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Rare Earth Recovery from Weathered Carbonatite Deposits: Mineralogical Constraints, Process Development, and Selective Sulfation Strategies

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Abstract

Weathered carbonatite deposits are increasingly important rare-earth-element (REE) resources because prolonged lateritic alteration can enrich REE while simultaneously producing complex, fine-grained mineral assemblages that resist conventional beneficiation. This critical review evaluates the mineralogical controls that govern process selection, with particular emphasis on ferruginous saprolitic carbonatites and on the Araxá, Brazil, case as a model of ore-specific process development. The analysis integrates deposit evolution, REE host minerals, liberation and slime behavior, magnetic, gravity, and flotation responses, conventional sulfuric and caustic cracking, reduction-based pretreatment, selective sulfation, water leaching, impurity control, and downstream separation. A central argument is that bulk REE grade and the simple distinction between primary and weathered ore are insufficient for route selection. Instead, the decisive variables are the spatial association of monazite and secondary REE phases with Fe oxyhydroxides, silicates, apatite, and clay-sized material; the reactivity of Fe, Al, Ca, and silica during thermal and hydrometallurgical treatment; and the distribution of impurities between residue and pregnant leach solution. The review examines selective sulfation as a strategy to convert REE-bearing phases into water-leachable sulfates while limiting Fe and Al transfer, shifting selectivity from physical concentration to controlled chemical transformation. The review proposes a mineralogy-to-process framework, identifies a defensible operating window for selective sulfation, and defines scale-up priorities involving ore variability, acid economy, gas handling, sulfate balance, residue stability, and product specification. The resulting framework supports designing integrated, deposit-specific REE flowsheets rather than universal treatment schemes.

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Keywords: weathered carbonatite; rare earth elements; monazite; selective sulfation; process mineralogy; Araxá

Highlights

- Weathered carbonatites require route selection based on mineral association and impurity deportment, not bulk REE grade.
- Fine dissemination, slimes, and monazite–Fe–silica association explain the frequent limits of physical preconcentration.
- Selective sulfation can transfer selectivity from beneficiation to controlled thermal–chemical conversion and water leaching.
- Scale-up depends on ore variability, acid and sulfate closure, residue stability, and integration of purification with product targets.

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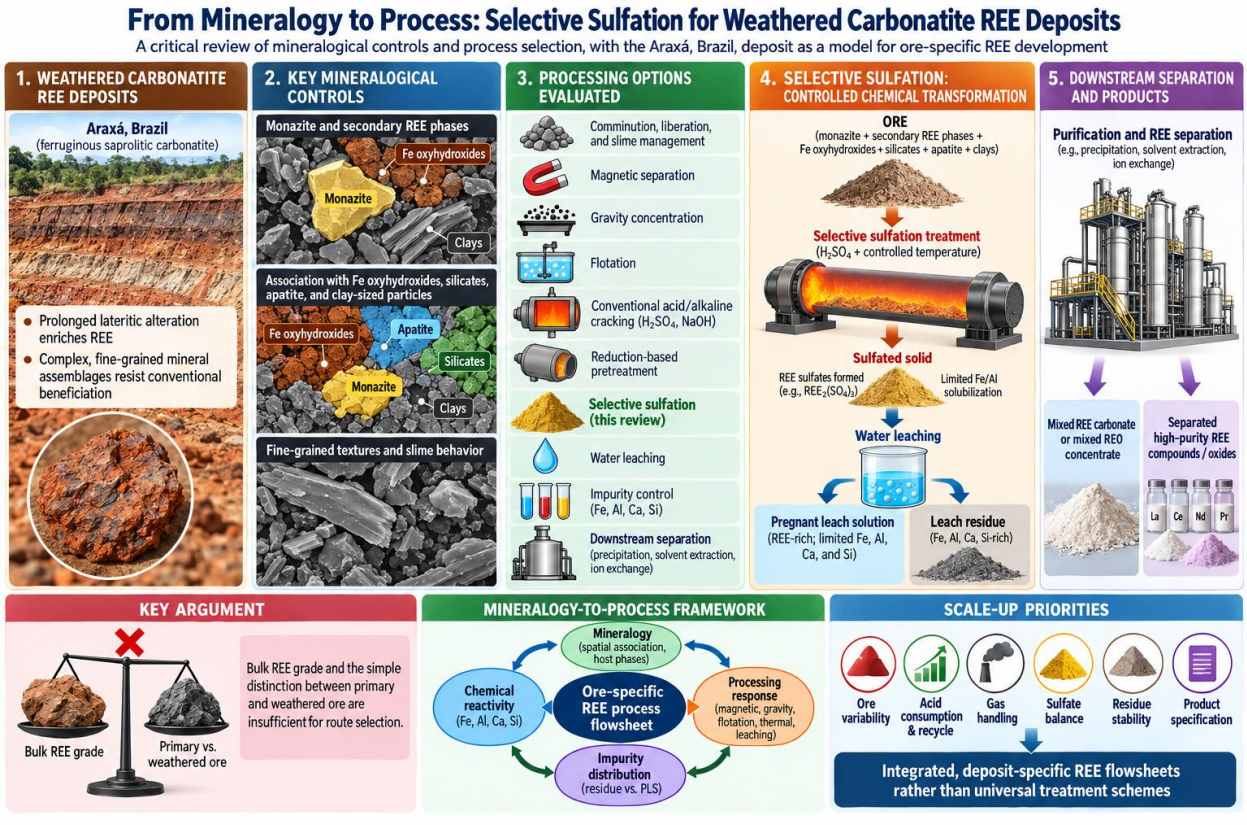
Graphical abstract



1. Introduction

Rare earth elements (REEs) are strategic to permanent magnets, high-performance alloys, catalysts, electronics, and energy-transition technologies, but their geological abundance does not translate directly into an easily diversified supply. The bottleneck is increasingly processability: ore texture, mineral host, grain size, impurity chemistry, and downstream separability determine whether a geological resource can become a robust metallurgical feed. This distinction matters especially for carbonatite-derived regoliths, where supergene alteration may enrich REEs while

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Pages: 1-53

also producing highly heterogeneous, fine-grained, Fe-rich, and clay-rich materials (Anenburg et al., 2021; Bailey et al., 2020; Pereira, 2026b; Siegfried et al., 2025; Verplanck et al., 2016).

Weathered carbonatites are therefore not merely "soft" versions of primary carbonatite ores. Weathering reorganizes the mineralogical system. Primary carbonates and apatite may dissolve or transform; Fe oxyhydroxides, secondary phosphates, clays, and residual monazite become more important; and REEs can be redistributed among discrete minerals, adsorbed fractions, or nanometric intergrowths. Studies of Araxá, Catalão, Mount Weld, Bear Lodge, Songwe Hill, Ngualla, and Mountain Pass show that this reorganization varies strongly among deposits, so transfer of a successful flowsheet from one ore to another is intrinsically risky (Al-Ali et al., 2020; Andersen et al., 2017; Antoniassi et al., 2020; Biondi & Braga, 2023; Braga & Biondi, 2023; Cook et al., 2023; Mano et al., 2026; Neumann & Medeiros, 2015; Santos et al., 2026; Watts et al., 2026; Witt et al., 2019; Zhukova et al., 2021).

This review treats the Araxá alkaline-carbonatite complex as a reference case for the broader problem of ore-specific REE processing. The central question is not whether a given unit operation can dissolve or float REE minerals under ideal conditions, but whether an integrated route can exploit the actual associations among monazite, Fe oxyhydroxides, silica-rich phases, apatite, and ultrafines while controlling Fe, Al, Ca, P, sulfate, and water in the pregnant leach solution (PLS). Figure 1 summarizes the analytical logic, while Table 1 formalizes the review questions and decision variables.

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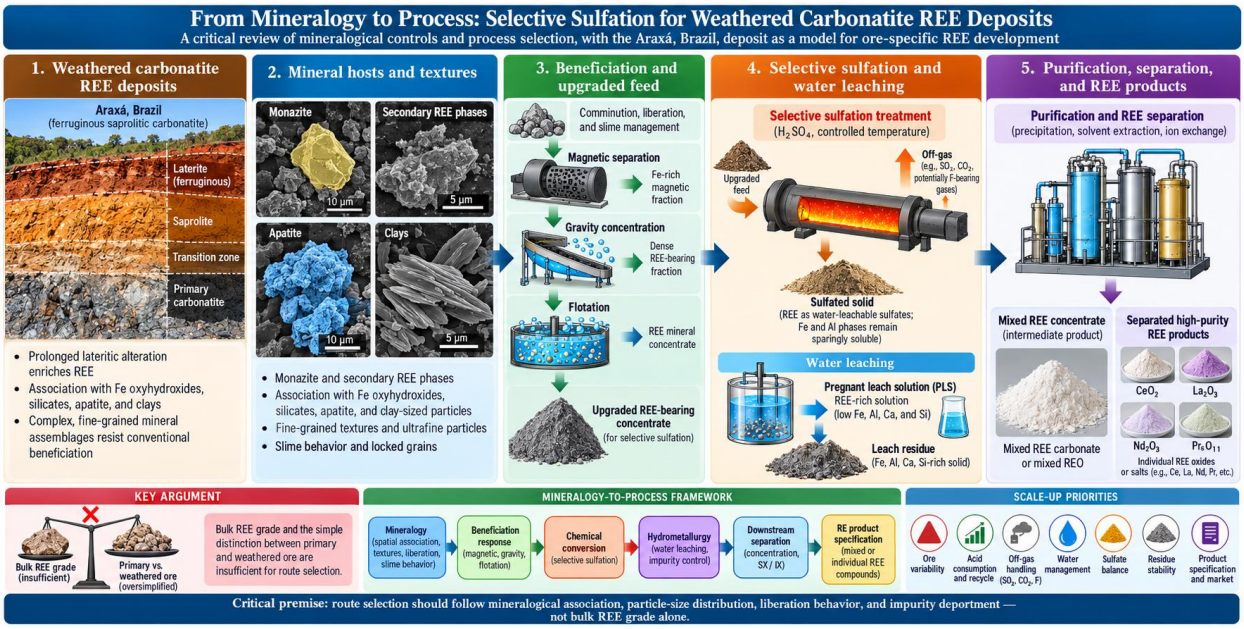

Figure 1. Author-developed ore-specific processing framework linking weathering, mineralogy, beneficiation response, chemical conversion, downstream purification, and product specification.

Note. Author-developed conceptual synthesis adapted from Anenburg et al. (2021), Antoniassi et al. (2020), Neumann and Medeiros (2015), and Teixeira (2020). The framework is not a prospectively validated universal process-selection algorithm; it is a structured synthesis for ore-specific hypothesis generation and testing.

Table 1. *Core review questions and analytical dimensions*

Review question	Key variables	Decision relevance
What controls REE deportment after weathering?	REE hosts, Fe oxyhydroxides, phosphate phases, clays, grain size	Defines liberation limits and chemical accessibility
Why does physical beneficiation often fail?	slimes, locked grains, density/magnetic overlap, surface chemistry	Determines whether preconcentration is justified
Which chemical route is most selective?	acid/alkali demand, phase conversion, Fe/Al/Ca/P transfer	Controls reagent intensity and purification load

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Can selective sulfation create a useful process window?	acid dose, temperature, time, sulfate stability, water leachability	Defines conversion–selectivity trade-off
What governs scale-up?	ore variability, heat/mass transfer, recycle, gas and residue management	Determines technical and environmental robustness

Note. The table is an original synthesis of the literature reviewed in this article.

Accordingly, the article first defines the evidence base and analytical framework, and then examines deposit evolution and REE mineralogy, the failure modes of conventional beneficiation, and the strengths and weaknesses of established chemical extraction routes. The synthesis makes three principal contributions: it treats mineralogy as the primary route-selection variable; it evaluates selective sulfation through a conversion–selectivity criterion rather than extraction alone; and it links thermal conversion to PLS purification, product specification, sustainability, and scale-up. Figure 1 and Table 1 establish this analytical logic, while Figures 2–7 and Tables 2–7 develop the corresponding mineralogical, process, and scale-up evidence in later sections. Throughout the review, a process is considered "selective" only when REE recovery is evaluated together with impurity transfer, reagent demand, residue quality, and downstream separability.

2. Review Methodology and Analytical Framework

2.1 Scope and critical-review logic

The review is structured as a structured critical narrative synthesis rather than a systematic review or a simple catalog of unit operations. Priority is given to literature that clarifies causal links between mineralogy and process performance: mineralogical characterization, liberation and surface-chemistry studies, phase-transformation work, thermodynamic analysis, leaching and purification experiments, process integration, and environmental or techno-economic assessment. Evidence from secondary resources and REE recycling is used only where it illuminates transferable precipitation, solvent-extraction, cerium-control, sulfate, or solution-chemistry

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Pages: 1-53

mechanisms; such evidence is not treated as direct validation of primary weathered-carbonatite behavior. The objective is to distinguish deposit-specific observations from mechanisms that can be tested across feeds.

2.2 Evidence corpus and thematic coverage

The geological and process-mineralogy corpus spans quantitative REE distribution in carbonatites, lateritic enrichment, deeply weathered Brazilian deposits, and comparative studies of Bear Lodge, Mount Weld, Songwe Hill, Ngualla, Mountain Pass, Araxá, and Catalão (Al-Ali et al., 2020; Andersen et al., 2017; Anenburg et al., 2021; Antoniassi et al., 2020; Biondi & Braga, 2023; Braga & Biondi, 2023; Broom-Fendley et al., 2017; Cocker, 2014; Cook et al., 2023; Je & Lee, 2023; Knorsch et al., 2024; Mano et al., 2026; Moore et al., 2015; Neumann & Medeiros, 2015). Additional geological and mineralogical contributions address carbonatite-hosted residual deposits, supergene weathering, QEMSCAN-based characterization, geochronology, and the mineral-chemistry evolution of lateritic REE systems (Santos et al., 2026; Sarker et al., 2023; Siegfried et al., 2025; Tomazini da Conceição et al., 2022; Van Rythoven et al., 2020; Verplanck et al., 2016; Verplanck, Mercer, et al., 2026; Verplanck et al., 2025; Verplanck, Thompson, et al., 2026; Verplanck et al., 2023; Watts et al., 2026; Witt et al., 2019; Zhukova et al., 2021).

The beneficiation corpus covers monazite flotation, collector chemistry, ultrafine REE recovery, process mineralogy applied to flotation, physical preconcentration, and the specific effects of Fe ions, hydroxamates, fatty acids, kaolinite, and challenging complex gangues (Abaka-Wood et al., 2024; Adu et al., 2026; Akyildiz, Silva, et al., 2026; Akyildiz, Slabov, et al., 2026; Ben Ali et al., 2025; Frutuoso et al., 2026; Gajendra et al., 2025; Geneyton et al., 2021; Hajdu-Rahkama et al., 2026; Jordens et al., 2013). Recent studies extend this evidence base to combined collectors, fine cerium phosphate, carbonatite tailings, and ligand adsorption relevant to mineral surfaces (Liu et

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al., 2025; Mokgomola et al., 2024; Sauber et al., 2025; Shuai et al., 2024; Silva et al., 2023; Wu et al., 2026; Zheng et al., 2021; Zhou et al., 2026).

Thermal and sulfation evidence includes sulfuric acid baking, selective roasting, the behavior of Fe oxides and hydroxides, thermodynamic stability of La–Fe–Th–sulfate/phosphate systems, and sulfation applied to monazite, complex ferruginous ores, rare-earth concentrates, and secondary materials (Chen et al., 2020; Demol et al., 2022; Demol et al., 2024; Gontijo et al., 2020; Gontijo et al., 2022; Gontijo et al., 2023; Hou et al., 2024; Hou et al., 2025; Huang, Zhang, et al., 2025; Kim et al., 2020). This is complemented by studies of low-temperature sulfation, acid-cyclic decomposition, sulfation roasting kinetics, and selective extraction from phosphate or fluoride-bearing feeds (Li et al., 2023; Maluleke et al., 2023; Pereira, 2026e; Shi, Chen, Chen, et al., 2025; Shi, Chen, Jiang, et al., 2025; Teixeira, 2020; Teixeira et al., 2020; Wang & Hu, 2021; Yu et al., 2025).

The leaching and decomposition literature includes sulfuric, hydrochloric, caustic, alkali-activated, biological, pressure, two-step, and diagnostic leaching strategies, as well as process developments for apatite-, phosphorite-, monazite-, and carbonatite-related feeds (Ahani et al., 2025; Almohammed et al., 2026; Alves et al., 2021; Bayarsaikhan et al., 2025; Gao et al., 2026; Guo, Li, Wang, et al., 2026; He et al., 2025; Huang et al., 2026). The remaining studies provide context for NaOH treatment, alkaline decomposition, hydrothermal conversion, and integrated phosphorus–REE separation (Huang, He, et al., 2025; Li et al., 2022; Liu et al., 2022; Ma et al., 2026; Nascimento et al., 2025; Rattanaphra et al., 2025; Xie et al., 2024; Zhou et al., 2025).

Downstream separation evidence is necessarily broader because the chemical behavior of dissolved REEs can be learned from primary ores, phosphogypsum, mine water, magnets, battery leachates, and synthetic solutions. The corpus includes precipitation, oxidative cerium removal,

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oxalate crystallization, sulfate double salts, solvent extraction with organophosphorus systems, ion exchange, membrane extraction, electrochemical oxidation, and product conversion (Aldana et al., 2026; Anawati & Azimi, 2022; Arellano Ruiz et al., 2020; Chen et al., 2023; Chen et al., 2025; Crespo et al., 2026; Cunningham et al., 2026; Dashti, Sadri, et al., 2021; Dashti, Shakibania, et al., 2021; Dzulqornain et al., 2024; Echeverry-Vargas et al., 2023; Emil-Kaya et al., 2024; Guan et al., 2022; Guo, Li, Yin, et al., 2026; Guzhov et al., 2023; Han & Kim, 2021; Jang et al., 2026; Kang et al., 2026; Kaplan et al., 2026). Further contributions address selective LREE/HREE systems, resin-in-leach, carbonate/hydroxide/oxalate conversion, continuous cerium removal, and advanced separation concepts (Klemettinen et al., 2023; Kurkinen et al., 2026; Laskar et al., 2025; Masmoudi-Soussi et al., 2020; McNeice et al., 2020; Moldoveanu & Papangelakis, 2025; Moldoveanu & Papangelakis, 2026; Nawab et al., 2022; Petraglia et al., 2026; Sá et al., 2026; Salehi, Maroufi, Khayyam Nekouei, & Sahajwalla, 2025; Salehi, Maroufi, Khayyam Nekouei, Chinu, & Sahajwalla, 2025; Sauber et al., 2026; Saudi et al., 2026; Smerigan & Shi, 2026; Wang et al., 2026; Wang et al., 2025; Wei et al., 2020; Zhou et al., 2020).

Finally, broader system-level sources address life-cycle impacts, Brazilian supply-chain integration, in-situ REE leaching, automated mineralogy, thorium management, and comparative utilization of polymetallic REE ores (Bailey et al., 2020; Pereira, 2026a; Pereira, 2026b; Pereira, 2026c; Pereira, 2026d; Pereira, 2026f; Zhang et al., 2026). Taken together, the final corpus comprises 125 references and supports a mineralogy-to-product analysis rather than a route-by-route summary.

2.3 Search strategy, eligibility criteria, and citation chaining

Literature discovery used Google Scholar as the primary search platform, complemented by Crossref/DOI resolution, publisher webpages, institutional repositories, and reference-list

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Pages: 1-53

checking to verify metadata. The final search cutoff was 30 September 2026. Representative Boolean blocks included: ("weathered carbonatite" OR "carbonatite regolith" OR lateritic carbonatite) AND ("rare earth*" OR REE) AND (mineralogy OR monazite OR "process mineralogy"); (monazite OR bastnäsite OR synchysite OR parisite) AND (flotation OR beneficiation OR liberation OR ultrafine*) AND (carbonatite OR regolith); ("selective sulfation" OR "sulfuric acid baking" OR roasting) AND (monazite OR "rare earth*") AND (iron OR goethite OR hematite OR ferruginous); and ("rare earth*" AND (precipitation OR "solvent extraction" OR "ion exchange" OR cerium) AND (sulfate OR leachate OR PLS)). Searches were conducted in English; non-English records were retained only when an English title/abstract and sufficient traceable metadata were available. Eligible document types were peer-reviewed journal articles, doctoral theses/dissertations, authoritative government datasets/reports, and selected book chapters where they supplied indispensable mechanistic or scale-up evidence. Preprints, non-traceable web material, records without sufficient bibliographic metadata, and studies lacking direct or mechanistically transferable relevance were excluded. Backward citation searching from foundational studies and forward citation searching of key process-mineralogy, sulfation, and separation papers were used to identify additional records. Duplicate records were removed at DOI/title level, and the final corpus contained 125 references.

2.4 Evidence-directness classification

To make evidentiary transfer explicit, the literature is classified by directness rather than by perceived scientific quality: Class I, direct evidence from weathered carbonatites or their regolith-derived feeds; Class II, evidence from related REE ores, concentrates, or closely analogous ferruginous/phosphate-bearing feeds; Class III, transferable mechanistic evidence on mineral reactions, sulfation, phase stability, or solution chemistry; and Class IV, downstream separation evidence whose governing chemistry is largely independent of the original ore mineralogy. Claims

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about ore behavior are based preferentially on Classes I–II, whereas Classes III–IV are used to interpret mechanisms or design downstream tests that still require validation on authentic PLS or solids. A representative audit matrix is supplied as Supplementary Table S1.

3. Weathered Carbonatites as REE Process Systems

3.1 Carbonatite protoliths and supergene transformation

Carbonatites are petrologically diverse and can host REEs in fluorcarbonates, phosphates, apatite, and accessory phases. During deep tropical weathering, carbonate dissolution and fluid–rock interaction reorganize this primary assemblage into residual and secondary mineral associations. The process may increase local REE grade, but it also destroys the simple mineralogical relationships that underpin conventional beneficiation. Quantitative studies show that REE distribution must be resolved by mineral species and texture rather than inferred from whole-rock assays (Anenburg et al., 2021; Broom-Fendley et al., 2017; Siegfried et al., 2025; Verplanck et al., 2016).

Araxá is especially instructive because Nb, P, Fe, Ba, and light rare-earth-element (LREE) mineralization coexist in a strongly weathered alkaline-carbonatite system. Geological and regolith studies describe saprolitic and lateritic domains in which REE-bearing phosphates occur with Fe-rich and silica-rich alteration products (Biondi & Braga, 2023; Braga & Biondi, 2023; Neumann & Medeiros, 2015). Comparable supergene enrichment mechanisms have been documented at Bear Lodge and Mount Weld, but the resulting mineral assemblages are not identical, reinforcing the need for deposit-specific flowsheet logic (Andersen et al., 2017; Cook et al., 2023; Moore et al., 2015; Santos et al., 2026; Verplanck, Mercer, et al., 2026; Verplanck et al., 2025; Verplanck, Thompson, et al., 2026; Verplanck et al., 2023; Zhukova et al., 2021).

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Pages: 1-53

Figure 2 illustrates the conceptual progression from fresh carbonatite to ferruginous regolith. The figure is not intended as a universal stratigraphic model; rather, it highlights the metallurgical consequence of weathering: REE host phases become embedded within a chemically reactive matrix whose Fe, Al, Ca, P, and silica contents strongly influence acid consumption, sulfate formation, filtration, and PLS purification.

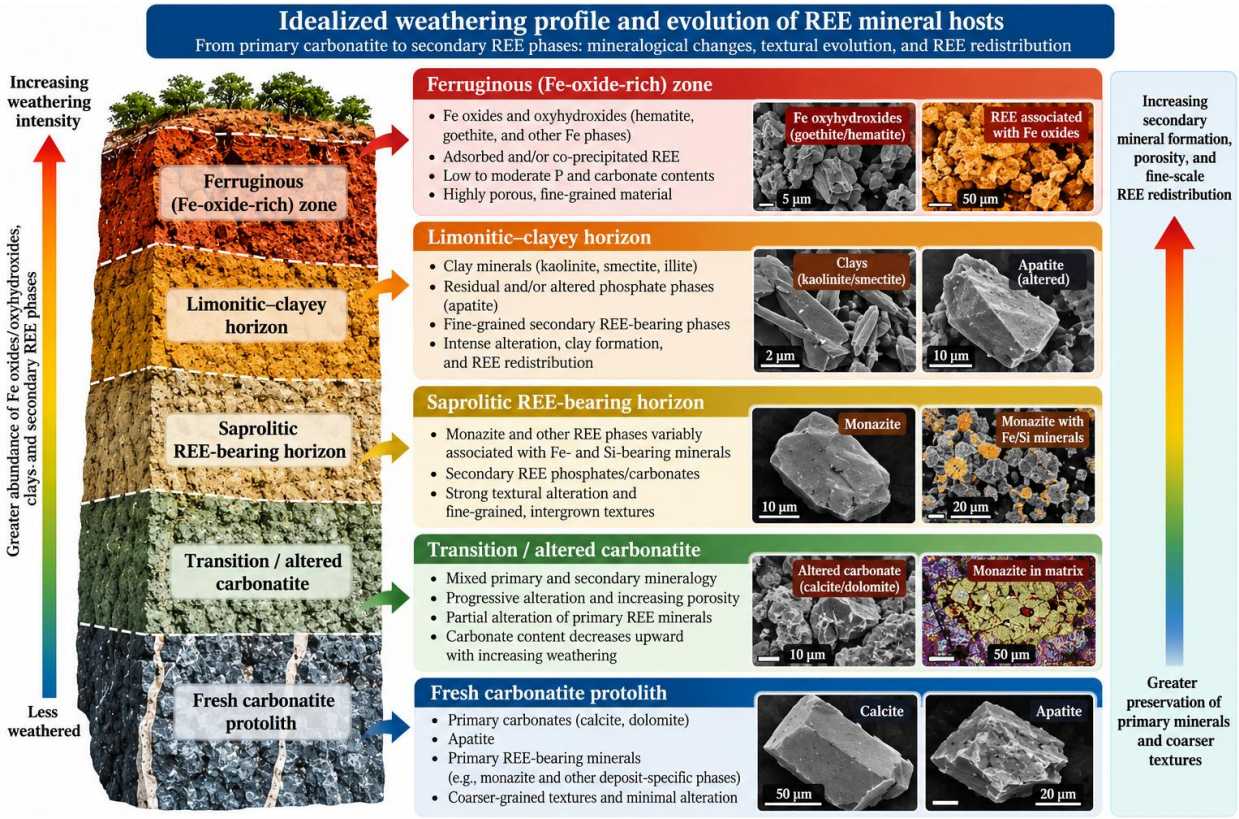

Figure 2. *Idealized lateritic weathering profile and evolution of rare-earth mineral hosts in a carbonatite-derived regolith.*

Note. Original synthesis adapted from Braga and Biondi (2023), Cook et al. (2023), Cocker (2014), and Siegfried et al. (2025).

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Pages: 1-53

3.2 REE host minerals and textural association

Monazite is a recurrent LREE carrier in weathered carbonatite systems, but its metallurgical behavior depends on grain size, liberation, alteration state, and association with Fe oxyhydroxides and silicate gangue. Automated and process-mineralogy studies of deeply weathered Brazilian deposits show that a significant fraction of REE value may occur in fine or compositionally complex particles, where liberation by grinding can create additional slimes rather than a clean concentrate (Antoniassi et al., 2020; Neumann & Medeiros, 2015; Pereira, 2026c; Van Rythoven et al., 2020).

The presence of secondary REE phases further complicates the picture. Supergene systems may contain rhabdophane-like phases, florencite-type phosphates, REE-bearing apatite, or surface-associated REEs on fine alteration products. Experimental work on mineral replacement and diagnostic leaching demonstrates that these phases can differ strongly in reactivity and in their response to thermal or hydrometallurgical treatment (Gao et al., 2026; Knorsch et al., 2024; Li et al., 2023; Mano et al., 2026). As a result, “monazite ore” is often an insufficient process descriptor for weathered carbonatites. Table 2 compares representative carbonatite and carbonatite-derived REE systems and summarizes the principal implications for flowsheet transferability.

Table 2. *Comparison of representative carbonatite and carbonatite-derived REE systems*

Deposit/system	Dominant process issue	Implication for transferability
Araxá, Brazil	weathered, Fe-rich, phosphate-bearing, fine dissemination	preconcentration may be weak; selective chemical conversion is attractive
Catalão, Brazil	alkaline-carbonatite regolith with LREE-bearing monazite associations	mineralogical variability requires diagnostic characterization
Mount Weld, Australia	strong lateritic enrichment and complex oxidized mineralogy	high grade does not eliminate need for mineral-specific treatment

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Bear Lodge, USA	supergene fractionation and oxidized REE assemblages	REE deportment can change substantially during weathering
Songwe Hill, Malawi	fluorcarbonate-bearing carbonatite with process-mineralogy controls	flotation behavior is tied to mineral chemistry and liberation
Ngualla, Tanzania	weathered bastnäsite zone over carbonatite	weathering can create a distinct beneficiation and leaching feed

Note. Adapted from Al-Ali et al. (2020), Andersen et al. (2017), Braga and Biondi (2023), Cook et al. (2023), Mano et al. (2026), and Witt et al. (2019).

Table 2 emphasizes that weathered carbonatites form a family of process systems rather than a single ore type. Their common feature is not a specific mineral but a strong coupling between supergene mineralogy and process response. This raises the next question: can physical beneficiation simplify the feed enough to justify inclusion before chemical extraction?

4. Why Conventional Beneficiation Often Underperforms

4.1 Liberation, ultrafines, and slime generation

Physical concentration is attractive because every tonne rejected before chemical treatment can reduce acid, alkali, water, and energy demand. However, this logic depends on a recoverable contrast between valuable and gangue minerals. In weathered carbonatites, REE minerals are frequently fine, intergrown, and associated with porous Fe-rich or clay-rich particles. Additional grinding can increase liberation only at the cost of a rapidly growing ultrafine fraction, where entrainment, high reagent adsorption, and poor selectivity become dominant (Adu et al., 2026; Frutuoso et al., 2026; Hajdu-Rahkama et al., 2026; Silva et al., 2023).

The consequence is a liberation paradox: the size reduction needed to expose monazite can simultaneously move the system into a particle-size regime in which flotation, gravity concentration, dewatering, and solid–liquid separation become less reliable. Recent flotation studies confirm that collector type, dosage, mineral transformation, and dissolved ions can improve response, but they do not eliminate the fundamental constraints imposed by ultrafine dissemination and mixed surfaces (Abaka-Wood et al., 2024; Akyildiz, Silva, et al., 2026; Akyildiz, Slabov, et

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al., 2026; Liu et al., 2025; Sauber et al., 2025; Wu et al., 2026; Zheng et al., 2021; Zhou et al., 2026).

4.2 Magnetic and gravity separation

Magnetic separation can be effective when REE minerals and Fe-bearing gangue have sufficiently distinct magnetic responses. In deeply weathered ferruginous feeds, however, the Fe-rich matrix may be distributed across composite particles and may itself carry or physically entrap REE phases. Rejecting magnetic material can therefore reject REE value, whereas retaining it may provide little upgrading. Gravity concentration faces a similar problem when valuable phases are very fine, locked with gangue, or accompanied by dense Fe minerals. Physical separation may still serve as a conditioning or scavenging step, but it should not be assumed to produce a high-grade concentrate without mineralogical evidence (Ben Ali et al., 2025; Gajendra et al., 2025; Jordens et al., 2013; Mokgomola et al., 2024; Shuai et al., 2024).

4.3 Flotation and surface-chemistry constraints

Monazite flotation is chemically plausible because phosphate mineral surfaces interact with fatty acids and hydroxamate collectors, yet real weathered ores present competing adsorption sites, dissolved multivalent ions, clays, and Fe-rich fines. The flotation response of monazite, bastnäsite, parisite, and synchysite can differ, and the same collector dosage can shift selectivity as mineral chemistry changes (Abaka-Wood et al., 2024; Akyildiz, Silva, et al., 2026; Akyildiz, Slabov, et al., 2026; Geneyton et al., 2021; Sauber et al., 2025). Fe^{3+} can alter monazite surface behavior, while mixed collectors or selective activation can improve recovery under specific conditions (Geneyton et al., 2021; Zheng et al., 2021). These findings support careful reagent engineering but do not justify treating flotation as universally robust for regolith ores.

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The failure modes are synthesized in Figure 3 and Table 3. Their central implication is that preconcentration should be assessed by net system benefit: REE recovery retained, mass rejected, chemical demand avoided, water demand added, and the downstream penalty created by fine tailings. A modest upgrade can still be valuable if it materially reduces impurity loading, but a high mass rejection is not beneficial if REEs follow the rejected Fe-rich or slime fractions.

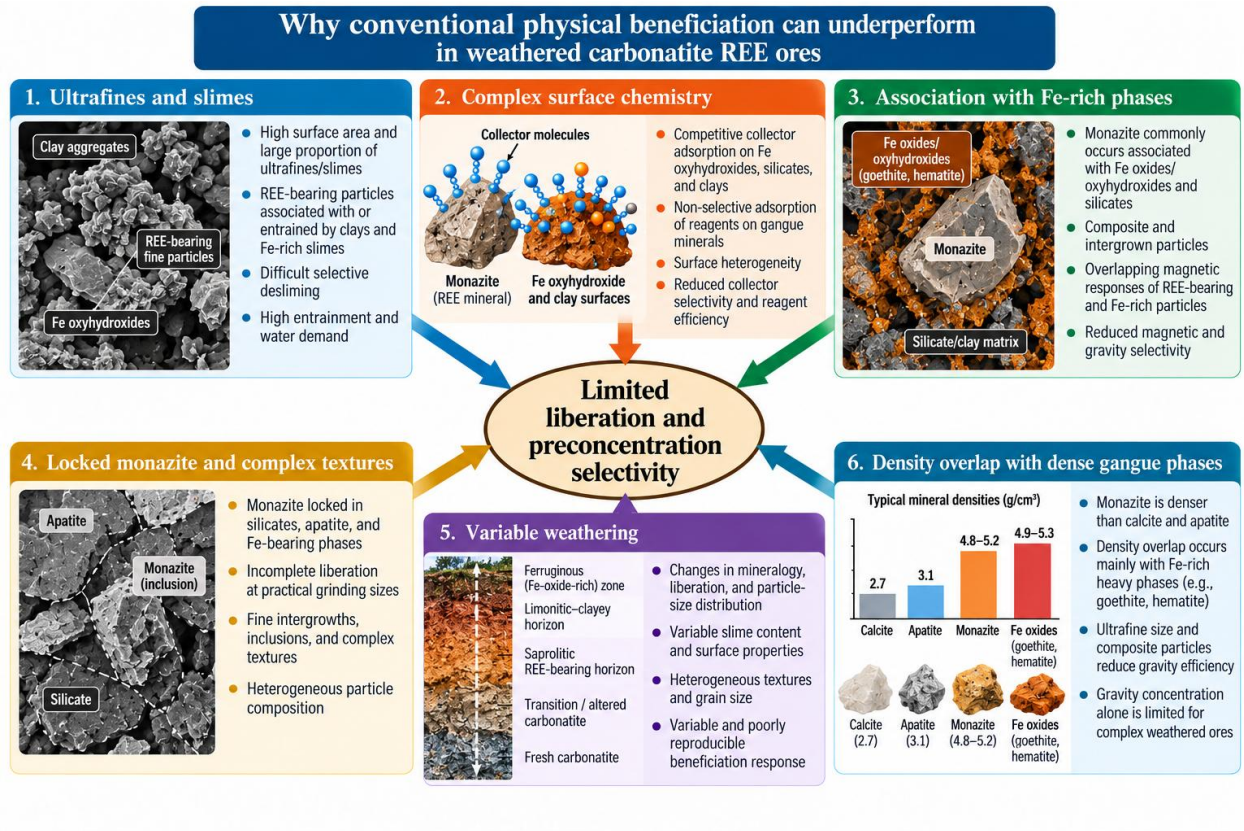

Figure 3. *Interacting mineralogical and particle-size constraints that limit physical preconcentration of weathered carbonatite REE ores.*

Note. Original synthesis adapted from Abaka-Wood et al. (2024), Adu et al. (2026), Jordens et al. (2013), and Shuai et al. (2024).

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Table 3. *Failure modes of conventional beneficiation in weathered carbonatite REE ores*

Operation	Potential advantage	Dominant limitation	Decision criterion
Desliming	removes high-surface-area fines	REEs may be concentrated in the slime fraction	REE loss vs reagent/water benefit
Magnetic separation	rejects Fe-rich gangue in favorable textures	REE-bearing composites may share magnetic response	REE deportment by magnetic fraction
Gravity concentration	low-reagent density separation	fine size and dense Fe phases reduce contrast	recoverable density contrast above cut size
Flotation	potential mineral selectivity	slimes, ions, clays, collector competition, variable REE minerals	grade–recovery response on real ore
Fine grinding	improves nominal liberation	creates ultrafines and increases surface area	net improvement in downstream selectivity

Note. Adapted from Jordens et al. (2013), Gajendra et al. (2025), Mokgomola et al. (2024), and recent monazite flotation studies cited in Section 4.

5. Conventional Chemical Extraction Routes and Their Limits

5.1 Sulfuric acid cracking and baking

Sulfuric acid is one of the most established reagents for decomposing refractory REE phosphates and concentrates. Acid baking or roasting can convert REE-bearing phases into soluble sulfate species, followed by water leaching. The route is chemically powerful, but in complex Fe-, Al-, Ca-, and phosphate-rich weathered ores, nonselective acid consumption and impurity activation can become decisive. Sulfation chemistry is therefore not a single reaction but a network of phase transformations whose outcome depends on acid dosage, temperature, gas evolution, water activity, and the competing stability of Fe, Al, Ca, Th, and REE sulfate or phosphate species (Chen et al., 2020; Demol et al., 2022; Demol et al., 2024; Gontijo et al., 2022; Hou et al., 2024; Hou et al., 2025; Kim et al., 2020; Maluleke et al., 2023; Teixeira et al., 2020).

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

Recent work has shown that iron oxides and hydroxides can influence acid baking and that controlling their sulfation behavior can improve selectivity rather than simply treating Fe as an inert gangue component (Demol et al., 2022; Gontijo et al., 2020; Gontijo et al., 2023). This point is crucial for weathered carbonatites, because goethite, hematite, and related phases are not peripheral impurities; they can dominate the matrix. The engineering question thus becomes how to exploit differences in sulfate stability and decomposition rather than maximizing total conversion.

5.2 Caustic and alkaline decomposition

Alkaline decomposition is a classical alternative for monazite because it can break the phosphate structure and produce a REE-bearing hydroxide or oxide intermediate, while phosphorus is transferred to soluble sodium phosphate species. Contemporary studies continue to optimize NaOH roasting, hydrothermal alkaline conversion, CaO–NaOH–H2O treatment, and subsequent hydrochloric leaching (Huang et al., 2026; Huang, He, et al., 2025; Liu et al., 2022; Nascimento et al., 2025; Rattanaphra et al., 2025; Zhou et al., 2025). The route can be attractive when phosphate removal is a priority, but its reagent intensity, washing demand, sodium balance, and handling of silicate-rich gangue may become problematic for low-grade weathered ores.

5.3 Acid leaching, pressure leaching, and hybrid routes

Direct or staged leaching can be effective for more reactive REE hosts, especially after pre-leaching or phase activation. Studies on apatite concentrates, phosphorites, carbonatites, and phosphate-related materials demonstrate the value of diagnostic leaching and two-step routes that decouple gangue dissolution from REE extraction (Ahani et al., 2025; Almohammed et al., 2026; Gao et al., 2026; Guo, Li, Wang, et al., 2026; Li et al., 2022; Ma et al., 2026; Xie et al., 2024). Researchers have also explored biological pretreatment and alkali activation to change mineral

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

accessibility before acid contact (Bayarsaikhan et al., 2025; He et al., 2025). The limitation is again selectivity: high extraction alone is not sufficient if Fe, Al, P, Ca, Mg, or silica create a PLS that is costly to purify.

5.4 Route comparison

Figure 4 and Table 4 compare the principal route families. The comparison deliberately avoids a universal ranking. A route that is optimal for a high-grade monazite concentrate may be poorly matched to a low-grade ferruginous saprolite, and a chemically elegant reaction can fail at scale if reagent recycle, filtration, sulfate balance, or impurity rejection are not integrated.

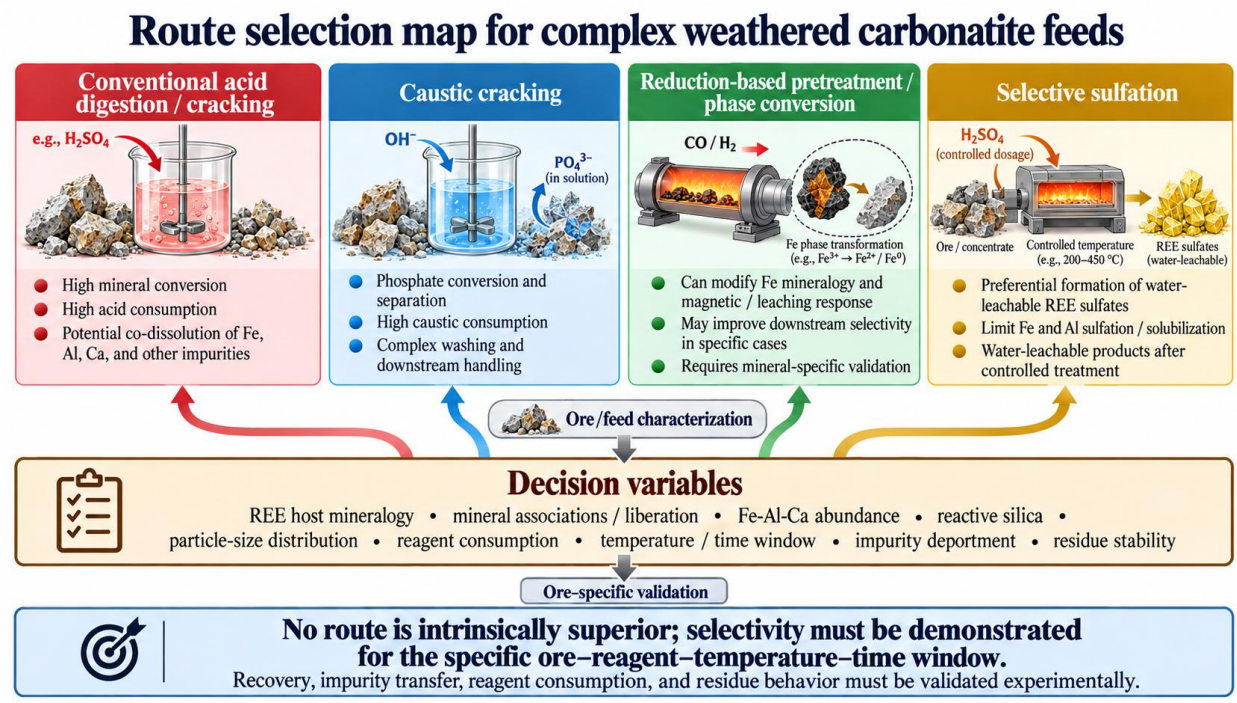

Figure 4. *Conceptual route-selection map for weathered carbonatite REE feeds.*

Note. Original synthesis adapted from Alves et al. (2021), Kim et al. (2020), Maluleke et al. (2023), Teixeira (2020), and Zhou et al. (2025).

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

Table 4. *Critical comparison of chemical extraction routes*

Route	Primary strength	Main weakness for weathered carbonatites	Best-fit condition
Concentrated H2SO4 cracking/baking	strong decomposition of refractory phosphates	acid consumption and broad impurity sulfation	higher-grade or well-characterized feeds with manageable impurities
Caustic/alkaline decomposition	phosphate removal and robust monazite attack	NaOH demand, washing, sodium/silica management	phosphate-rich feeds where alkali recycle is viable
Direct acid leaching	simple flowsheet	limited attack of refractory monazite or high gangue dissolution	reactive secondary REE phases or activated feeds
Pressure/hybrid leaching	can intensify extraction and staging	higher equipment and control complexity	feeds benefiting from selective pre-leach or pressure activation
Selective sulfation + water leach	potential REE conversion with Fe/Al suppression	requires narrow thermal–chemical window and acid/sulfate management	ferruginous weathered ores where chemical selectivity may reduce, but not necessarily eliminate, the need for intensive beneficiation

Note. Adapted from the route-development literature reviewed in Sections 5–7.

6. Mineralogical Constraints Governing Process Selection

6.1 Monazite–Fe association

The association between monazite and Fe oxyhydroxides is one of the most important constraints in the Araxá-type problem. It affects every stage: physical separation, acid consumption, sulfation competition, filtration, and PLS purification. If REE-bearing particles are physically locked with goethite or hematite, magnetic rejection becomes risky. If Fe phases are highly reactive toward sulfuric acid, the same matrix consumes reagent and can generate Fe sulfate species that later dissolve. Conversely, controlled thermal conditions may transform Fe sulfates to less soluble

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

oxides while preserving REE sulfate solubility (Demol et al., 2022; Gontijo et al., 2020; Gontijo et al., 2023; Teixeira, 2020; Teixeira et al., 2020).

6.2 Reactive silica and Al-bearing phases

Silica and Al-bearing phases are not passive gangue. In this review, "reactive silica" refers operationally to poorly crystalline, amorphous, highly weathered, or high-surface-area Si-bearing material that reacts appreciably with acid or alkali under the process conditions, rather than to all crystalline quartz. Such phases can consume reagent, form gels or polymeric silica during neutralization, retain liquor, and impair filtration. Al-bearing clays and secondary phases can behave similarly, while their sulfation or dissolution changes PLS chemistry. Consequently, bulk SiO2 and Al2O3 assays should be complemented by phase identification, size-resolved mineralogy, and solution-reactivity tests when route selection depends on acid/alkali demand or solid–liquid separation.

6.3 Particle size as a chemical variable

Particle size is often treated as a comminution variable, yet in weathered ores it also controls chemical accessibility, entrainment of fines, washing efficiency, and heat/mass transfer during roasting. Ultrafine fractions may react rapidly with acid but also retain mother liquor and increase soluble impurity carryover. Coarser composite particles may react incompletely unless acid distribution and residence time are sufficient. An ore-specific process therefore requires particle-size-resolved mineralogy and leaching response, not only bulk extraction tests (Adu et al., 2026; Antoniassi et al., 2020; Hajdu-Rahkama et al., 2026; Neumann & Medeiros, 2015; Silva et al., 2023).

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

6.4 A mineralogy-to-process decision rule

A defensible decision sequence is: first, define the target product specification and the acceptable impurity envelope; second, identify the REE host phases and their liberation size; third, quantify REE deportment into Fe-rich, clay-rich, phosphate-rich, and silicate-rich particle classes; fourth, test whether any low-cost physical step rejects mass without disproportionate REE loss; fifth, screen chemical routes by impurity transfer as well as REE extraction; and sixth, select the downstream purification route only after the PLS composition is established. This reverses a common development error in which a preferred reagent system is chosen before the mineralogical constraints and final product requirements are quantified. The mineralogy-to-process framework is an author-developed conceptual synthesis derived from the reviewed evidence and has not yet been prospectively validated as a universal process-selection model.

7. Selective Sulfation as an Ore-Specific Process Strategy

7.1 Conceptual basis

Selective sulfation aims to exploit differences in reaction and thermal stability among REE-bearing phases and major gangue components. In the idealized sequence, sulfuric acid reacts with REE-bearing minerals during controlled heating to form water-leachable REE sulfates, while Fe and Al sulfate species are either not formed extensively or decompose to less soluble oxides before the water-leaching step. This shifts the key selectivity event from mineral–bubble or mineral–field contrast to a chemically controlled phase-transformation window (Gontijo et al., 2020; Gontijo et al., 2022; Maluleke et al., 2023; Teixeira, 2020; Teixeira et al., 2020).

The approach is especially attractive for a feed in which conventional beneficiation cannot isolate monazite without high REE losses. Instead of attempting to produce a clean mineral concentrate, the process accepts a complex ore but engineers reaction conditions so that the desired REE species

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

report preferentially to solution. The concept is consistent with broader sulfation studies showing that acid dose and roasting severity can strongly modify the balance among conversion, impurity activation, and leachability (Chen et al., 2020; Hou et al., 2024; Li et al., 2023; Shi, Chen, Chen, et al., 2025; Shi, Chen, Jiang, et al., 2025; Wang & Hu, 2021; Yu et al., 2025).

7.2 Process window and VRESS-type development

The Araxá development case includes a selective-sulfation route referred to as VRESS (Vale Rare Earth Selective Sulphation). Its defining logic is a process-development philosophy rather than a universally transferable flowsheet: thermodynamic and mineralogical evidence are used to identify conditions in which REE conversion is high while Fe, Th, and other impurity transfer remain constrained. Source-level verification of Teixeira (2020) supports REE extraction up to approximately 80%, Fe and Th extraction below 1%, sulfuric-acid consumption below 0.34 kg H_2SO_4 per kilogram of ore, and a strong furnace-atmosphere effect: the temperature associated with maximum REE extraction decreased from about 700 °C in air to about 400 °C under reducing conditions while maintaining similar REE extraction. The previously combined statement of 350 kg H_2SO_4/t, 700 °C, 4 h, and ~93% REE extraction is not retained because that exact condition–response combination could not be verified as a single Teixeira (2020) experiment; the ~93% value reported in related Gontijo et al. (2023) work belongs to a different feed/acid-baking context and should not be conflated with the thesis benchmark. All numerical conditions are therefore treated as feed-specific development observations, not universal optima.

Figure 5 and Table 5 show why a useful operating region is expected, but it is multidimensional rather than a simple temperature optimum. The window depends simultaneously on ore mineralogy, acid/ore ratio, temperature, residence time, furnace atmosphere, moisture, particle-size distribution, acid distribution, agglomeration, and heat/mass transfer. Below the required

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

chemical or thermal severity, REE-bearing phases may remain incompletely converted. Beyond the useful region, excess sulfate inventory, impurity activation, sintering/agglomeration, SOx and acid-mist load, corrosion risk, and energy demand can rise without a proportional gain in useful REE transfer. The preferred condition is therefore the feed-specific region that maximizes whole-flowsheet performance rather than a single extraction number.

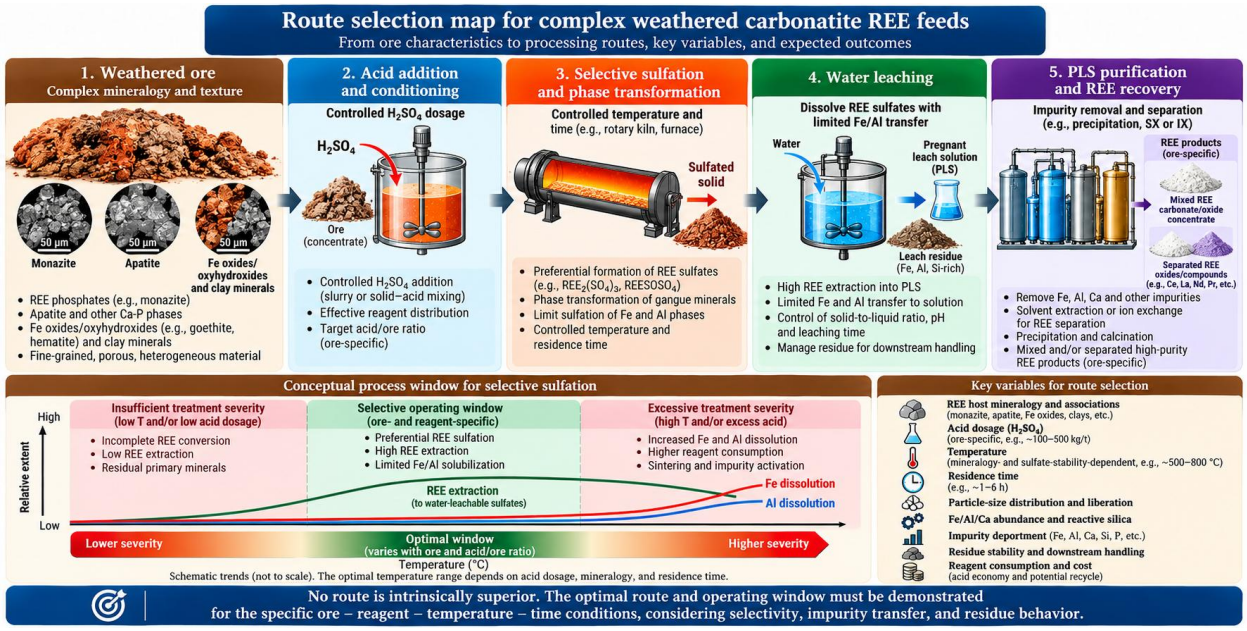

Figure 5. Conceptual multidimensional selective-sulfation window for a ferruginous weathered-carbonatite-type feed; the illustrated optimum is feed-specific and not a universal quantitative operating range.

Note. Original synthesis adapted from Gontijo et al. (2020, 2022, 2023), Maluleke et al. (2023), Teixeira (2020), and Teixeira et al. (2020). Temperature, acid dosage, time, atmosphere, moisture, acid distribution, particle size, and heat/mass transfer interact; no single condition is transferable without ore-specific validation.

Table 5. *Key variables controlling selective sulfation performance*

Variable	Low-severity risk	High-severity risk	Optimization target

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

H2SO4 dosage	incomplete REE conversion	excess sulfate, impurity activation, reagent cost	minimum dose giving high REE conversion
Temperature	slow/partial sulfation	sintering, sulfate decomposition, energy demand	maximize useful REE/Fe–Al selectivity at acceptable energy and gas load
Residence time	incomplete reaction	unnecessary energy use and overconversion	time to reach phase-conversion plateau
Particle size	acid-access limitation in coarse composites	ultrafine handling and entrainment	balance reaction accessibility and solid handling
Moisture/acid distribution	nonuniform reaction	local over-acidification and agglomeration	homogeneous acid–ore contact
Fe/Al mineralogy	uncontrolled sulfate formation	high PLS impurity load	promote insoluble Fe/Al-bearing products before leach
Furnace atmosphere	insufficient control of oxidation/reduction state	changed sulfate/oxide stability and gas composition	select atmosphere jointly with temperature and mineralogy
Heat and mass transfer	local under-conversion and acid maldistribution	hot spots, sintering, volatilization, uneven decomposition	reproduce reaction window across the full solids inventory

Note. Adapted from Gontijo et al. (2020, 2022, 2023), Teixeira (2020), and related sulfation studies cited in Section 7.

7.3 Thermodynamics, kinetics, and phase confirmation

Thermodynamic calculations are useful for identifying plausible stability fields but cannot substitute for phase-resolved experiments. Weathered ores are multiphase, acid distribution is nonuniform, and metastable intermediates can control practical kinetics. The most convincing development program therefore couples equilibrium calculations with XRD, automated mineralogy, thermal analysis, evolved-gas analysis where possible, and sequential leaching. The purpose is to verify not only that REEs become soluble but also which Fe, Al, Ca, P, and sulfur-bearing phases form and decompose across the treatment window (Gontijo et al., 2022; Shi et al., 2025; Teixeira, 2020; Teixeira et al., 2020).

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

8. Leaching, PLS Purification, and Impurity Control

8.1 Water leaching after sulfation

Water leaching is strategically important because it converts a high-temperature chemical treatment into a low-acid extraction step. If selective sulfation is successful, the roasted solid contains water-soluble REE sulfates and a largely insoluble Fe/Al-rich residue. Practical leach design must report liquid-to-solid ratio, temperature, residence time, sulfate concentration, PLS REE concentration, wash-water requirement, wash efficiency, retained-liquor loss, fine-particle retention, and residue moisture. Extraction to PLS should therefore be distinguished from recovery through solid–liquid separation: dissolved REEs retained in wet cake or lost in wash/purge streams are not recovered product. The objective is a concentrated REE-bearing PLS with minimal Fe, Al, Ca, P, and suspended solids, because every impurity carried forward increases downstream neutralization and separation burden.

8.2 Neutralization and staged impurity removal

Staged pH adjustment is a straightforward means of removing Fe and Al from sulfate or chloride leachates, but the separation window can be narrow and REE co-precipitation can become significant as pH increases. Sequential precipitation studies show the value of controlling oxidation state, ligand environment, and supersaturation rather than relying on a single terminal pH (Anawati & Azimi, 2022; Chen et al., 2023; Echeverry-Vargas et al., 2023; Masmoudi-Soussi et al., 2020). Where staged neutralization windows around pH 3.5 and 5.0 are proposed for an Araxá-type PLS, they must be validated on authentic solution against actual speciation, kinetics, solid properties, and REE co-precipitation; they are not fixed universal set points.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

8.3 Phosphorus, calcium, and sulfate management

Phosphorus can enter solution from partially decomposed phosphate phases and can precipitate with REEs or interfere with downstream separation. Calcium can control sulfate activity through gypsum or double-salt formation, while sulfate concentration affects both REE solubility and precipitation behavior. Thermodynamic analyses and double-sulfate studies demonstrate that sulfate chemistry can be used constructively, but it must be integrated with water balance and product recovery (Guzhov et al., 2023; Han & Kim, 2021; Laskar et al., 2025).

Table 6 summarizes a practical purification sequence. It is deliberately modular because the correct order depends on PLS composition. A process that successfully suppresses Fe during roasting may require only limited neutralization; a less selective roast may shift cost and complexity downstream. This interdependence is why extraction and purification cannot be optimized independently.

Table 6. *Modular purification sequence for a REE-rich pregnant leach solution*

Stage	Primary purpose	Key control	Main risk
Clarification/filtration	remove suspended fines	flocculation, filtration, wash displacement	REE entrainment in retained liquor
Early neutralization	remove Fe-rich hydrolysis products	pH and oxidation state	REE co-precipitation
Intermediate neutralization	remove Al and residual impurities	pH, sulfate activity, residence time	gel formation and REE loss
P/Ca management	avoid phosphate or sulfate scaling	speciation and supersaturation	uncontrolled double salts / gypsum
Ce-specific step	separate Ce by controlled oxidation/precipitation when desired	Eh–pH and oxidant dose	co-oxidation or entrainment
REE concentration/separation	produce mixed or separated REE products	SX/IX/precipitation circuit design	high stage count and reagent recycle demand

Note. Adapted from Anawati and Azimi (2022), Chen et al. (2023), Han and Kim (2021), and the downstream separation literature reviewed in Section 9.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

9. Separation and Production of REE Products

9.1 Cerium as a process lever

Cerium is unique among the common light REEs because Ce(III) can be oxidized to Ce(IV), enabling selective precipitation or extraction strategies that are not available to La, Pr, or Nd under the same conditions. Researchers have investigated oxidative precipitation using hydrogen peroxide, hypochlorite, or electrochemical methods in mixed REE systems (Aldana et al., 2026; McNeice et al., 2020; Moldoveanu & Papangelakis, 2025; Moldoveanu & Papangelakis, 2026; Sauber et al., 2026; Wang et al., 2026). Thermal treatment followed by selective hydrochloric leaching provides another route to exploit cerium chemistry (Sá et al., 2026). In an integrated flowsheet, early Ce removal can reduce the mass entering solvent extraction and alter the economics of downstream separation.

9.2 Precipitation and intermediate products

Oxalate precipitation remains a common route to concentrate REEs before calcination to oxides, and its selectivity depends on acidity, oxalate dosage, competing metals, and supersaturation (Crespo et al., 2026; Klemettinen et al., 2023; Nawab et al., 2022). Alternative carbonate, hydroxide, and double-sulfate pathways can be preferable depending on the desired product and recycle scheme (Guzhov et al., 2023; Laskar et al., 2025; Wang et al., 2025). The choice of intermediate should therefore link to the final product portfolio rather than be treated as a generic purification step.

9.3 Solvent extraction, ion exchange, and advanced separations

Solvent extraction remains the dominant high-resolution method for separating neighboring REEs, but the stage count can be large and strongly dependent on feed composition. Studies using Cyanex 272, Cyanex 572, TBP, HEH/EHP-type systems, and synergistic mixtures demonstrate that

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

separation factors can be tuned through extractant chemistry, acidity, complexation, and oxidation state (Arellano Ruiz et al., 2020; Chen et al., 2025; Dashti, Sadri, et al., 2021; Dashti, Shakibania, et al., 2021; Dzulqornain et al., 2024; Guo, Li, Yin, et al., 2026; Kaplan et al., 2026; Salehi, Maroufi, Khayyam Nekouei, & Sahajwalla, 2025; Salehi, Maroufi, Khayyam Nekouei, Chinu, & Sahajwalla, 2025; Saudi et al., 2026; Wei et al., 2020). Resin-in-leach, dynamic ion exchange, membrane-based extraction, and electrochemical concepts provide complementary options when the process objective is preconcentration or selective removal rather than full separation (Jang et al., 2026; Kang et al., 2026; Kurkinen et al., 2026; Petraglia et al., 2026; Zhou et al., 2020).

The practical target for a weathered-carbonatite operation may therefore be one of several product configurations: a mixed rare-earth carbonate or hydroxide, a mixed oxide, a Ce-depleted concentrate, a didymium-rich Pr–Nd stream, or individually separated oxides. Product specifications should be defined early because they determine how much separation complexity is economically justified. Figure 6 integrates these upstream and downstream choices within a single flowsheet logic.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

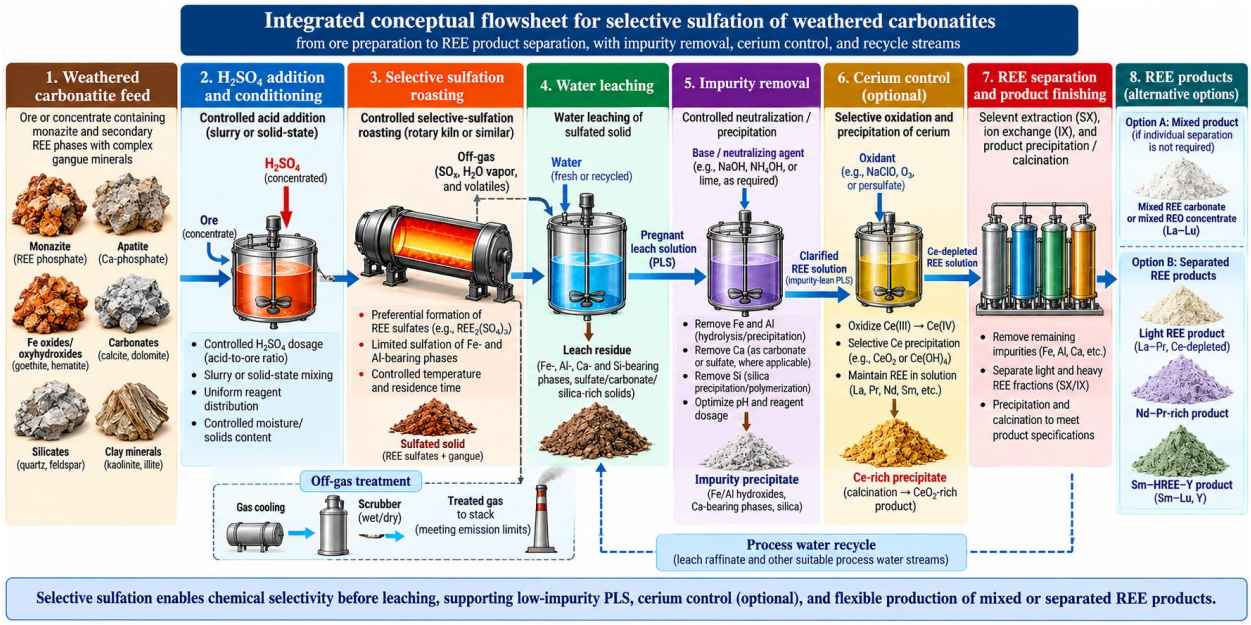

Figure 6. Author-developed conceptual integrated flowsheet synthesizing selective sulfation, water leaching, impurity removal, cerium control, and REE product separation from multiple literature routes; it is not a single experimentally validated pilot or commercial flowsheet.

Note. Author-developed synthesis adapted from the process-development, precipitation, solvent-extraction, and ion-exchange studies reviewed in Sections 7–9. Individual modules require validation on the intended ore and authentic PLS before integration.

10. Comparative Process Assessment and Sustainability

10.1 Recovery is not a sufficient performance metric

A critical weakness in REE process development is using extraction percentage as the dominant success metric. Terminology should distinguish extraction to the PLS, recovery through purification, overall recovery to an intermediate product, and overall recovery to a specification-compliant final product. For weathered carbonatites, a route that achieves high REE extraction but dissolves large amounts of Fe, Al, Ca, or P may simply move the separation problem downstream.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

Useful metrics include the selectivity ratio S_REE/Fe = X_REE/X_Fe (and analogous REE/Al ratios where data permit), the impurity burden I_imp/REE = m_dissolved impurities/m_REE transferred to PLS, PLS REE concentration, reagent consumption per kilogram of REO, water demand, sulfate or sodium inventory, residue mass and stability, energy per tonne of ore and per kilogram of REO, and the number of downstream stages required. Whole-flowsheet recovery should explicitly include retained-liquor losses during filtration/washing, co-precipitation during neutralization, precipitation losses, solvent-extraction and ion-exchange losses, and purge/recycle losses. The optimum is therefore defined by final product recovery and quality, not by roast or leach extraction alone.

Recommended minimum reporting: X_REE, X_Fe, X_Al, S_REE/Fe, S_REE/Al, I_imp/REE, PLS REE concentration, and R_overall = R_leach × R_solid–liquid separation × R_purification × R_product.

10.2 Life-cycle and resource-efficiency considerations

Life-cycle studies of REE production show that upstream mineralogy and processing route materially affect energy use, chemical consumption, emissions, and residue generation (Bailey et al., 2020). For weathered carbonatites, the environmental advantage of selective sulfation will depend on whether lower impurity dissolution and simpler purification offset the thermal energy required for roasting. Acid recovery, heat integration, low-carbon electricity or fuel, water recycle, and useful valorization of Fe- or phosphate-bearing residues can change the overall balance. These variables should be quantified through process simulation and prospective life-cycle assessment rather than assumed from laboratory selectivity alone (Smerigan & Shi, 2026). Prospective TEA/LCA should report energy per tonne of feed and, preferably, per kilogram of REO; reagent

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

demand per kilogram of REO; water demand per tonne of feed; residue generation per tonne of feed; transport/logistics assumptions; and alternative electricity/fuel supply scenarios.

10.3 Brazilian integration and strategic context

Brazilian carbonatite complexes offer a distinctive integration opportunity because REE mineralization can occur within broader Nb–P–Fe systems. This creates both complexity and potential synergies, but existing Nb–P–Fe infrastructure should be treated as an opportunity rather than an assured economic synergy: existing mining, comminution, tailings, water, and chemical infrastructure may reduce greenfield requirements, while coexisting phosphate or niobium operations can create opportunities for shared beneficiation, reagent supply, or residue management (Biondi & Braga, 2023; Braga & Biondi, 2023; Pereira, 2026a; Pereira, 2026b; Pereira, 2026d). Thorium management and radiological characterization must be included wherever monazite processing concentrates Th-bearing phases (Gontijo et al., 2022; Pereira, 2026f).

Comparative assessment should also recognize that global REE supply chains are heterogeneous. Ion-adsorption clays, bastnäsite concentrates, monazite-rich placers, lateritic monazite, carbonatite regoliths, mine tailings, and secondary resources require different process logic. Lessons can be transferred at the level of chemistry and separation mechanisms, but not by copying entire flowsheets. The review therefore favors modular process design: ore-specific front-end conversion coupled to standardized downstream separation blocks wherever chemistry permits.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

11. Scale-Up Challenges, Technology Risks, and Research Priorities

11.1 Ore variability and geometallurgy

Ore variability is the first scale-up risk because a selective window defined on one composite can disappear when Fe mineralogy, clay content, monazite grain size, moisture, apatite abundance, or reactive silica changes. A geometallurgical program should therefore use representative variability composites and link drill-core or mining-domain mineralogy to acid demand, roasting response, water-leach extraction, PLS concentration, and PLS impurity load. The minimum useful model is not grade-only but a multivariate domain classification that predicts reagent demand, element-by-element deportment, and selectivity from mineralogical descriptors; size-resolved mineralogy should be reported where liberation or slime behavior changes the route response.

11.2 Roaster design, heat and mass transfer, and gas handling

Laboratory acid-baking tests usually provide excellent mixing and short thermal diffusion distances. At pilot scale, acid distribution, moisture, agglomeration, bed permeability, heat transfer, sulfate decomposition, and gas evolution become coupled. Selection among rotary-kiln, fluidized-bed, multiple-hearth, or other roasting concepts should therefore follow reaction-mechanism evidence and solids behavior. Off-gas design must quantify SOx generation, water vapor, entrained sulfuric-acid mist, particulate carryover, and any volatile impurity species; these loads determine gas cooling, scrubbing, demisting, corrosion-resistant materials, and occupational/environmental controls. Where technically feasible, sulfuric-acid or sulfur-bearing reagent recovery should be integrated with the thermal and hydrometallurgical circuits. Thermal integration should also assess sensible-heat recovery, feed preheating, and the effect of recycle gases or reducing atmosphere on sulfate/oxide stability.

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

11.3 Acid economy and sulfate closure

The acid demand reported for the Araxá-type development literature is high enough that acid regeneration and sulfate management are likely to determine operating cost and environmental performance. Gross acid addition must be distinguished from acid chemically consumed, acid recovered/regenerated, sulfate recycled, and downstream neutralizing-agent demand. A complete flowsheet should close sulfur across input acid/reagents and sulfur reporting to product, PLS, wash water, precipitates, residue, purge streams, and off-gas. A useful reporting metric is $\eta_S = (S_{product} + S_{PLS} + S_{residue} + S_{off\text{-}gas} + S_{purge})/S_{input}$, with the expectation that a validated flowsheet approaches full accountable closure within analytical uncertainty. The same element-by-element balance should be reported for total REEs, Fe, Al, Ca, P, and Th/U where relevant. Without this closure, laboratory selectivity can translate into excessive neutralization demand, sulfate-rich effluent, or unrecognized REE loss. Research should therefore prioritize acid recycle, counter-current washing, wash-water integration, solution concentration, sulfate crystallization where appropriate, and integration between roasting and hydrometallurgy.

11.4 Pilot demonstration and decision gates

Figure 7 and Table 7 convert the main uncertainties into a staged development plan. The highest-priority pilot questions are those that can invalidate the flowsheet: variability of ore response, reproducibility of selective sulfation, acid–solid contacting, solid handling during roasting, leach-residue filtration/washing, off-gas behavior, and the stability of the purification window. After bench reproducibility is demonstrated, continuous pilot operation should be prioritized over additional isolated batch optimization because residence-time distribution, recycle accumulation, heat/mass transfer, and solids behavior emerge only under continuous conditions. Product separation should be demonstrated with authentic PLS rather than synthetic solutions alone

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

because trace impurities can alter precipitation, solvent extraction, and ion exchange. The final product-development gate should include recycle closure and repeat production of specification-compliant material.

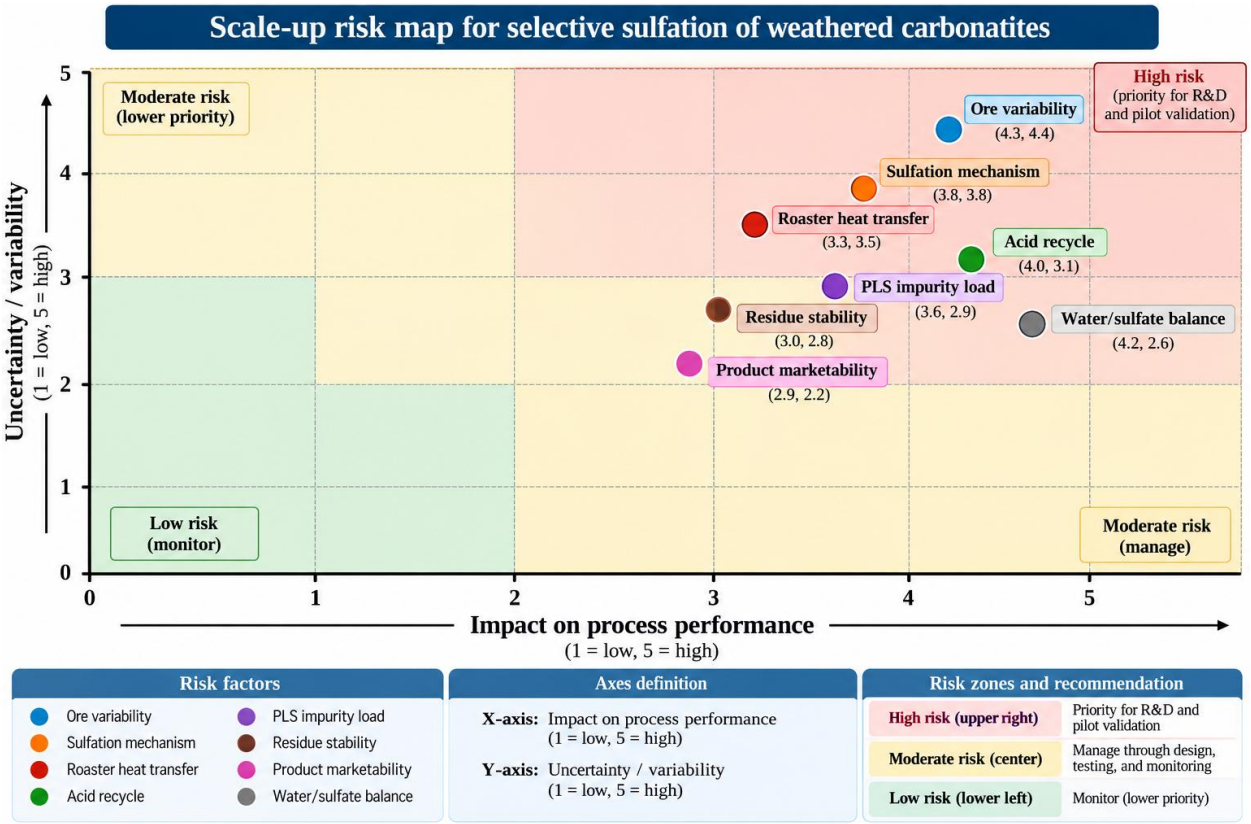

Figure 7. Qualitative scale-up risk map for selective sulfation of weathered carbonatite REE ores.

Note. Original qualitative expert synthesis based on scale-up issues identified in the reviewed process-development literature. Positions on the 1–5 axes are heuristic prioritization aids, not validated probabilities, empirical risk scores, or quantitative failure frequencies.

Table 7. *Research and scale-up decision gates*

Gate	Evidence required	Go criterion	Primary failure signal

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

Mineralogy–response model	variability composites + automated mineralogy + diagnostic tests	predictable acid demand and REE/impurity response by ore domain	large unexplained variability
Bench selective sulfation	phase analysis + element-by-element mass balance + repeatability	high REE extraction with controlled Fe/Al/Th transfer and reproducible selectivity metrics	selectivity only at isolated test point
Continuous thermal pilot	continuous solids handling, acid distribution, heat/mass transfer, off-gas, and sulfur accounting	stable conversion, manageable gas/solids behavior, and accountable sulfur distribution	agglomeration, hot spots, sulfate loss
Integrated leach/purification	counter-current washing + authentic-PLS neutralization/purification	low REE loss, reproducible impurity removal, acceptable PLS concentration and wash-water balance	gel formation or excessive co-precipitation
Product circuit	Ce step + precipitation/SX/IX on authentic PLS with recycle testing	specification-compliant product with recycle closure and repeatability	stage count or reagent demand becomes excessive
TEA/LCA validation	mass/energy balance with recycle and residue data	competitive cost and defensible environmental profile	benefit disappears after recycle/energy accounting

Note. Original synthesis. TEA = techno-economic assessment; LCA = life-cycle assessment.

11.5 Research priorities

Six research priorities emerge. First, particle-scale and size-resolved mineralogical mapping should be coupled directly to leach and roasting response so that reaction selectivity can be predicted from ore texture. Second, sulfation kinetics should be measured across realistic acid distributions, atmospheres, and moisture states, not only on homogeneous laboratory mixtures. Third, Fe and Al phase evolution requires in-situ or time-resolved characterization to confirm the

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

mechanism by which impurities are suppressed. Fourth, acid and sulfate recycle should be incorporated before pilot optimization, because recycle composition can change equilibrium and kinetics. Fifth, downstream product studies should compare mixed REE products with higher-value Pr–Nd or separated-oxide routes using the same authentic PLS and system boundary. Sixth, residue stability should be operationally demonstrated through residual acidity, sulfate leachability, retained REE value, Th/U inventory where relevant, mineralogical stability, environmental leaching behavior, geotechnical handling properties, and regulatory classification.

Additional opportunities include biological or mild pretreatment, selective ligand-assisted leaching, membrane separations, electrochemical cerium control, and digital optimization of roasting and purification (Bayarsaikhan et al., 2025; Cunningham et al., 2026; Jang et al., 2026; Wang et al., 2026). These should be evaluated as modules that address a defined bottleneck, not as replacements for mineralogical understanding. The broader literature on Bayan Obo and other polymetallic REE systems similarly shows that comprehensive utilization is most credible when product and residue pathways are designed together (Zhang et al., 2026).

12. Conclusions

Weathered carbonatite REE deposits are process systems created by supergene transformation, not simply lower-strength analogs of primary carbonatite ores. Their defining challenge is the coupling of fine REE-bearing phases with Fe oxyhydroxides, silicates, clays, apatite, and other reactive gangue. This mineralogical complexity explains why conventional magnetic, gravity, and flotation routes may provide limited or unstable preconcentration and why bulk REE grade is a poor standalone basis for flowsheet selection.

The most defensible development strategy is ore-specific. Process mineralogy should establish REE hosts, liberation scale, impurity deportment, and variability domains before chemical

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

treatment is selected, while the intended product specification should constrain the acceptable PLS impurity envelope from the outset. Selective sulfation is particularly relevant where physical separation is weak because it can shift part of the selectivity burden to controlled phase transformation, but it does not automatically eliminate the value of modest preconcentration. The useful operating region is multidimensional and feed-specific, balancing conversion, Fe/Al/Th suppression, acid demand, temperature, atmosphere, time, moisture, acid distribution, heat/mass transfer, and downstream solution quality.

For the Araxá-type case, the next development stage should not focus only on increasing extraction. It should demonstrate continuous reaction control across variable ore, close the sulfuric acid and sulfate balances, confirm residue stability, quantify REE losses during purification, and produce representative final products from authentic PLS. The central conclusion is that successful recovery from weathered carbonatites will come from integrating mineralogy, thermal chemistry, hydrometallurgy, separation science, and process systems engineering into a single route-selection framework. Future demonstrations should therefore report whole-flowsheet recovery to specification-compliant product, element-by-element and sulfur closure, gross and net acid demand, PLS concentrations, water and energy intensities, off-gas control, residue stability, and recycle behavior under representative ore variability. Existing evidence supports selective sulfation as a promising ore-specific strategy, but not as a universally superior commercial route.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 12/08/2026 - **Accepted:** 24/09/2026
Vol: 01.05
DOI: 10.66104/wsf0bc19
Pages: 1-53

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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