management guidance. https://international-aluminium.org/wp-content/uploads/2022/04/BRManagementGuidance.pdf

48. Jiang, Z., Quan, X., Zhao, S., & Zeng, K. (2021). Dealkalization and leaching behavior of Fe, Al, Ca, and Si of red mud by waste acid from titanium white production. ACS Omega, 6(48), 32798–32808. https://doi.org/10.1021/acsomega.1c04713

49. Joyce, P. J., & Björklund, A. (2019). Using life cycle thinking to assess the sustainability benefits of complex valorization pathways for bauxite residue. Journal of Sustainable Metallurgy, 5, 69–84. https://doi.org/10.1007/s40831-019-00209-x

50. Joyce, P. J., Hertel, T., Goronovski, A., Tkaczyk, A. H., Pontikes, Y., & Björklund, A. (2018). Identifying hotspots of environmental impact in the development of novel inorganic polymer paving blocks from bauxite residue. Resources, Conservation and Recycling, 138, 87–98. https://doi.org/10.1016/j.resconrec.2018.07.006

51. Khairul, M. A., Zanganeh, J., & Moghtaderi, B. (2019). The composition, recycling and utilisation of Bayer red mud. Resources, Conservation and Recycling, 141, 483–498. https://doi.org/10.1016/j.resconrec.2018.11.006

52. Kiskira, K., Lymperopoulou, T., Lourentzatos, I., Tsakanika, L. A., Pavlopoulos, C., Papadopoulou, K., & Ochsenkühn-Petropoulou, M. (2023). Bioleaching of scandium from bauxite residue using fungus Aspergillus niger. Waste and Biomass Valorization, 14(10), 3377–3390. https://doi.org/10.1007/s12649-023-02116-5

53. Kiskira, K., Lymperopoulou, T., Tsakanika, L. A., Pavlopoulos, C., Papadopoulou, K., Ochsenkühn, K. M., & Ochsenkühn-Petropoulou, M. (2021). Study of microbial cultures for the bioleaching of scandium from alumina industry by-products. Metals, 11(6), 951. https://doi.org/10.3390/met11060951

54. Klauber, C., Gräfe, M., & Power, G. (2011). Bauxite residue issues: II. Options for residue utilization. Hydrometallurgy, 108(1–2), 11–32. https://doi.org/10.1016/j.hydromet.2011.02.007

55. Kong, H., Zhou, T., Yang, X., Gong, Y., Zhang, M., & Yang, H. (2022). Iron recovery technology of red mud—A review. Energies, 15(10), 3830. https://doi.org/10.3390/en15103830

56. Kong, H., Zhou, T., Yang, X., Gong, Y., Zhang, M., & Yang, H. (2023). Summary of research progress on metallurgical utilization technology of red mud. Minerals, 13(6), 737. https://doi.org/10.3390/min13060737

57. Li, S., Pan, J., Zhu, D., Guo, Z., Shi, Y., Dong, T., Lu, S., & Tian, H. (2021). A new route for separation and recovery of Fe, Al and Ti from red mud. Resources, Conservation and Recycling, 168, 105314. https://doi.org/10.1016/j.resconrec.2020.105314

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

58. Liu, W., Chen, X., Li, W., Yu, Y., & Yan, K. (2014). Environmental assessment, management and utilization of red mud in China. Journal of Cleaner Production, 84, 606–610. https://doi.org/10.1016/j.jclepro.2014.06.080

59. Liu, X., Han, Y., He, F., Gao, P., & Yuan, S. (2021). Characteristic, hazard and iron recovery technology of red mud—A critical review. Journal of Hazardous Materials, 420, 126542. https://doi.org/10.1016/j.jhazmat.2021.126542

60. Liu, X., Yang, J., Ma, S., Wang, D., & Zhou, W. (2026). From hazardous solid waste to resource utilization: A technical review of efficient iron resource recovery from red mud. Reviews in Chemical Engineering, 42(2), 113–133. https://doi.org/10.1515/revce-2025-0040

61. Liu, Y., & Naidu, R. (2014). Hidden values in bauxite residue (red mud): Recovery of metals. Waste Management, 34(12), 2662–2673. https://doi.org/10.1016/j.wasman.2014.09.003

62. Long, H., Zhang, Z., Wang, X., Liu, X., & Xue, Y. (2026). Progress and perspectives on the total-component valorization of red mud: Bridging green metallurgy and sustainable cementitious materials. Journal of Environmental Chemical Engineering, 14(5), 124111. https://doi.org/10.1016/j.jece.2026.124111

63. Lyu, F., Hu, Y., Wang, L., & Sun, W. (2021). Dealkalization processes of bauxite residue: A comprehensive review. Journal of Hazardous Materials, 403, 123671. https://doi.org/10.1016/j.jhazmat.2020.123671

64. Marin Rivera, R., Xakalashe, B., Ounoughene, G., Binnemans, K., Friedrich, B., & Van Gerven, T. (2019). Selective rare earth element extraction using high-pressure acid leaching of slags arising from the smelting of bauxite residue. Hydrometallurgy, 184, 162–174. https://doi.org/10.1016/j.hydromet.2019.01.005

65. Meng, F., Li, X., Shi, L., Li, Y., Gao, F., & Wei, Y. (2020). Selective extraction of scandium from bauxite residue using ammonium sulfate roasting and leaching process. Minerals Engineering, 157, 106561. https://doi.org/10.1016/j.mineng.2020.106561

66. Meng, X., Zhao, H., Zhao, Y., Shen, L., Gu, G., & Qiu, G. (2023). Effective recovery of rare earth from (bio)leaching solution through precipitation of rare earth-citrate complex. Water Research, 233, 119752. https://doi.org/10.1016/j.watres.2023.119752

67. Moni, S. M., Mahmud, R., High, K., & Carbajales-Dale, M. (2020). Life cycle assessment of emerging technologies: A review. Journal of Industrial Ecology, 24(1), 52–63. https://doi.org/10.1111/jiec.12965

68. Narayanan, R. P., Kazantzis, N. K., & Emmert, M. H. (2018a). Selective process steps for the recovery of scandium from Jamaican bauxite residue (red mud). ACS Sustainable Chemistry & Engineering, 6(1), 1478–1488. https://doi.org/10.1021/acssuschemeng.7b03968



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

69. Narayanan, R. P., Kazantzis, N. K., & Emmert, M. H. (2019). Process for scandium recovery from Jamaican bauxite residue: A probabilistic economic assessment. Materials Today: Proceedings, 9, 578–586. https://doi.org/10.1016/j.matpr.2018.10.378

70. Narayanan, R. P., Ma, L.-C., Kazantzis, N. K., & Emmert, M. H. (2018b). Cost analysis as a tool for the development of Sc recovery processes from bauxite residue (red mud). ACS Sustainable Chemistry & Engineering, 6(4), 5333–5341. https://doi.org/10.1021/acssuschemeng.8b00107

71. Ning, G., Zhang, B., Liu, C., Li, S., Ye, Y., & Jiang, M. (2018). Large-scale consumption and zero-waste recycling method of red mud in steel making process. Minerals, 8(3), 102. https://doi.org/10.3390/min8030102

72. Niu, A., & Lin, C. (2024a). Bauxite residue (red mud) treatment: Current situation and promising solution. Science of the Total Environment, 948, 174757. https://doi.org/10.1016/j.scitotenv.2024.174757

73. Niu, A., & Lin, C. (2024b). Trends in research on characterization, treatment and valorization of hazardous red mud: A systematic review. Journal of Environmental Management, 351, 119660. https://doi.org/10.1016/j.jenvman.2023.119660

74. Padhan, A., & Paul, B. (2022). Assessment of bauxite residue as secondary resource for rare earth metal and valorization challenges: A perspective. Resources, Conservation & Recycling Advances, 14, 200078. https://doi.org/10.1016/j.rcradv.2022.200078

75. Padhan, A., & Paul, B. (2025). Unlocking the potential of red mud: Advanced strategies for economic optimization and sustainable recovery of critical minerals. Journal of Environmental Management, 389, 126040. https://doi.org/10.1016/j.jenvman.2025.126040

76. Pedram, H., Hosseini, M. R., & Bahrami, A. (2020). Utilization of Aspergillus niger strains isolated from pistachio husk and grape skin in the bioleaching of valuable elements from red mud. Hydrometallurgy, 198, 105495. https://doi.org/10.1016/j.hydromet.2020.105495

77. Pepper, R. A., Couperthwaite, S. J., & Millar, G. J. (2016). Comprehensive examination of acid leaching behavior of mineral phases from red mud: Recovery of Fe, Al, Ti, and Si. Minerals Engineering, 99, 8–18. https://doi.org/10.1016/j.mineng.2016.09.012

78. Pereira, A., & Paul, B. (2025). The large-scale sustainable utilization status of bauxite residue (red mud): Challenges and perspectives for China. Environmental Reviews, 33, 1–16. https://doi.org/10.1139/er-2024-0007

79. Pereira, A. C. (2025). Transformation of goethite into hematite: Mechanisms, technological routes, and industrial applications. IKR Journal of Engineering and Technology, 1, 1. https://doi.org/10.5281/zenodo.17265013



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

80. Pereira, A. C. (2026a). Bauxite residue (red mud) from the Bayer process: A critical review of management, safe storage, valorization, critical-metal recovery, and industrial integration. Journal International Review of Research Studies, 1(10), 1–46. https://doi.org/10.66104/90twks68

81. Pereira, A. C. (2026b). Brazil's rare earth elements landscape: From geological endowment to mine-to-magnet integration—Operations, resources, bottlenecks, market prospects, and research gaps. Nexus Science Review, 1(4), 1–59. https://doi.org/10.66104/7tpw1x21

82. Pereira, A. C. (2026c). Controlling co-precipitation in hydrometallurgy: From physicochemical parameters to process design and technology readiness. IKR Journal of Engineering and Technology, 2, 46–77. https://doi.org/10.5281/zenodo.20357561

83. Pereira, A. C. (2026d). Conventional ion-exchange and chelating resins for metal recovery: A critical comparison of selectivity, dynamic performance, regeneration, and process integration. International Journal of Current Science Research and Review, 9(9), 4916–4945. https://doi.org/10.5281/zenodo.22658215

84. Pereira, A. C. (2026e). From lime scrubbing to magnesium bisulfite circulation: A critical review of SO_2 capture, sulfite recovery, and process intensification. IKR Journal of Multidisciplinary Studies, 2(5). https://doi.org/10.5281/zenodo.22681179

85. Pereira, A. C. (2026f). Gallium recovery from ores and secondary resources (2020–2025): A critical review of process chemistry, selectivity challenges, and industrial readiness. RECIMA21 – Revista Científica Multidisciplinar, 7(3), e737479. https://doi.org/10.47820/recima21.v7i3.7479

86. Pereira, A. C. (2026g). Hydrometallurgical recovery of rare earth elements from metallurgical slags (2020–2026): A critical review. International Journal of Current Science Research and Review, 9(4), 1784–1812. https://doi.org/10.47191/ijcsrr/V9-i4-12

87. Pereira, A. C. (2026h). Improving filterability of hydroxide precipitates in hydrometallurgical hydrolysis processes: A critical review. IKR Journal of Engineering and Technology, 2, 21–45. https://doi.org/10.5281/zenodo.20098962

88. Pereira, A. C. (2026i). Jarosite formation as an iron-precipitation route in hydrometallurgy: Process chemistry, kinetics, impurity deportment, solid–liquid separation, and residue sustainability—A critical review. IKR Journal of Engineering and Technology, 2, 89–112. https://doi.org/10.5281/zenodo.21969803

89. Pereira, A. C. (2026j). Rare earth recovery from weathered carbonatite deposits: Mineralogical constraints, process development, and selective sulfation strategies. Nexus Science Review, 1(5), 1–37. https://doi.org/10.66104/wsf0bc19

90. Pereira, A. C. (2026k). Selective iron suppression through sulfation, oxidative calcination, and pH-controlled atmospheric leaching of a ferruginous oxidized copper ore.



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

International Journal of Current Science Research and Review, 9(7), 4155–4175. https://doi.org/10.47191/ijcsrr/V9-i7-59

91. Pereira, A. C. (2026l). Selective sulfation roasting and water leaching of a ferruginous nickel laterite at reduced commercial-acid addition: Particle-size-fraction response, iron rejection, and process-value screening. Nexus Science Review, 1(4). https://doi.org/10.66104/ypw4n767

92. Pereira, A. C. (2026m). Sulfuric acid regeneration from magnesium sulfate streams: Process chemistry, recovery technologies, and industrial challenges. International Journal of Current Science Research and Review, 9(5), 2797–2832. https://doi.org/10.47191/ijcsrr/V9-i5-54

93. Pereira, A. C. (2026n). Sulfuric acid regeneration from nickel laterite processing: Technologies, process chemistry, scale-up challenges, and circular economy perspectives. Journal International Review of Research Studies, 1(6), 1–58. https://doi.org/10.66104/3r2y1s96

94. Pereira, A. C., Santos, J. R. dos, & Silva, J. V. F. da. (2025). Selective recovery of zinc from steelmaking dust via sulfation and hydrometallurgical processing: A purification strategy for high-quality zinc sulfate production. Brazilian Applied Science Review, 9, e81925. https://doi.org/10.34115/basrv9n2-002

95. Peys, A., Hertel, T., & Snellings, R. (2022). Co-calcination of bauxite residue with kaolinite in pursuit of a robust and high-quality supplementary cementitious material. Frontiers in Materials, 9, 913151. https://doi.org/10.3389/fmats.2022.913151

96. Pilla, G., Hertel, T., Blanpain, B., & Pontikes, Y. (2025). A sustainable approach for concurrent recovery of metals from H2-reduced bauxite residue (“red mud”): Process optimization. Resources, Conservation and Recycling, 215, 108051. https://doi.org/10.1016/j.resconrec.2024.108051

97. Power, G., Gräfe, M., & Klauber, C. (2011). Bauxite residue issues: I. Current management, disposal and storage practices. Hydrometallurgy, 108(1–2), 33–45. https://doi.org/10.1016/j.hydromet.2011.02.006

98. Qu, Y., Li, H., Shi, B., Gu, H., Yan, G., Liu, Z., & Lian, B. (2022). Bioleaching performance of titanium from bauxite residue under a continuous mode using Penicillium tricolor. Bulletin of Environmental Contamination and Toxicology, 109(1), 61–67. https://doi.org/10.1007/s00128-022-03518-2

99. Rai, S., Wasewar, K. L., & Agnihotri, A. (2017). Treatment of alumina refinery waste (red mud) through neutralization techniques: A review. Waste Management & Research, 35(6), 563–580. https://doi.org/10.1177/0734242X17696147

100. Rai, S., Wasewar, K. L., Mukhopadhyay, J., Yoo, C. K., & Uslu, H. (2012). Neutralization and utilization of red mud for its better waste management. Archives of Environmental Science, 6, 13–33. https://doi.org/10.1016/j.wasman.2011.12.012



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

101. Raj, R., Yadav, B., Yadav, J. S., & Kumar, S. (2024). Red mud utilisation for sustainable construction and soil improvement: A comprehensive review. Discover Sustainability, 5, 398. https://doi.org/10.1007/s43621-024-00619-2

102. Reid, S., Tam, J., Yang, M., & Azimi, G. (2017). Technospheric mining of rare earth elements from bauxite residue (red mud): Process optimization, kinetic investigation, and microwave pretreatment. Scientific Reports, 7, 15252. https://doi.org/10.1038/s41598-017-15457-8

103. Sahu, R. C., Patel, R. K., & Ray, B. C. (2010). Neutralization of red mud using CO2 sequestration cycle. Journal of Hazardous Materials, 179, 28–34. https://doi.org/10.1016/j.jhazmat.2010.02.052

104. Samal, S., Ray, A. K., & Bandopadhyay, A. (2013). Proposal for resources, utilization and processes of red mud in India—A review. International Journal of Mineral Processing, 118, 43–55. https://doi.org/10.1016/j.minpro.2012.11.001

105. Shah, S. S., Palmieri, M. C., Sponchiado, S. R. P., & Bevilaqua, D. (2020). Enhanced bio-recovery of aluminum from low-grade bauxite using adapted fungal strains. Brazilian Journal of Microbiology, 51(4), 1909–1918. https://doi.org/10.1007/s42770-020-00342-w

106. Shah, S. S., Palmieri, M. C., Sponchiado, S. R. P., & Bevilaqua, D. (2022). A sustainable approach on biomining of low-grade bauxite by Penicillium simplicissimum using molasses medium. Brazilian Journal of Microbiology, 53(2), 831–843. https://doi.org/10.1007/s42770-022-00683-8

107. Shoppert, A., Loginova, I., Napol'skikh, J., Valeev, D., & Loginov, P. (2022a). High-selective extraction of scandium from bauxite residue (red mud) by acid leaching with MgSO4. Materials, 15(4), 1343. https://doi.org/10.3390/ma15041343

108. Shoppert, A., Loginova, I., Napol'skikh, J., Valeev, D., & Loginov, P. (2022b). Selective scandium extraction from bauxite residue (red mud) obtained by alkali fusion-leaching method. Materials, 15(2), 433. https://doi.org/10.3390/ma15020433

109. Silveira, N. C. G., Martins, M. L. F., Bezerra, A. C. S., & Araújo, F. G. S. (2021). Red mud from the aluminium industry: Production, characteristics, and alternative applications in construction materials—A review. Sustainability, 13(22), 12741. https://doi.org/10.3390/su132212741

110. Singh, V., Bano, S., Chauhan, V. B., Sharma, A., & Kumar, S. (2024). Red mud as a sustainable road construction material: An experimental investigation. Construction and Building Materials, 411, 134549. https://doi.org/10.1016/j.conbuildmat.2023.134549

111. Song, T., Gu, Y., Wang, Y., & Li, F. (2026). Red mud valorization: From waste management to metal resource recovery in the circular economy. Journal of

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

Environmental Management, 415, 130631. https://doi.org/10.1016/j.jenvman.2026.130631

112. Soto-Montandon, F., Gillane, R., Marcellin, E., Harrison, S. T. L., & Villa-Gomez, D. (2025). Bioleaching for critical metal recovery from bauxite residue—Unlocking waste valorization. Frontiers in Bioengineering and Biotechnology, 13, 1685819. https://doi.org/10.3389/fbioe.2025.1685819

113. Sutar, H., Mishra, S. C., Sahoo, S. K., & Maharana, H. S. (2014). Progress of red mud utilization: An overview. American Chemical Science Journal, 4, 255–279. https://doi.org/10.9734/ACSJ/2014/7258

114. Svobodova-Sedlackova, A., Calderón, A., Fernandez, A. I., Chimenos, J. M., Berlanga, C., Yücel, O., Barreneche, C., & Rodriguez, R. (2024). Mapping the research landscape of bauxite by-products (red mud): An evolutionary perspective from 1995 to 2022. Heliyon, 10, e24943. https://doi.org/10.1016/j.heliyon.2024.e24943

115. Swain, B., Akcil, A., & Lee, J. C. (2022). Red mud valorization an industrial waste circular economy challenge: Review over processes and their chemistry. Critical Reviews in Environmental Science and Technology, 52(4), 520–570. https://doi.org/10.1080/10643389.2020.1829898

116. Tanvar, H., & Mishra, B. (2025). Environmental management by recycling of bauxite residue. Journal of Advanced Manufacturing and Processing, 7(3), e70010. https://doi.org/10.1002/amp2.70010

117. Thonemann, N., Schulte, A., & Maga, D. (2020). How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. Sustainability, 12(3), 1192. https://doi.org/10.3390/su12031192

118. U.S. Geological Survey. (2024). Mineral commodity summaries 2024. https://doi.org/10.3133/mcs2024

119. U.S. Geological Survey. (2025). Mineral commodity summaries 2025. https://doi.org/10.3133/mcs2025

120. Vakilchap, F., Mousavi, S. M., & Shojaosadati, S. A. (2016). Role of Aspergillus niger in recovery enhancement of valuable metals from produced red mud in Bayer process. Bioresource Technology, 218, 991–998. https://doi.org/10.1016/j.biortech.2016.07.059

121. Van Wyk, N., Fischer, D., Wilbers, D., Harrison, S. T. L., Kotsiopoulos, A., & Dopson, M. (2024). Toward the bioleaching of bauxite residue by Gluconobacter oxydans. Journal of Applied Microbiology, 135(11), lxae279. https://doi.org/10.1093/jambio/lxae279

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

122. Wang, J., Liu, B., Wang, D., & Sun, R. (2026). Characterization of red mud and its utilization in preparing alternative cementitious materials: A review. Cleaner Materials, 19, 100378. https://doi.org/10.1016/j.clema.2026.100378

123. Wang, P., & Liu, D. Y. (2012). Physical and chemical properties of sintering red mud and Bayer red mud and the implications for beneficial utilization. Materials, 5(10), 1800–1810. https://doi.org/10.3390/ma5101800

124. Wang, S., Jin, H., Deng, Y., & Xiao, Y. (2021). Comprehensive utilization status of red mud in China: A critical review. Journal of Cleaner Production, 289, 125136. https://doi.org/10.1016/j.jclepro.2020.125136

125. Wang, Y., Zhao, H., Li, J., & Chen, Q. (2023). Recovery of valuable metals from red mud: A comprehensive review. Science of the Total Environment, 904, 166686. https://doi.org/10.1016/j.scitotenv.2023.166686

126. Xiao, Y.-J., Tiong, M., Mo, K. H., Guo, M.-Z., & Ling, T.-C. (2022). Recycling Bayer and sintering red muds in brick production: A review. Journal of Zhejiang University-SCIENCE A, 23, 335–357. https://doi.org/10.1631/jzus.A2100476

127. Xue, S., Zhu, F., Kong, X., Wu, C., Huang, L., Huang, N., & Hartley, W. (2016). A review of the characterization and revegetation of bauxite residues (red mud). Environmental Science and Pollution Research, 23, 1120–1132. https://doi.org/10.1007/s11356-015-4558-8

128. Yang, F., Zhang, J., Xie, M., Cui, W., & Dong, X. (2025a). Evaluation of compression index of red mud by machine learning interpretability methods. Computers and Geotechnics, 181, 107130. https://doi.org/10.1016/j.compgeo.2025.107130

129. Yang, J., Liu, X., Cui, K., Lyu, J., Liu, H., & Qiu, J. (2025b). Hazards and dealkalization technology of red mud—A critical review. Minerals, 15(4), 343. https://doi.org/10.3390/min15040343

130. Yang, T., Wang, Y., Sheng, L., He, C., Sun, W., & He, Q. (2020). Enhancing Cd(II) sorption by red mud with heat treatment: Performance and mechanisms of sorption. Journal of Environmental Management, 255, 109866. https://doi.org/10.1016/j.jenvman.2019.109866

131. Yang, Y., Wang, X., Wang, M., Wang, H., & Xian, P. (2015). Recovery of iron from red mud by selective leach with oxalic acid. Hydrometallurgy, 157, 239–245. https://doi.org/10.1016/j.hydromet.2015.08.021

132. Yuan, S., Liu, X., Gao, P., & Han, Y. (2020). A semi-industrial experiment of suspension magnetization roasting technology for separation of iron minerals from red mud. Journal of Hazardous Materials, 394, 122579. https://doi.org/10.1016/j.jhazmat.2020.122579



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

133. Zeng, H., Tang, H., Sun, W., & Wang, L. (2022). Strengthening solid–liquid separation of bauxite residue through the synergy of charge neutralization and flocculation. Separation and Purification Technology, 285, 120296. https://doi.org/10.1016/j.seppur.2021.120296

134. Zhang, J., Guan, W., Jia, Y., Guo, X., & Qi, L. (2026). Comprehensive utilization of RM (bauxite residue): Progress, challenges, and future prospects. Journal of Environmental Chemical Engineering, 14(2), 121308. https://doi.org/10.1016/j.jece.2026.121308

135. Zhang, J., Yao, Z., Wang, K., Wang, F., Jiang, H., Liang, M., Wei, J., & Airey, G. (2021). Sustainable utilization of bauxite residue (red mud) as a road material in pavements: A critical review. Construction and Building Materials, 270, 121419. https://doi.org/10.1016/j.conbuildmat.2020.121419

136. Zhang, N., Li, H., & Liu, X. (2016a). Hydration mechanism and leaching behavior of bauxite-calcination-method red mud-coal gangue based cementitious materials. Journal of Hazardous Materials, 314, 172–180. https://doi.org/10.1016/j.jhazmat.2016.04.040

137. Zhang, N., Li, H.-X., & Liu, X.-M. (2016b). Recovery of scandium from bauxite residue—red mud: A review. Rare Metals, 35(12), 887–900. https://doi.org/10.1007/s12598-016-0805-5

138. Zhang, N., Liu, X., Sun, H., & Li, L. (2011a). Evaluation of blends bauxite-calcination-method red mud with other industrial wastes as a cementitious material: Properties and hydration characteristics. Journal of Hazardous Materials, 185, 329–335. https://doi.org/10.1016/j.jhazmat.2010.09.038

139. Zhang, R., Zheng, S., Ma, S., & Zhang, Y. (2011b). Recovery of alumina and alkali in Bayer red mud by the formation of andradite-grossular hydrogarnet in hydrothermal process. Journal of Hazardous Materials, 189, 827–835. https://doi.org/10.1016/j.jhazmat.2011.03.004

140. Zhang, T., Yan, J., Li, Z., Wang, H., Han, P., & Ye, S. (2025). Utilization of red mud: Recovery of iron and aluminum by enhanced separation based on a new combined roasting process. Journal of Environmental Management, 377, 124669. https://doi.org/10.1016/j.jenvman.2025.124669

141. Zhang, X., Li, Y., Chen, G., & Wang, T. (2023). CO2 mineralization into waste-valorized lightweight artificial aggregate. Construction and Building Materials, 409, 133861. https://doi.org/10.1016/j.conbuildmat.2023.133861

142. Zhao, Q., Li, X., Wang, H., & Zhou, J. (2024). Technologies for recovery of iron from red mud: Processes, challenges and opportunities. Sustainable Materials and Technologies, 41, e01053. https://doi.org/10.1016/j.susmat.2024.e01053



Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 17/08/2026 - **Accepted:** 08/10/2026
Vol: 01.05
DOI: 10.66104/x41pvm52
Pages: 1-47

143. Zhou, T., Li, X., Zhao, Y., Zhao, S., & Yang, H. (2023). Extraction of iron and alumina from red mud with a non-harmful magnetization sintering process. Minerals, 13(3), 452. https://doi.org/10.3390/min13030452

144. Zhou, W., Shi, X., Lu, X., Qi, C., Luan, B., & Liu, F. (2020). The mechanical and microstructural properties of refuse mudstone-GGBS-red mud based geopolymer composites made with sand. Construction and Building Materials, 253, 119193. https://doi.org/10.1016/j.conbuildmat.2020.119193

145. Zhu, X., Li, W., Guan, X., & An, B. (2015). A review on recovery of scandium from red mud. Rare Metals, 34, 1–10. https://doi.org/10.1007/s12598-014-0358-7

CC BY