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Bauxite Residue (Red Mud) from the Bayer Process: A Critical Review of Management, Safe Storage, Valorization, Critical-Metal Recovery, and Industrial Integration

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Abstract.

Bauxite residue (BR), commonly termed red mud, is the strongly alkaline, fine-grained solid generated during Bayer alumina refining. This critical review synthesizes a primary contemporary corpus of 145 publications from January 2020 to 23 September 2026, supplemented by a small set of pre-2020 foundational sources used only for historical and mechanistic context, and evaluates BR as an integrated management-and-resource system rather than an isolated waste stream. The analysis connects residue mineralogy, soluble and structural alkalinity, rheology, dewatering, geotechnical behavior, neutralization, revegetation, high-volume material use, functional applications, and recovery of Fe, Al, Ti, Sc, rare-earth elements, V, and Ga. No single route simultaneously maximizes residue uptake, metal selectivity, water recovery, environmental performance, and economic value. Mechanical dewatering and engineered dry placement reduce water inventory and can improve caustic recovery, but they do not eliminate chemical liability. Neutralization and dealkalization can enable rehabilitation and downstream utilization; however, reagent demand, salt formation, secondary-residue behavior, and long-term leaching must be treated as system variables. Construction materials represent the largest technically plausible mass-scale class of applications, although realistic regional absorption is constrained by logistics, standards, and market demand; critical-metal recovery offers greater value density but generally requires more intensive separation and purification. Pilot-scale scandium recovery demonstrates that selective products can be produced, while life-cycle studies show that drying and valorization may shift, rather than eliminate, environmental burdens. The review therefore proposes an author-developed cascade decision framework in which water and alkali recovery, conditioning, selective recovery, bulk utilization, and residual-risk management are sequenced according to site-specific feed, infrastructure, market, and regulatory conditions rather than treated as an invariant flowsheet. Priority research needs include standardized feed characterization, element-specific mass closure, comparable service-condition leaching protocols, integrated mass-water-energy balances, sustained pilot

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campaigns, product and regulatory qualification, and coupled life-cycle assessment (LCA), techno-economic analysis (TEA), and technology-readiness-level (TRL) assessment.

Keywords: bauxite residue; red mud; Bayer process; dealkalization; critical metals; circular economy

Highlights

- Dewatering reduces water inventory, but chemical alkalinity remains a design constraint.
- Bulk construction uses provide mass scale; critical-metal recovery provides value density.
- Pilot scandium recovery shows selectivity is feasible, but integration controls viability.
- LCA, TEA, leaching risk, and TRL must be evaluated on a common system boundary.

The review is organized around the premise that BR management, chemical conditioning, valorization, and final risk control are coupled decisions. Figure 1 summarizes this integrated logic before the detailed critical analysis.



Figure 1. *Integrated management-to-valorization framework for bauxite residue.*
Note. Author-generated graphical synthesis, adapted from the process categories and decision variables discussed across the reviewed corpus (Agrawal & Dhawan, 2021; Chen et al., 2022; Liu et

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al., 2021; Lyu et al., 2021; Niu & Lin, 2024; Song et al., 2026; Vielma et al., 2025; J. Zhang et al., 2026).

The framework emphasizes that no route should be judged by a single unit-operation metric. A technology that improves extraction, strength, or filtration may still be unattractive if it increases water demand, creates a difficult secondary residue, concentrates mobile contaminants, or produces a material without a credible market or end-of-life pathway.

1. Introduction

Bauxite residue is formed when bauxite is digested in concentrated caustic liquor during the Bayer process, and the insoluble fraction is separated from sodium aluminate solution. Depending on ore grade and refinery conditions, approximately 0.9–1.5 t of dry residue can be generated per tonne of alumina, and recent reviews place global annual generation above 200 Mt with cumulative inventories above 4 Gt. The residue is therefore simultaneously a high-volume geotechnical material, an alkaline chemical inventory, and a secondary mineral resource. Its dominant Fe–Al–Si–Ti mineral matrix, fine particle size, soluble and structural sodium, variable moisture content, and trace-element inventory make the management problem intrinsically site specific (Davris et al., 2021; Duarte & Fourie, 2026; Liu et al., 2021; Niu & Lin, 2024; Silveira et al., 2021; Song et al., 2026; Vielma et al., 2025; J. Zhang et al., 2026).

Foundational work predating the contemporary review window remains essential for interpreting present-day evidence. The 2011 Hydrometallurgy series established enduring principles for BR storage, utilization, alkalinity, and in situ rehabilitation, including the strong dependence of performance on residue origin, soda chemistry, volume, cost, and long-term liability (Power et al., 2011; Klauber et al., 2011; Gräfe et al., 2011; Gräfe & Klauber, 2011). Evans (2016) subsequently documented the historical transition in storage and beneficial-use practice and emphasized why technically successful demonstrations do not automatically translate into large-scale uptake. These sources are used here as historical and mechanistic anchors; the formally coded contemporary evidence corpus remains restricted to 2020–2026.

The literature published since 2020 shows a marked change in emphasis. Earlier debates often contrasted wet impoundment with beneficial use, whereas current work increasingly

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treats filtration, dry stacking, neutralization, rehabilitation, cementitious use, metal recovery, and water reuse as interacting components of one process system. Reviews on dealkalization, iron recovery, construction materials, critical metals, and comprehensive utilization repeatedly converge on the same limitation: BR is not a single standardized feedstock, and therefore performance claims cannot be transferred between refineries without mineralogical, chemical, and geotechnical qualification (Agrawal & Dhawan, 2021; Chen et al., 2022; Fang et al., 2025; Liu et al., 2021; Liu et al., 2026; Lyu et al., 2021; Raj et al., 2024; Song et al., 2026; Wang et al., 2026; Yang et al., 2025; J. Zhang et al., 2026).

This heterogeneity has two consequences for critical-review methodology. First, comparing technologies through a single performance metric is misleading. A route that achieves high metal extraction may consume concentrated acid, require thermal activation, or create silica-rich filtration problems; conversely, a cement route may tolerate low extraction efficiency but fail because soluble Na, rheology, early hydration, or long-term leaching limits the acceptable BR fraction. Second, technology readiness depends strongly on the interfaces between unit operations. Solid-liquid separation, impurity deportment, recycle chemistry, and product specifications often determine feasibility more strongly than the nominal equilibrium reaction (Agrawal & Dhawan, 2022; Gao et al., 2024; Kar et al., 2023; Pan et al., 2023; Pavón Regaña et al., 2025; Pereira, 2026a; Pilla et al., 2025; Tanvar & Mishra, 2022; Zhang et al., 2020; Zhao et al., 2024).

The present review therefore evaluates BR through five coupled questions: (i) how mineralogy, alkalinity, rheology, and trace-element deportment govern management choices; (ii) how far dewatering and engineered storage can reduce physical risk without transferring chemical risk; (iii) which conditioning steps are required before construction, environmental, or rehabilitation uses; (iv) when selective recovery of Fe, Al, Ti, Sc, rare-earth elements (REEs), V, Ga, or Na justifies its process intensity; and (v) which LCA, TEA, leaching-risk, and TRL metrics are required for a defensible scale-up decision. The temporal scope is January 2020 to 23 September 2026, extending the original 2020-2025 review frame to include the 2026 literature represented in the curated corpus.

For navigation, Figure 1 provides the integrated review map, Figure 2 defines the evidence-synthesis workflow, Figure 3 presents the management hierarchy, Figure 4 shows

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the metal-recovery logic, and Figure 5 summarizes scale-up gates. Table 1 links residue properties to process consequences; Table 2 compares dewatering and storage strategies; Table 3 compares dealkalization and rehabilitation options; Table 4 synthesizes high-volume construction routes; Table 5 covers functional and environmental applications; Table 6 compares major metal-recovery pathways; and Table 7 integrates LCA, TEA, risk, and readiness criteria.

2. Review methodology and analytical framework

2.1 Corpus, scope, and evidence coding

The primary evidence base comprises a curated bibliography of 145 publications dated from January 2020 through 23 September 2026. It includes experimental studies, pilot- and semi-industrial demonstrations, systematic and critical reviews, geotechnical and rehabilitation studies, life-cycle assessments, techno-economic analyses, and process-development papers. The bibliography was finalized before preparation of the present synthesis, but platform-specific identification, deduplication, screening, and exclusion records were not retained and therefore cannot be retrospectively reconstructed. Accordingly, this article does not claim formal PRISMA reporting and does not reconstruct or invent upstream identification or exclusion counts. Instead, it uses a structured evidence-synthesis workflow informed by systematic-review principles. Direct relevance to BR management, treatment, utilization, recovery, or long-term risk was required for inclusion in the contemporary corpus. The working-language criterion for analytical coding was availability of sufficient English-language bibliographic and source information to evaluate methods and results; language-specific exclusion counts cannot be reconstructed from the retained records. The thematic evidence blocks represented in the corpus were: (i) BR generation, mineralogy, alkalinity, and geotechnical behavior; (ii) dewatering, filtration, rheology, transport, and storage; (iii) dealkalization, neutralization, stabilization, and rehabilitation; (iv) construction and functional applications; (v) Fe, Al, Ti, Sc/REE, V, Ga, and Na recovery; and (vi) integrated flowsheets, environmental performance, economics, and readiness. During revision, targeted backward citation chaining from recent reviews was used only to identify

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five pre-2020 foundational BR sources for historical and mechanistic context; these contextual references were not added to the 145-publication contemporary coding corpus.

Each contemporary paper was interpreted along six analytical dimensions: feed definition and BR origin; conditioning or reaction pathway; solid-liquid separation, water, reagent, and recycle implications; product or recovered-metal specification; environmental and long-term stability evidence; and evidence class/readiness. Review papers were used to map the field and identify recurring bottlenecks, whereas primary studies were prioritized for process-specific claims. Pilot or field evidence was weighted more heavily than bench-scale optimization when readiness was discussed, while bench studies remained essential for resolving phase transformations, selectivity mechanisms, and emerging solvent or biological routes. Supplementary Table S1 indexes the 145 contemporary publications against the requested evidence fields: citation, BR origin, mineralogical/chemical characterization, process route, process scale, mass yield, water/reagent information, target product, secondary residue, environmental test, evidence class/readiness, and principal limitation. Where a field cannot be recovered reliably from the retained bibliographic record or from information explicitly reported in this review, it is marked 'NR' rather than retrospectively inferred.

2.2 Evidence classes and technology-readiness interpretation

For readiness interpretation, the review uses the European Commission nine-level TRL convention as a reference vocabulary, from basic-principle observation (TRL 1) to an actual system proven in an operational environment (TRL 9) (European Commission, 2014). However, a numerical TRL is not assigned solely because a paper is described as laboratory-, pilot-, or field-scale. Continuous operating duration, integration of upstream and downstream unit operations, feed variability, automation and control, safety, materials compatibility, product qualification, environmental performance, and operation in a relevant or operational environment are also considered. When the published evidence is insufficient for a defensible numerical assignment, the review uses the broader descriptors laboratory, bench-integrated, pilot, field demonstration, or industrially implemented.

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Figure 2 shows the evidence workflow. The key methodological choice is to distinguish measured performance from inferred industrial readiness: a high laboratory extraction, adsorption capacity, or compressive strength is not treated as equivalent to a viable flowsheet.

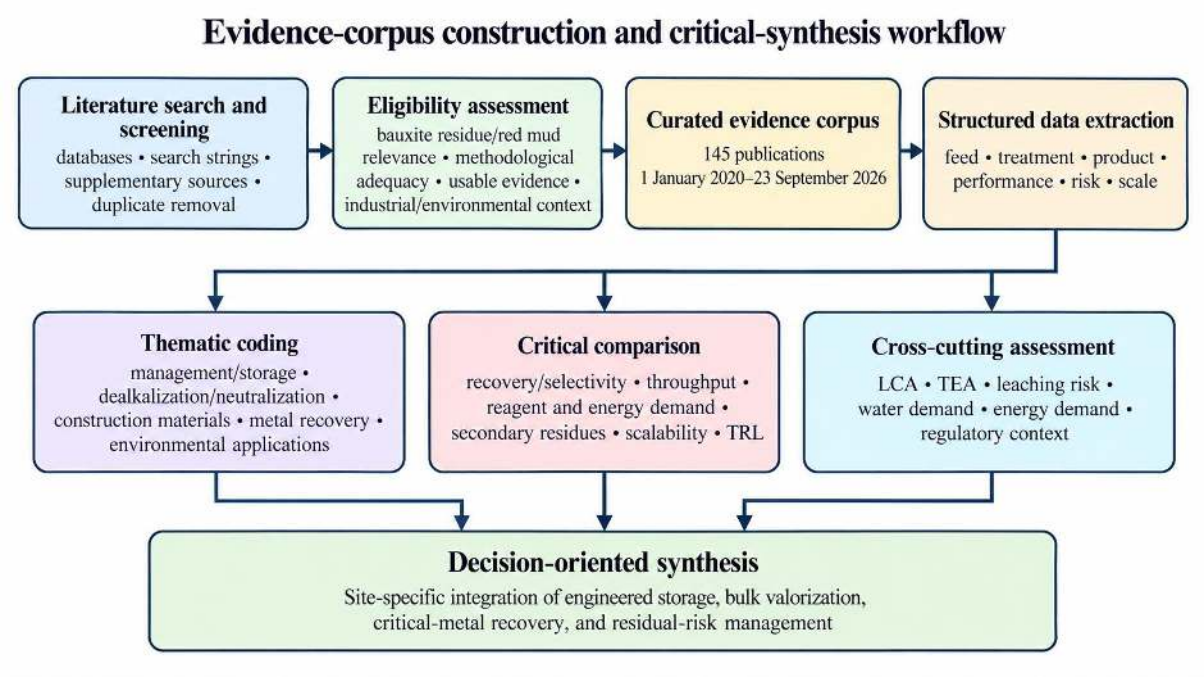

Figure 2. *Evidence-corpus construction and critical-synthesis workflow.*
Note. Author-generated synthesis. The workflow is a structured evidence-synthesis process informed by systematic-review principles; it is not presented as formal PRISMA reporting because upstream identification, deduplication, screening, and exclusion counts are unavailable for retrospective reconstruction. The primary contemporary corpus contains 145 publications.

The synthesis also distinguishes between mass-scale and value-scale outcomes. Cement, geopolymer, road, and steel-sector routes can potentially consume large quantities, whereas Sc, REE, V, and Ga recovery targets small mass fractions with potentially high unit value. The critical systems question is whether these routes can be cascaded so that high-value recovery does not destroy the mineralogical or chemical attributes required for subsequent high-volume utilization.

3. Generation, composition, mineralogy, and risk-relevant properties

3.1 Mineralogical and chemical variability

BR composition reflects bauxite mineralogy, digestion severity, desilication reactions, lime addition, washing efficiency, and residue handling. Iron-bearing phases commonly

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dominate the mass, while Al-bearing remnants, desilication products, Ti phases, quartz or silicates, and Na-bearing alkaline phases determine reactivity. The literature shows that the same nominal "red mud" label can describe residues with materially different Fe/Al ratios, Ti content, soluble alkalinity, particle-size distributions, and trace-element hosts. Scandium, for example, is not uniformly distributed and may associate with Fe-rich or other refractory phases, which is why leaching selectivity varies strongly with origin (Gentzmann et al., 2021; Liu et al., 2021; Niu & Lin, 2024; Silveira et al., 2021; Tian et al., 2023; Vielma et al., 2025; Wang et al., 2026; J. Zhang et al., 2026).

This variability makes bulk chemical composition insufficient for route selection. Phase identity, degree of crystallinity, specific surface area, pore-water chemistry, and particle aggregation influence both processing and environmental behavior. Geotechnically, fine-grained BR can exhibit coupled chemical–mechanical behavior: changes in pore-fluid composition or amendment chemistry can alter interparticle forces, yield stress, consolidation, and hydraulic properties. Spatial variation in salt and alkalinity within disposal areas further complicates sampling and risk extrapolation (Duarte & Fourie, 2026; Prasad, 2024; Shaygan et al., 2020; Tian et al., 2023; Yang et al., 2024).

3.2 Alkalinity, trace elements, and long-term release

Alkalinity is expressed through free caustic, soluble sodium salts, exchangeable sodium, and alkaline mineral phases that release alkalinity over time. Consequently, a single pH measurement cannot describe long-term chemical liability. Leaching and column studies show that dealkalization performance depends on the form of Na, mineral dissolution or reconstruction, water-to-solid ratio, and the creation of new Ca-, Mg-, Fe-, or carbonate-bearing phases. Potentially toxic elements may become more or less mobile during treatment, rehabilitation, or weathering, so trace-element speciation must be tracked together with pH and total concentration (Charan et al., 2025; Di Carlo & Courtney, 2020; Goronovski & Tkaczyk, 2021; Merdy et al., 2024; Saha et al., 2025; Wan et al., 2024; Wu et al., 2020; Wu et al., 2021; Yang et al., 2024).

Table 1 summarizes the residue properties that most directly control management and valorization decisions.

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Table 1
Residue properties that control management and valorization decisions

Property	Why it matters	Process consequence	Representative evidence
Fe–Al–Si–Ti mineralogy	Controls reactivity, magnetic behavior, and acid/alkali consumption	Mineralogy must precede route selection; bulk oxide assays alone are inadequate	(Gentzmann et al., 2021; Liu et al., 2021; Song et al., 2026; J. Zhang et al., 2026)
Soluble and structural Na	Controls pH, pore solution, cement compatibility, and long-term release	Washing, dealkalization, or phase reconstruction may be required	(Danner & Justnes, 2020; Lyu et al., 2021; Wu et al., 2020; Yang et al., 2025)
Fine particle-size distribution (PSD) and rheology	Controls settling, filtration, pumping, dusting, and consolidation	Flocculant selection and dewatering must be linked to transport and placement	(Patil & Thorat, 2022; Prasad, 2024; Tian et al., 2023; Trampus & França, 2020; Zeng et al., 2022a; Zeng et al., 2022b)
Trace elements and radionuclides	Control leaching, product acceptance, and regulatory classification	Sequential extraction, long-term leaching, and radiological assessment may be required	(Charan et al., 2025; Goronovski & Tkaczyk, 2021; Ji et al., 2025; Saha et al., 2025; Wan et al., 2024)
Sc/REE/V/Ga deportment	Controls achievable selectivity and reagent demand	Selective recovery requires mineral-host information and impurity management	(Abhilash & Schippers, 2021; Dhiman et al., 2024; Gentzmann et al., 2021; Li et al., 2026; W. Li et al., 2021; Zhu et al., 2024)

Note. Representative ranges and behaviors are feed dependent; the table is a decision aid rather than a universal composition specification.

Accordingly, BR utilization rate should not be treated as an intrinsic material property. Utilization is an outcome of matching a characterized residue to a defined application while explicitly managing water, Na, trace elements, and residual solids.

4. Dewatering, filtration, transport, and safe storage

4.1 Mechanical dewatering and paste behavior

Mechanical dewatering is the first major leverage point because it simultaneously affects water recovery, caustic losses, transport, stack geometry, and the inventory of mobile liquor. Vacuum filtration, pressure filtration, and intensified approaches have been examined as routes to dry-cake disposal. The literature consistently identifies filtration and washing as enabling operations rather than merely disposal steps, because efficient cake formation can recover water and dissolved alkali while producing a feed with more stable handling properties (Patil & Thorat, 2022; Tao et al., 2025; Zeng et al., 2022a; Zeng et al., 2022b).

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Importantly, water recovered is not synonymous with water qualified for internal reuse: dissolved Na, sulfate, chloride, organics, trace elements, and impurity accumulation may restrict recycle to the Bayer circuit or another unit operation. The same distinction applies to alkali: recovered alkalinity must meet composition and impurity constraints before it can be credited as refinery-reusable reagent.

Flocculation and coagulation must be understood together with rheology. Work on paste production shows that polymer type, charge density, dosage, and combinations can alter overflow clarity, compaction, and sediment yield stress. The process target is therefore multi-objective: maximize water recovery and solids throughput while maintaining a pumpable or stackable rheology and avoiding excessive reagent carryover. A residue that dewaters efficiently in a laboratory filter may still be difficult to convey or spread if its yield stress, thixotropy, or shear history is not represented (Prasad, 2024; Trampus & França, 2020; Zeng et al., 2022a; Zeng et al., 2022b).

4.2 Dry stacking, hydrology, and geotechnical controls

Dry stacking reduces free-water inventory and can improve the physical risk profile relative to conventional slurry storage, but it does not eliminate the need for engineered drainage, erosion control, dust suppression, and geochemical monitoring. Hydrological modelling demonstrates that cover design, infiltration, drainage, and seasonal water balance influence pore-water evolution and leachate generation. Global geotechnical reviews also emphasize the wide parameter variability of BR, which limits the defensibility of generic shear-strength or compressibility values (Duarte & Fourie, 2026; Shaygan et al., 2020; Tian et al., 2023).

Safe storage is therefore best defined as a controlled state rather than a disposal technology. It requires a chain from thickening and filtration through haulage or conveying, layer placement, drainage, surface-water management, dust control, and closure. Ecological-disposal concepts, capping blends, and in situ amendments can reduce long-term liabilities, but their performance depends on maintaining physical stability as chemistry evolves (Jiang et al., 2025; Ke et al., 2021; Taki et al., 2023).

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Figure 3 places these operations in an author-developed default decision hierarchy. The logic prioritizes source reduction and recovery of water/alkali before chemical conditioning and requires that valorization not compromise the stability of the residual sink; however, the sequence is explicitly subject to site-specific optimization, and integrated thermal or chemical steps may legitimately combine or invert stages when feed mineralogy, infrastructure, product specifications, or regional markets justify doing so.

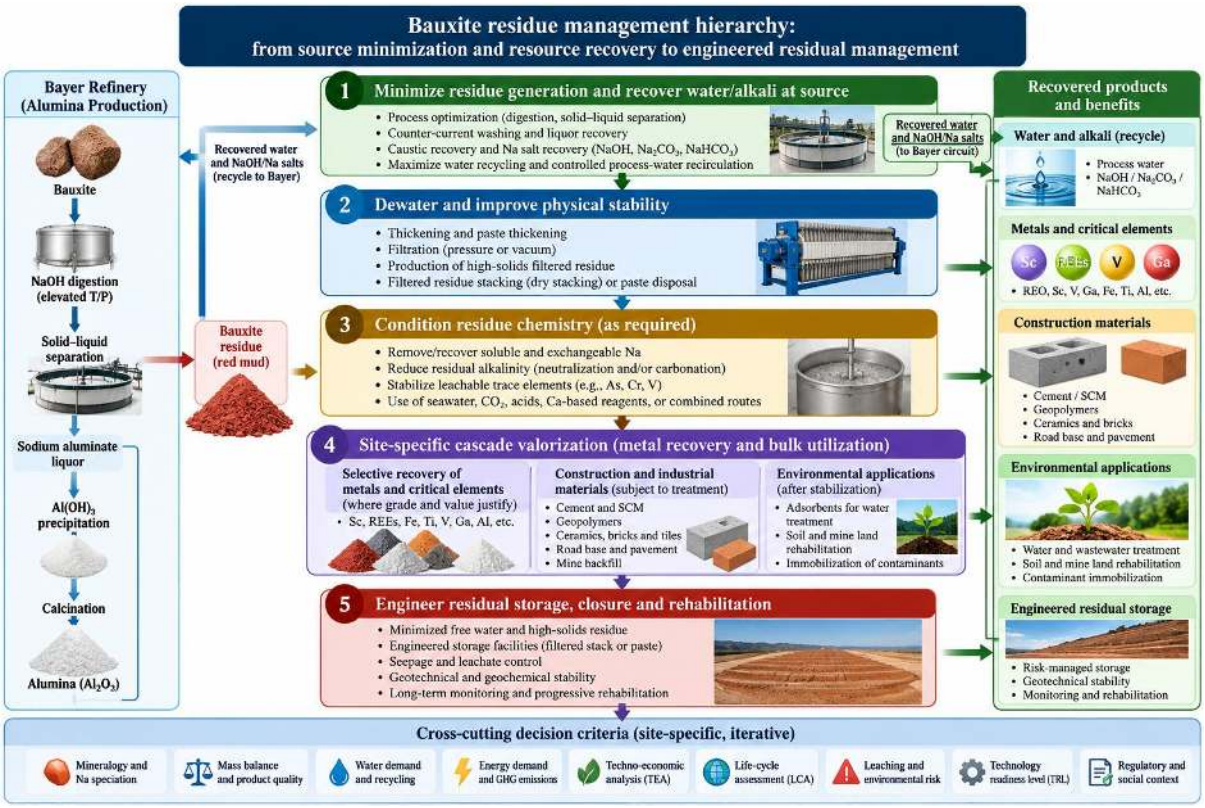

Figure 3. *Management hierarchy from water recovery to the engineered residual sink.*
Note. Author-developed decision framework synthesized from Duarte and Fourie (2026), Patil and Thorat (2022), Shaygan et al. (2020), and Taki et al. (2023). The hierarchy is a default decision logic, not a universally mandatory process sequence.

Table 2 compares the principal dewatering, transport, and storage strategies and the decision metrics required to distinguish laboratory performance from field suitability.

Table 2
Dewatering, transport, and storage strategies

Strategy	Primary benefit	Critical limitation	Decision metric
Thickening/paste	Water recovery and reduced slurry volume	Rheology can constrain pumping and placement	Underflow solids, yield stress, overflow quality

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Strategy	Primary benefit	Critical limitation	Decision metric
Vacuum filtration	Continuous dewatering and washing	Fine PSD can limit cake permeability	Cake moisture, wash efficiency, throughput
Pressure filtration	Lower cake moisture and dry-stack compatibility	Capital, cycle time, cloth performance, and washing integration	Specific filtration rate, moisture, filtrate quality
Filter aids/flocculant synergy	Improved aggregation and permeability	Chemical carryover and feed specificity	Dose per tonne, filtrate clarity, cake release
Dry stack / engineered placement	Lower free-water inventory and improved water balance	Dust, erosion, trafficability, drainage, and long-term consolidation	Water balance, factor of safety, seepage, closure performance

Note. Synthesized from Patil & Thorat, 2022; Prasad, 2024; Shaygan et al., 2020; Tao et al., 2025; Tian et al., 2023; Trampus & França, 2020; Zeng et al., 2022a; Zeng et al., 2022b. "Dry" placement does not imply chemically inert residue.

5. Dealkalization, neutralization, stabilization, and rehabilitation

5.1 Chemical neutralization and phase reconstruction

Dealkalization is not a single reaction. It can involve dissolution of free caustic, ion exchange, conversion of Na-bearing aluminosilicates, precipitation of Ca/Mg phases, carbonation, or acid neutralization. Reviews published in 2021–2026 converge on a site-specific approach because each route trades reagent demand, salt generation, solid-liquid separation, and downstream compatibility differently (Kannan et al., 2021; Liu et al., 2026; Lyu et al., 2021; Y. Wang, Zhang, et al., 2021; Yang et al., 2025).

Calcium-bearing reagents and gypsum are especially important because Ca can exchange with Na and form or stabilize lower-alkalinity phases. Field-scale work combining gypsum and an industrial Fe salt reported a residue pH of approximately 7.60 after one year, illustrating that laboratory neutralization can be translated into field conditioning when mineralogical mechanisms are controlled. Phosphogypsum, desulfurization gypsum, and other Ca-rich by-products additionally create industrial-symbiosis opportunities, although sulfate loading and long-term salt behavior require monitoring (Huang et al., 2024; Tian et al., 2021; Wu et al., 2024; Zhou et al., 2025).

Acid routes can rapidly reduce pH and dissolve alkaline phases, but selectivity is central. Waste-acid integration, acid treatment of desilication products, and freeze–thaw/acid washing illustrate routes for coupling neutralization with resource recovery or improved leaching.

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Their critical limitations are acid consumption, soluble-metal mobilization, silica behavior, corrosion, and the need to treat acidic or saline effluents (Jiang et al., 2021; Peng et al., 2020; Rui et al., 2024; Zhang et al., 2020).

Brine and seawater neutralization use Mg and Ca precipitation chemistry and can produce a lower-pH solid suitable for rehabilitation in appropriate coastal or saline contexts. The trade-off is salinity: neutralizing alkalinity does not automatically produce a soil-like medium, and residual salts may limit plant establishment or create leaching concerns. Biological neutralization with fermented wastes or bio-acids offers a lower-temperature alternative and can simultaneously support microbial succession, but residence time, organic-carbon stability, and field reproducibility remain scale-up questions (Kannan et al., 2021; Menzies & Kopittke, 2021; Qin et al., 2023).

5.2 Ecological rehabilitation and long-term evidence

Rehabilitation studies show that successful conversion of BR into a growth medium requires both chemical and physical improvement. Gypsum, organic amendments, microbial interventions, and engineered capping blends can improve aggregation, nutrient cycling, and plant establishment. Long-term field trials are particularly valuable because they expose the amended residue to wetting–drying cycles, plant uptake, microbial succession, and evolving pore-water chemistry that short laboratory tests cannot reproduce (Di Carlo & Courtney, 2020; Ke et al., 2021; Merdy et al., 2024; Miura et al., 2023; Miura et al., 2025; Phillips & Courtney, 2022; Scullett-Dean et al., 2023; Taki et al., 2023).

The critical environmental endpoint is not pH alone. Vanadium and other trace elements can change speciation and mobility as redox conditions, organic matter, and mineral phases evolve. Five-year leaching experiments, field technosol studies, and revegetation assessments therefore support a monitoring framework that includes pH, electrical conductivity, alkalinity, major ions, trace-element fluxes, and ecotoxicological response (Charan et al., 2025; Di Carlo & Courtney, 2020; Merdy et al., 2024; Saha et al., 2025; Wan et al., 2024).

Table 3 compares the dominant dealkalization, stabilization, and rehabilitation pathways, emphasizing their scale-up constraints.

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Table 3
Dealkalization, stabilization, and rehabilitation pathways

Route	Dominant mechanism	Strength	Scale-up concern
Washing / water leaching	Removal of soluble caustic and salts	Simple integration with refinery water circuits	Water demand and structural Na remain
Gypsum / Ca-bearing amendments	Ca–Na exchange and phase stabilization	Low-temperature, compatible with rehabilitation	Sulfate balance and solids separation
Fe–Ca synergistic treatment	Charge balance and mineral-lattice stabilization	Field evidence for strong pH reduction	Availability, dosing control, long-term mineral stability
Seawater / brines	Mg/Ca precipitation and alkalinity consumption	Can be attractive at suitable sites	Salinity and brine management
Acid / waste-acid treatment	Neutralization plus dissolution/reconstruction	Fast chemistry and potential recovery integration	Acid consumption, corrosion, dissolved impurities, silica
Biological/organic amendment	Bio-acid generation, aggregation, microbial succession	Supports rehabilitation and circular use of organics	Residence time, heterogeneity, field reproducibility

Note. Synthesized from Huang et al., 2024; Jiang et al., 2021; Kannan et al., 2021; Li et al., 2020; Liu et al., 2026; Lyu et al., 2021; Menzies & Kopittke, 2021; Peng et al., 2020; Qin et al., 2023; Rui et al., 2024; Tian et al., 2021; Wu et al., 2024; Yang et al., 2025; Zhou et al., 2025. Treatment success should be evaluated by long-term leaching and rehabilitation performance, not endpoint pH alone.

6. High-volume material valorization

6.1 Cement, supplementary cementitious materials, and clinker routes

Construction materials represent the largest technically plausible mass-scale class of BR applications because mineral-product markets can consume feedstocks at orders of magnitude greater tonnage than critical-metal products. This technical incorporation capacity must not be equated with realistic regional market absorption: cement, road, brick, aggregate, and other outlets are constrained by transport distance, local demand, standards, permitting, customer qualification, and competing raw materials. Untreated BR is also not automatically a conventional supplementary cementitious material (SCM). Soluble Na, Fe-rich mineralogy, low intrinsic reactivity of some phases, high water demand, and particle interactions can modify hydration and fresh-state behavior. Consequently, the literature has shifted from simple replacement percentages toward mineralogy-controlled activation, co-calcination, alkali management, durability, leaching, and application-specific product qualification.

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Fe-rich calcium sulfoaluminate-ferrite clinker concepts, co-calcination with low-grade kaolinitic clay, and limestone–calcined-clay-type systems illustrate three different strategies: incorporate BR directly into a new clinker phase assemblage, activate BR jointly with a reactive aluminosilicate, or use BR as one component of a lower-clinker binder. These approaches can reduce the penalty of low standalone reactivity, but they require careful control of alkalis, sulfate balance, phase formation, and durability (Hertel et al., 2021; Peys et al., 2024; Su et al., 2026; Wenzel et al., 2025; Wenzel et al., 2026).

6.2 Alkali-activated binders, geopolymers, ceramics, roads, and steel-sector use

Alkali-activated binders and geopolymers can exploit the alkaline character of BR rather than treating it only as a contaminant. High-strength systems have been developed by combining BR with fly ash, slag, or other reactive components, and curing regime strongly affects gel development and engineering properties. The central scale-up issue is activator intensity: a binder that performs well mechanically but depends on large quantities of commercial sodium silicate or hydroxide may transfer environmental and economic burdens from clinker to activator production (Bai et al., 2023; Bai et al., 2022; Hoang et al., 2020; Kumar et al., 2021; Zakira et al., 2023).

Ceramic and sintered products use Fe oxides as colorants and can immobilize constituents through vitrification or phase formation, while road-base and stabilized-soil applications exploit particle packing and binder reactions at large volume. Recent pavement studies increasingly pair strength and durability measurements with leaching or health-risk assessment, which is essential because construction use places BR in diffuse contact with water rather than inside a controlled storage facility (Dixit & Das, 2025; Ji et al., 2025; Pereira, 2025a; Pereira, 2025b; Raj et al., 2024; Tan et al., 2024; Vakili et al., 2025; Wang et al., 2025; Zhang et al., 2021).

A separate industrial-symbiosis route links alumina refining to iron and steel production. Ferroalumina concepts, H_2-reduced BR, and pilot-scale slag-pellet use seek to exploit the Fe-rich fraction while transferring alumina-bearing phases into slag or cementitious products. These routes are attractive because they combine large mass throughput with existing high-temperature infrastructure, but their value depends on impurity tolerance, reductant source,

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energy intensity, slag quality, and the ability to avoid a secondary residue that simply reproduces the original disposal problem (Karamoutsos et al., 2021; Pilla et al., 2025; Pilla et al., 2024; Qin et al., 2025).

Table 4 synthesizes the principal high-volume construction and metallurgical routes and the constraints that determine practical BR incorporation.

Table 4
High-volume construction and metallurgical utilization routes

Route	Functional role of BR	Main technical opportunity	Primary constraint
Portland cement / SCM	Fine mineral addition; Al/Fe source; filler/reactive fraction	Large market and low additional unit operations when compatible	Na, water demand, variable reactivity, durability
Co-calcined / blended cement	BR coupled with reactive clay or pozzolan	Tailored phase assemblage and lower clinker factor	Thermal treatment and feed consistency
CSA/ferrite clinker	Fe/Al-bearing raw material	Uses BR chemistry as clinker feed rather than inert filler	Kiln chemistry, alkalis, and product qualification
Alkali-activated binder / geopolymer	Aluminosilicate/Fe-rich precursor or filler	High strength with suitable co-precursors	Activator footprint, curing, shrinkage, Na balance
Ceramics / bricks	Fe-rich ceramic feed and fluxing contribution	Sintering can stabilize constituents	Energy demand and gas/phase control
Road / soil stabilization	Fine aggregate/filler/reactive component	High-volume regional use	Long-term leaching, moisture cycling, specification
Steelmaking / slag pellets	Fe-bearing feed; slag-forming Al/Si phases	Industrial symbiosis and high throughput	Reduction energy, impurities, slag valorization

Note. Synthesized from Cui et al., 2024; Danner & Justnes, 2020; Dixit & Das, 2025; Hertel et al., 2021; Hoang et al., 2020; Karamoutsos et al., 2021; Kumar et al., 2021; Z. Li et al., 2021; Patangia et al., 2023; Pereira, 2025a; Pereira, 2025b; Peys et al., 2024; Qin et al., 2025; Raj et al., 2024; Romano et al., 2025; Salim et al., 2023; Scaratti et al., 2021; Su et al., 2026; Tan et al., 2024; Vakili et al., 2025; Wang et al., 2025; Wang et al., 2026; Y. Wang, Liu, et al., 2021; Wenzel et al., 2025; Wenzel et al., 2026; Zakira et al., 2023; Zhang et al., 2021.

7. Functional and environmental applications

7.1 Adsorbents, coagulants, catalysts, and water treatment

BR contains Fe- and Al-rich surfaces that can bind oxyanions, dyes, and emerging contaminants after appropriate activation or modification. Recent studies extend the

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traditional use of red-mud-derived adsorbents from phosphate, arsenic, and dyes toward PFAS and engineered recoverable adsorbents. The field is shifting from "high capacity" as the sole endpoint to regeneration, hydraulic performance, constituent release, and post-use disposal (An et al., 2023; Pang et al., 2025; Singh et al., 2024; M. Wang & Liu, 2021).

The same mineral chemistry can support coagulants, conditioners, and catalysts, but functionalization must be judged against the chemical cost of activation. A material that requires extensive acid washing, metal salt addition, or thermal treatment should be compared with conventional sorbents on a functional-unit basis, not simply on the premise that the feedstock is a waste. Systematic reviews of water-treatment uses reinforce this need for consistent leaching and regeneration protocols (Rangappa et al., 2026; M. Wang & Liu, 2021).

7.2 Soil, mine-land, and ecological applications

Environmental application of BR to soils or rehabilitation systems is only defensible after alkalinity, salinity, and trace-element mobility are controlled. Constructed wetlands, gypsum and organic amendments, microbial treatments, and capped technosols demonstrate that BR can be incorporated into environmental systems, but these are treatment systems rather than unrestricted disposal pathways. Their value lies in controlled geochemical buffering, nutrient retention, and soil formation, with monitoring maintained over multiple seasons or years (Ke et al., 2021; Menzies & Kopittke, 2021; Merdy et al., 2024; Miura et al., 2023; Miura et al., 2025; O'Connor & Courtney, 2020; Phillips & Courtney, 2022; Saha et al., 2025; Scullett-Dean et al., 2023; Taki et al., 2023; Wan et al., 2024).

Table 5 summarizes functional and environmental applications of treated BR and the evidence required before scale-up.

Table 5
Functional and environmental applications of treated bauxite residue

Application	Mechanism	Evidence priority before scale-up	Residual risk
Adsorbent for dyes/organics	Surface complexation, electrostatic interaction, modified active sites	Capacity plus kinetics, regeneration, competing ions, and leaching	Spent sorbent classification and metal release

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Application	Mechanism	Evidence priority before scale-up	Residual risk
PFAS adsorption	Interaction with modified mineral surface	Breakthrough tests, real-water matrices, regeneration	PFAS transfer to solid and end-of-life management
Coagulant/conditioner/catalyst feedstock	Fe/Al chemistry and engineered surface	Chemical-input inventory and product consistency	Activation chemicals and secondary waste
Constructed wetland/leachate treatment	Biogeochemical retention and neutralization	Long-term hydraulic and geochemical field performance	Accumulation in wetland solids
Technosol/rehabilitation medium	Amendment-driven pH, aggregation, nutrient, and microbial changes	Multi-year plant, pore-water, and trace-element monitoring	Salinity, V/trace-metal mobility, erosion

Note. Synthesized from An et al., 2023; Di Carlo & Courtney, 2020; Ke et al., 2021; Menzies & Kopittke, 2021; Merdy et al., 2024; Miura et al., 2023; Miura et al., 2025; O'Connor & Courtney, 2020; Pang et al., 2025; Phillips & Courtney, 2022; Rangappa et al., 2026; Saha et al., 2025; Scullett-Dean et al., 2023; Singh et al., 2024; Taki et al., 2023; Wan et al., 2024; M. Wang & Liu, 2021.

8. Recovery of Fe, Al, Ti, Sc, REEs, V, Ga, and alkali

8.1 Iron, aluminum, sodium, and titanium as bulk-value targets

The largest recoverable mass fractions are generally Fe and Al, but high recovery does not guarantee a marketable product. Iron routes include magnetization roasting, reductive smelting, H_2 reduction, and combined thermal–hydrometallurgical schemes. Semi-industrial suspension magnetization roasting has demonstrated the scale potential of selective Fe concentration, while more recent H_2-based approaches seek lower-carbon reduction and concurrent valorization of the non-ferrous fraction (Cardenia et al., 2021; Karamoutsos et al., 2021; S. Li et al., 2021; Liu et al., 2025; Liu et al., 2021; Pilla et al., 2025; Pilla et al., 2024; Qin et al., 2025; Yuan et al., 2020).

Alumina and soda recovery are attractive because they can return value to the refinery circuit. Ca-rich slag leaching, low-temperature recovery concepts, and integrated Fe–Al–Ti separation show that the residual matrix can be redesigned rather than simply leached indiscriminately. The controlling challenge is phase engineering: refractory Al in sodalite/cancrinite-like phases, silica gel formation, and impurity co-dissolution can make nominal extraction yields misleading if the downstream liquor is difficult to purify (Agrawal

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& Dhawan, 2022; Behera et al., 2026; Kar et al., 2023; S. Li et al., 2021; Vafeias et al., 2021; Wang et al., 2023; Zhang et al., 2020).

Titanium can be recovered through reductive smelting followed by slag leaching, integrated valorization routes, or leaching–hydrolysis/boiling schemes that produce Ti-bearing products such as anatase. These flowsheets illustrate a recurring principle: Ti recovery improves when Fe and Al deportment is deliberately managed upstream, because an apparently Ti-rich residue can still carry problematic Si, Na, or Fe phases (Pietrantonio et al., 2021; Qu et al., 2023; Stopić et al., 2024; Y. Zhang et al., 2026).

8.2 Scandium and rare-earth elements

Scandium is the most intensively studied high-value element in BR because it can be enriched relative to many primary ores, although absolute concentrations remain low. Research since 2020 spans mineral-host characterization, acid and carbonate leaching, alkali fusion, sulfation roasting, solvent extraction, ion exchange, bioleaching, deep eutectic solvents, and reductive pretreatment. The critical variable is not extraction alone but the separation factor between Sc and the orders-of-magnitude larger Fe, Al, and Ti inventory (Abhilash & Schippers, 2021; Akcil et al., 2024; Gentzmann et al., 2021; Jammulamadaka et al., 2025; Kumaş et al., 2026; Mao et al., 2025; Pasechnik et al., 2021; Rychkov et al., 2021; Shoppert et al., 2022; Shoppert et al., 2024; Swain & Akcil, 2026; Swain et al., 2022; Zhou et al., 2021; Zhu et al., 2020).

Pilot evidence is particularly instructive. A year-long pilot campaign using sulfuric-acid leaching followed by selective-ion-recovery technology treated about 10 t of Greek BR and produced a crude concentrate containing approximately 22 wt.% Sc. Reported elution recovery was about 93%, and Sc was concentrated by more than three orders of magnitude relative to the residue. These results demonstrate that selectivity can be engineered at pilot scale, but they also expose the central economic questions: acid consumption, high-pulp-density operation, impurity control, resin capacity, water use, and the fate of neutralized leach residue (Davris et al., 2021).

REE recovery follows similar logic but is complicated by the low total concentration and the diversity of mineral hosts. Sulfation roasting–water leaching, citric-acid leaching, mixed

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chemical–biological routes, and bioleaching can improve selectivity or reduce mineral-acid intensity, yet long residence times and downstream separation remain significant barriers. Reviews in 2025–2026 increasingly frame REE recovery as a cascade problem in which critical metals are extracted without preventing later use of the bulk residue (Cozzolino et al., 2024; Ilkhani et al., 2024; Li et al., 2026; Panda et al., 2021; Ray et al., 2025; Shalchian et al., 2024; Soto-Montandon et al., 2025; Swain & Akcil, 2026; Swain et al., 2022).

8.3 Vanadium, gallium, and emerging selective routes

Vanadium and gallium are lower-abundance targets whose recovery is highly sensitive to oxidation state, complexation, and impurity competition. Oxalic-acid/sulfite systems, weak-acid gallium leaching, solvent extraction, and siderophore-assisted concepts illustrate the expanding chemical toolbox. Broader gallium-recovery literature also shows why deportment and impurity control should be designed before extraction optimization: a high leach yield has limited value if Ga reports to a liquor dominated by Al, Fe, or Zn-like competing species (Azimi et al., 2024; Dhiman et al., 2024; W. Li et al., 2021; Pereira, 2026b; Pereira, 2026c; Saha et al., 2025; Zhu et al., 2024).

Solvometallurgical and chloride-assisted approaches, including solid-chloride leaching and deep eutectic solvents (DES), seek to improve selectivity or reduce aqueous-effluent volumes. Their appeal derives partly from the well-established limitations of conventional acid leaching: reagent neutralization creates salts, silica can impair filtration, and impurity co-dissolution can impose expensive purification. However, claims of greener processing require solvent-recovery data, corrosion assessment, water-sensitivity analysis, toxicity evaluation, and credible recycle loops (Kim et al., 2021; Kim et al., 2026; Madhavi et al., 2026; Rüşen et al., 2026).

Biological routes occupy a similar position. They can dissolve target metals under mild bulk conditions and may generate organic acids in situ, but industrial relevance depends on timescale, pulp density, culture robustness, downstream recovery, and process-water management. Mixed cultures and fungal or bacterial systems are therefore better treated as potentially selective preconditioning or leaching modules than as inherently low-impact

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substitutes for all chemical processing (Abhilash & Schippers, 2021; Azimi et al., 2024; Cozzolino et al., 2024; Ilkhani et al., 2024; Panda et al., 2021; Soto-Montandon et al., 2025).

Figure 4 organizes the metal-recovery problem around preconditioning, selective leaching, purification, and secondary-residue gates.

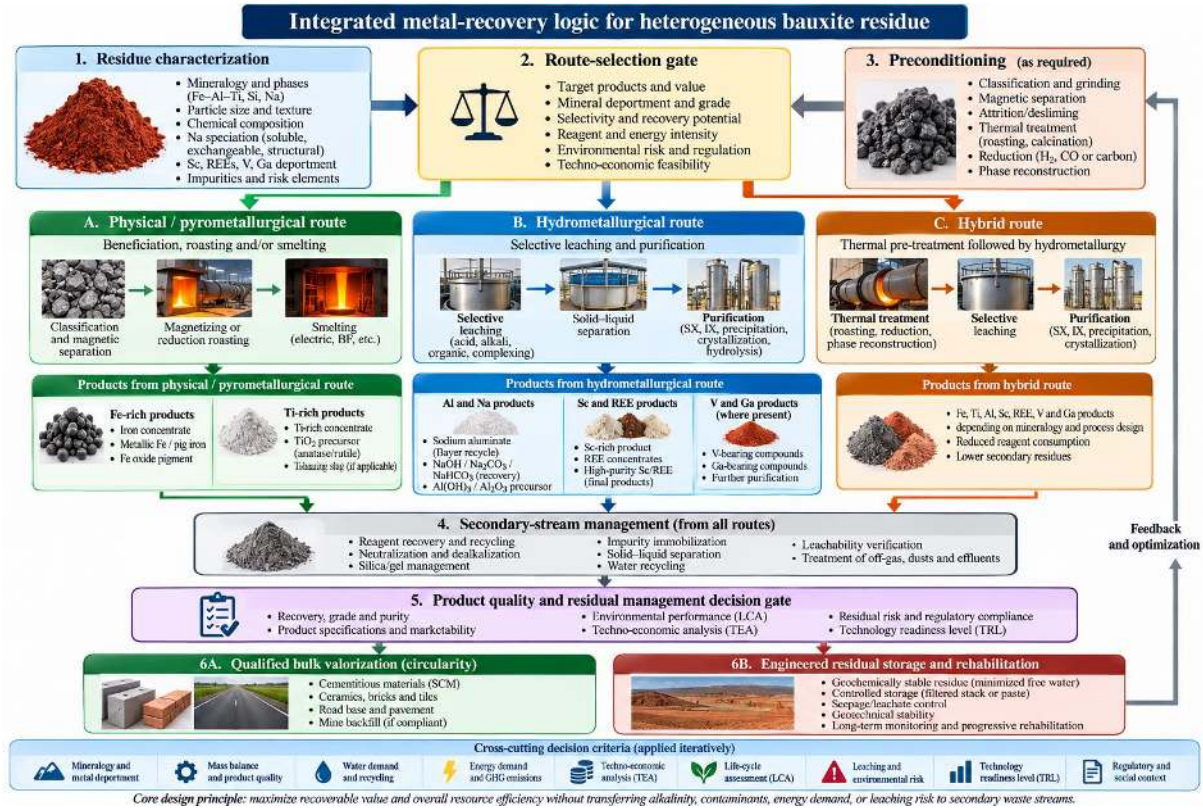

Figure 4. *Integrated metal-recovery logic for heterogeneous bauxite residue.*
Note. Author-generated synthesis, adapted from multimetal, Sc/REE, Fe–Al–Ti, Ti, V, and Ga recovery studies (Agrawal & Dhawan, 2022; Anawati & Azimi, 2022; Davris et al., 2021; Fang et al., 2025; Gao et al., 2024; S. Li et al., 2021; W. Li et al., 2021; Mao et al., 2025; Pan et al., 2023; Pilla et al., 2025; Qu et al., 2023; Rüşen et al., 2026; Song et al., 2026; Stopić et al., 2024; Tanvar & Mishra, 2022; Zhu et al., 2024).

Table 6 compares major metal-recovery pathways by process logic, demonstrated strength, and critical scale-up limitations.

Table 6
Critical comparison of major metal-recovery pathways

Target/pathway	Process logic	Demonstrated strength	Critical scale-up issue

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Target/pathway	Process logic	Demonstrated strength	Critical scale-up issue
Fe: magnetization/reduction	Transform Fe phases, then magnetic or phase separation	High Fe recovery/concentration and semi-industrial evidence	Energy/reductant source, gangue rejection, product quality
Al/Na: slag or low-temperature recovery	Reconstruct phases, leach Al/Na selectively, recycle liquor	Potential refinery integration and reduced residue mass	Silica, caustic balance, impurity recycle
Ti: reduction + slag leaching / hydrolysis	Concentrate Ti in slag or dissolve and reprecipitate	Potential production of Ti-rich/anatase products	Energy, Fe separation, acid use, Ti product specification
Sc: acid leach + IX/SIR/SX	Dissolve trace Sc then strongly concentrate/purify	Pilot production of ~22 wt.% Sc crude concentrate	Acid consumption, impurity selectivity, resin/SX performance
REEs: roasting/leach/organic/bioleach	Modify host phases and selectively dissolve REEs	Multiple selective routes demonstrated at laboratory scale	Low feed grade, long residence time, downstream separation
V/Ga: selective complexation/leaching	Exploit oxidation state and ligand selectivity	Targeted recovery from polymetallic matrix	Co-dissolution and small mass fraction
Solvo/DES/chloride routes	Reduce water use or alter selectivity window	Expanded solvent and ligand design space	Solvent recycle, corrosion, toxicity, materials compatibility

Note. Synthesized from Abhilash & Schippers, 2021; Agrawal & Dhawan, 2022; Akcil et al., 2024; Anawati & Azimi, 2022; Behera et al., 2026; Cardenia et al., 2021; Cozzolino et al., 2024; Davris et al., 2021; Dhiman et al., 2024; Fang et al., 2025; Gao et al., 2024; Ilkhani et al., 2024; Jammulamadaka et al., 2025; Kar et al., 2023; Kim et al., 2021; Kim et al., 2026; Kumaş et al., 2026; Li et al., 2026; S. Li et al., 2021; W. Li et al., 2021; Liu et al., 2025; Madhavi et al., 2026; Mao et al., 2025; Pan et al., 2023; Panda et al., 2021; Pasechnik et al., 2021; Pietrantonio et al., 2021; Pilla et al., 2025; Qu et al., 2023; Ray et al., 2025; Rüşen et al., 2026; Rychkov et al., 2021; Samal, 2021; Shalchian et al., 2024; Shoppert et al., 2022; Shoppert et al., 2024; Soto-Montandon et al., 2025; Stopić et al., 2024; Swain & Akcil, 2026; Swain et al., 2022; Tanvar & Mishra, 2022; Vafeias et al., 2021; Wang et al., 2023; Yuan et al., 2020; Y. Zhang et al., 2026; Zhou et al., 2021; Zhu et al., 2020; Zhu et al., 2024. IX = ion exchange; SIR = selective-ion recovery; SX = solvent extraction; DES = deep eutectic solvent.

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9. Integrated flowsheets, industrial symbiosis, and process intensification

9.1 From single-product optimization to cascade processing

The most important strategic change in the 2020–2026 literature is the move from single-product "valorization" to cascade processing. In the author-developed synthesis proposed here, water and alkali are recovered early where quality-compatible recycle is feasible, Fe-rich fractions are removed or converted where justified, critical metals are selectively extracted from a smaller stream, and the remaining mineral fraction is matched to cement, ceramic, road, or rehabilitation uses. This framework responds directly to the low concentration of high-value metals and the enormous bulk mass that remains after their recovery (Agrawal & Dhawan, 2022; Gao et al., 2024; Pavón Regaña et al., 2025; Song et al., 2026; Tanvar & Mishra, 2022; J. Zhang et al., 2026). It is a decision framework synthesized from the reviewed evidence rather than a universally optimal or mandatory process sequence.

Integrated flowsheets also create negative interactions. Strong acid leaching can destroy cementitious potential; high-temperature reduction can improve Fe separation but change Ti/Al mineralogy; chloride or sulfate addition can complicate downstream construction use; and aggressive washing can create a water-treatment load. Process integration must therefore optimize the sequence, not each step independently, and site-specific conditions may justify combining, reordering, or inverting nominal cascade stages. Every candidate cascade should close not only total solid and liquid mass but also element-specific balances across products, recycle liquors, purge streams, dust/emissions, and secondary residues. At minimum, Na, Fe, Al, Si, Ti, the target critical metals, and environmentally relevant trace elements should be reconciled. An apparent decrease in residue mass is not sufficient if these species are merely redistributed outside the stated system boundary. Co-precipitation control is particularly important in downstream purification because Fe, Al, and trace metals can be lost or contaminate products when pH and supersaturation are poorly managed (Anawati & Azimi, 2022; Kim et al., 2026; Liu et al., 2025; Pereira, 2026a; Pilla et al., 2025; Pilla et al., 2024; Vafeias et al., 2021; Zhang et al., 2020).

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9.2 Industrial symbiosis and regional fit

Industrial symbiosis is strongest when a neighboring industry can accept BR-derived material with minimal upgrading. Examples include coupling alumina refining with iron/steel production, using industrial gypsum or waste acids for conditioning, co-processing with clay or slag in cement systems, and converting mixed industrial residues into road or ceramic products. Broader mining-waste and ceramic literature reinforces the importance of regional market volume, transport distance, product standards, and aesthetic or processing constraints. Unqualified "zero-waste" terminology is therefore avoided: such a claim is defensible only if secondary solids, liquids, emissions, rejected products, transport burdens, and end-of-life obligations are included within the system boundary (Huang et al., 2024; Jiang et al., 2021; Karamoutsos et al., 2021; Pereira, 2025a; Pereira, 2025b; Peys et al., 2024; Qin et al., 2025; Scaratti et al., 2021). Similarly, waste diversion is not by itself evidence of circularity; a defensible circularity claim should demonstrate displacement of virgin raw material, recovery of a process reagent, production of a qualified secondary product, and/or verified reduction of environmental liability.

The resulting hierarchy is therefore a default decision logic subject to site-specific optimization: identify unavoidable residue and recoverable process water; qualify recovered water and alkali for realistic reuse; stabilize or selectively transform the chemistry; direct large mineral fractions to specification-compliant products with credible regional demand; recover critical metals where concentration and separation justify the additional process intensity; and engineer a final sink for material that does not meet product or environmental requirements. Alternative ordering may be preferable where, for example, a thermal transformation simultaneously improves metal separation and modifies the residual mineralogy for a downstream material route. Comprehensive-utilization reviews and multi-dimensional assessment studies support this systems view while also emphasizing that principles are more transferable than numerical process criteria (Padhan & Paul, 2025; Pavón Regaña et al., 2025; Song et al., 2026; Vielma et al., 2025; J. Zhang et al., 2026; Zhao et al., 2024).

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10. Environmental performance, techno-economics, and technology readiness

10.1 Life-cycle assessment and burden shifting

Life-cycle assessment is essential because BR technologies often exchange one burden for another. Drying lowers water-related storage risk but consumes electricity and filtration materials; geopolymerization can avoid clinker but require activators; thermal metal recovery can produce high-quality concentrates but consume reductants and heat; and hydrometallurgy can operate at lower temperature while generating chemical reagents, neutralization salts, and wastewater. Radiological assessment is also relevant for zero-waste concepts because concentrating mineral fractions can change radionuclide distribution even when the starting residue is accepted for storage (Filippousi et al., 2025; Goronovski & Tkaczyk, 2021; Hengevoss et al., 2024; Tan et al., 2024).

A recent comparative LCA of BR management found that drying followed by valorization reduced several midpoint impacts relative to wet disposal, with reported reductions of approximately 21.6–77.7% for selected categories. However, the geopolymer scenario reduced global-warming impact by only about 12.8% while cumulative energy demand increased by about 54.2%. The critical lesson is not that geopolymerization is unfavorable; rather, it shows why results depend on functional unit, electricity mix, activator production, avoided-product credits, and system boundaries (Filippousi et al., 2025).

Scandium recovery illustrates another boundary problem. A process may have a high-value product and low mass yield, making allocation assumptions decisive. LCA of Sc production routes, radiological assessment, and regional economic sensitivity analyses show that claims of critical-metal circularity should include the treatment of the bulk residue and not assign all process burdens to a few kilograms of recovered metal without transparent allocation (Goronovski & Tkaczyk, 2021; Hengevoss et al., 2024; Narayanan et al., 2021). For cross-route interpretation, LCA should therefore be reported on two complementary bases: impacts per tonne of dry BR managed, which supports waste-management comparison, and impacts per functional product or service delivered, such as a tonne of specification-compliant binder or road material, a kilogram of purified Sc product, or a

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defined contaminant-removal service. Neither denominator is sufficient alone for routes that produce fundamentally different products.

10.2 Techno-economics and product-market coupling

Techno-economic analysis must distinguish avoided liability from product revenue. Dewatering can create value through water and caustic recovery and through lower storage requirements even when no saleable product is produced. Construction routes depend on low logistics cost and large local markets, whereas critical-metal routes can tolerate greater processing intensity per tonne but face low feed grades, complex purification, and price uncertainty. Accordingly, TEA should report both feed-based metrics (e.g., US$/t dry BR managed) and product-based metrics (e.g., US$/t qualified material or US$/kg purified metal), together with recovery-adjusted revenue, transport/logistics, avoided storage cost, purification cost, market-volume assumptions, and sensitivity to reagent, energy, logistics, and product prices. Conceptual plant costing for building materials, regional Sc sensitivity analysis, and recent economic-optimization reviews demonstrate that route comparisons can change materially when transportation, reagent recycle, and avoided-disposal costs are included (Narayanan et al., 2021; Padhan & Paul, 2025; Scaratti et al., 2021).

Product qualification is as important as process yield. A cement blend, road base, Sc concentrate, Ti product, or adsorbent must satisfy not only technical performance specifications but also relevant regulatory classification, standards compliance, customer qualification, radiological limits where applicable, and end-of-life obligations. Early-age cement studies, long-term roadbed leaching, pilot steelmaking, and pilot Sc recovery show that the strongest evidence comes when performance is measured in the context of the intended downstream process rather than as an isolated laboratory index (Davris et al., 2021; Ji et al., 2025; Qin et al., 2025; Romano et al., 2025). A technically compliant laboratory product may still be commercially unusable if regulatory or customer acceptance is absent.

10.3 Readiness gates and evidence required for scale-up

Technology readiness should be treated as a sequence of evidence gates rather than inferred from scale labels alone. Feed variability must be bounded; the process must demonstrate stable mass, water, and element-specific balances; the product must meet

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technical and regulatory specifications; environmental performance must remain acceptable under route-appropriate long-term testing; and economics must be robust to plausible ranges of reagent, energy, logistics, and product prices. Where the published evidence supports the full European Commission TRL criteria, a numerical TRL may be reported; otherwise, the broader evidence descriptors defined in Section 2.2 are used. Figure 5 summarizes the author-developed scale-up gates.

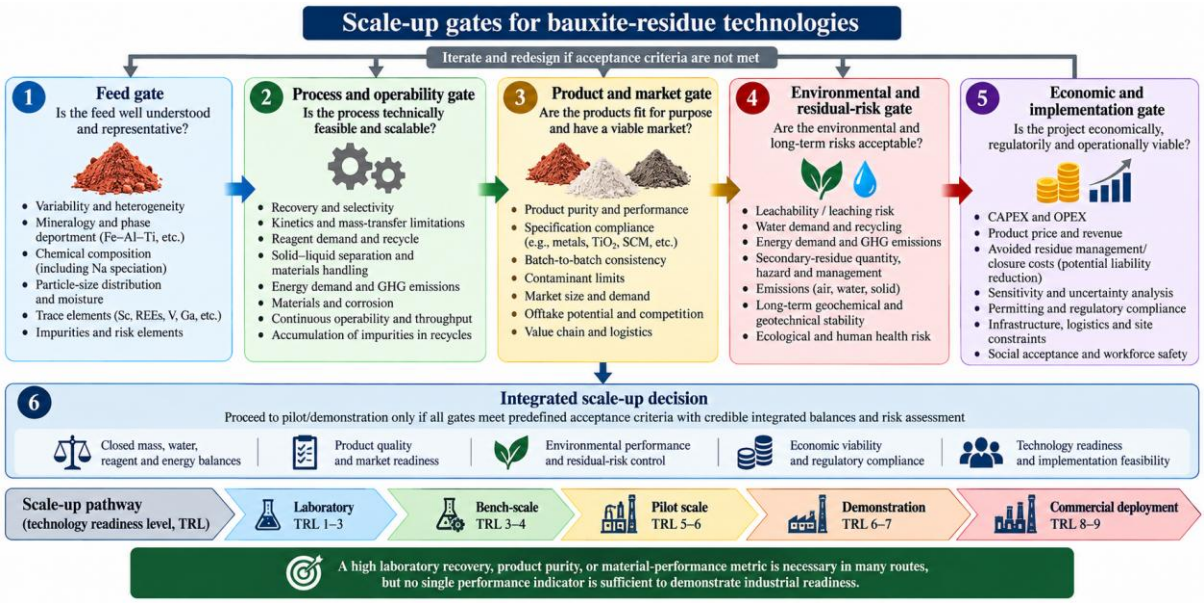

Figure 5. *Scale-up gates for bauxite-residue technologies.*
Note. Author-generated decision framework, adapted from pilot, field, LCA, TEA, and multi-criteria assessment literature (Davris et al., 2021; Filippousi et al., 2025; Hengevoss et al., 2024; Jiang et al., 2025; Narayanan et al., 2021; Padhan & Paul, 2025; Qin et al., 2025; Scaratti et al., 2021; Zhao et al., 2024). The figure is a synthesis for evidence appraisal and is not a formally validated TRL instrument.

Table 7 integrates the LCA, TEA, risk, and technology-readiness metrics needed for a defensible scale-up decision.

Table 7
Decision metrics for LCA, TEA, risk, and TRL assessment

Dimension	Minimum evidence	Preferred metric	Common failure mode
Mass, water, and element closure	All major solid/liquid streams closed; Na, Fe, Al, Si, Ti, target critical metals, and environmentally relevant trace elements reconciled	kg product/t dry BR; m^3 water/t; recovery/recycle fraction; element distribution and closure (%)	Reporting extraction or residue reduction without closing aqueous, secondary-residue, and element inventories

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Dimension	Minimum evidence	Preferred metric	Common failure mode
Energy/reagents	Direct plus upstream inputs, including pretreatment, neutralization, and recycle	GJ/t dry BR; kWh/t dry BR; kg reagent/t dry BR; multicycle reagent loss	Ignoring thermal pretreatment, neutralization, solvent/resin replacement, or impurity buildup
Environmental	Dual functional units, transparent boundaries/allocation, and route-specific exposure testing	kg CO_2e/t dry BR managed plus impact per functional product/service; service-condition leaching/risk indicators	Using only a tonne-BR denominator, a single leaching test, or waste diversion as a circularity proxy
Economics	CAPEX/OPEX, logistics, avoided storage cost, purification cost, product revenue, and market-volume assumptions	US$/t dry BR managed plus US$/t qualified product or US$/kg purified metal; sensitivity to key variables	Using product value without recovery-adjusted yield, purification, logistics, or market constraints
Product acceptance	Specification-relevant testing plus standards, regulatory classification, customer qualification, radiological limits where relevant, and end-of-life obligations	Grade, strength, durability, impurity/breakthrough limits, compliance status, and customer acceptance	Optimizing a surrogate laboratory metric without demonstrating external product acceptance
Readiness	Duration, integration, feed variability, automation/control, safety, product qualification, and relevant/operational environment	European Commission TRL only when criteria are documented; otherwise laboratory, bench-integrated, pilot, field demonstration, or industrially implemented	Assigning a precise or high TRL from batch yield or a scale label alone

Note. Framework synthesized from Davris et al. (2021), Filippousi et al. (2025), Goronovski and Tkaczyk (2021), Hengevoss et al. (2024), Jiang et al. (2025), Narayanan et al. (2021), Padhan and Paul (2025), Pavón Regaña et al. (2025), Qin et al. (2025), Scaratti et al. (2021), Song et al. (2026), Tan et al. (2024), Vielma et al. (2025), J. Zhang et al. (2026), and Zhao et al. (2024). CAPEX = capital expenditure; OPEX = operating expenditure. Environmental comparison should use both a dry-BR management basis and a functional product/service basis.

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11. Critical synthesis and research agenda

11.1 What has matured since 2020

Three areas show clear maturation. First, dewatering has moved from generic thickening concepts toward mechanistic control of flocculation, filter aids, rheology, and dry-placement requirements. Second, dealkalization increasingly combines mineral-phase understanding with field demonstrations rather than reporting only endpoint pH. Third, valorization is becoming more integrated: cement studies now examine mineralogy and hydration, metal-recovery studies increasingly include purification and secondary residues, and rehabilitation studies use multi-year field evidence (Huang et al., 2024; Liu et al., 2026; Patil & Thorat, 2022; Romano et al., 2025; Scullett-Dean et al., 2023; Tao et al., 2025; Wenzel et al., 2025; Wu et al., 2024; J. Zhang et al., 2026).

Critical-metal recovery has crossed an important threshold because pilot-scale Sc recovery demonstrates that a trace element can be concentrated selectively from BR under industrially relevant handling conditions. This result should not be generalized without qualification: mineral hosts vary among residues, acid and water balances are decisive, and every high-value recovery route leaves a much larger bulk mineral stream that still requires a technically and environmentally acceptable destination (Davris et al., 2021; Gentzmann et al., 2021; Jammulamadaka et al., 2025; Kumaş et al., 2026; Li et al., 2026; Song et al., 2026; Swain & Akcil, 2026).

11.2 Persistent gaps

The most persistent gap is comparability. Studies use different feed bases, drying conventions, leaching tests, curing regimes, extraction definitions, and functional units. A minimum reporting package should include dry-basis feed chemistry and mineralogy, soluble alkalinity, particle-size distribution (PSD), moisture, liquor chemistry, reagent consumption per tonne of dry BR, solid and liquid yields, product impurity levels, secondary-residue composition, water recovered, water qualified for reuse, alkali recovered, alkali qualified for refinery reuse, and an explicit sampling strategy. Integrated flowsheets should additionally report element-specific closure for Na, Fe, Al, Si, Ti, target critical metals, and

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environmentally relevant trace elements. Without these data, meta-analysis and scale-up remain weak even when individual experiments are technically sound.

A second gap is long-term performance. Road, soil, adsorbent, rehabilitation, storage, and construction applications expose BR-derived materials to fundamentally different hydraulic, chemical, mechanical, and biological conditions; no single standard leaching test can validate all routes. Testing should therefore be matched to the intended service condition and end-of-life scenario. Cement and geopolymer studies require durability and pore-solution evolution, not only 28-day strength. Metal-recovery routes require solvent/reagent recycle and impurity accumulation across multiple cycles. These needs are reflected across long-term leaching, field rehabilitation, pavement-risk, and cement-mineralogy studies (Ji et al., 2025; Merdy et al., 2024; Phillips & Courtney, 2022; Saha et al., 2025; Wan et al., 2024; Wenzel et al., 2025; Wenzel et al., 2026; Wu et al., 2021).

A third gap is the interface between process chemistry and materials handling. New leaching chemistries are often optimized without testing filtration, thickening, washing, or precipitation of the resulting slurry, even though silica gel, fine precipitates, or altered surface chemistry can dominate plant operability. Conversely, dewatering studies may optimize cake formation without considering whether the resulting chemistry is suitable for neutralization, cement use, or metal recovery. Future work should therefore use integrated process metrics rather than isolated unit-operation maxima (Patil & Thorat, 2022; Pereira, 2026a; Tao et al., 2025; Wang et al., 2023; Zeng et al., 2022a; Zeng et al., 2022b; Zhou et al., 2025).

11.3 Research priorities for 2026–2030

Priority 1 is feed classification: define a minimum BR characterization package that links mineralogy, Na forms, trace-element deportment, PSD, and rheology to candidate routes. Priority 2 is standardized environmental testing: pair rapid screening with route-specific column or field leaching, ecotoxicity, durability, and end-of-life scenarios. Priority 3 is water, alkali, and element closure: distinguish recovery from quality-compatible reuse and reconcile Na, Fe, Al, Si, Ti, target critical metals, and environmentally relevant trace elements across products, recycle loops, purge streams, emissions, and secondary residues. Priority 4 is cascade design: test whether selective metal recovery improves or degrades the properties of

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the remaining bulk fraction for cement, ceramics, roads, or rehabilitation. Priority 5 is impurity-aware purification: treat co-precipitation, solvent loading, resin saturation, and trace-product specifications as central design problems rather than downstream cleanup (Liu et al., 2026; Pereira, 2026a; Song et al., 2026; Yang et al., 2025; J. Zhang et al., 2026).

Priority 6 is pilot continuity: replace short batch demonstrations with campaigns long enough to reveal recycle buildup, filter degradation, corrosion, seasonal feed variability, operator constraints, and multicycle reagent/solvent accumulation. Priority 7 is electrification and low-carbon heat for thermal routes, including H_2-based reduction where material balances justify it. Priority 8 is market-coupled product qualification, including technical specifications, standards compliance, regulatory classification, customer acceptance, and realistic regional market volume for cementitious products, road materials, steelmaking feeds, and Sc/Ti concentrates. Priority 9 is harmonized LCA–TEA: report both per-tonne-dry-BR and per-functional-product/service metrics and disclose allocation, avoided-product credits, electricity mixes, transport distance, purification costs, and residue liabilities. Priority 10 is regional decision support: integrate transport, water scarcity, nearby industries, regulation, and existing storage assets into route selection (Filippousi et al., 2025; Hengevoss et al., 2024; Karamoutsos et al., 2021; Narayanan et al., 2021; Pavón Regaña et al., 2025; Pilla et al., 2025; Pilla et al., 2024; Qin et al., 2025; Scaratti et al., 2021; Song et al., 2026; Vielma et al., 2025; Zhao et al., 2024).

The overarching research question is therefore no longer simply, "Can BR be used?" It is, rather, "Which fraction of this specific BR, after which sequence of conditioning steps, can enter which market or environmental system with a demonstrably lower whole-system burden than continued storage?" This formulation connects BR chemistry with the industrial realities of tonnage, logistics, product standards, and long-term liability.

12. Conclusions

Bauxite residue cannot be reduced to either a single waste-disposal problem or a single secondary-resource opportunity. Its high volume, strong and partly structural alkalinity, fine particle size, variable mineralogy, and trace-element inventory create a coupled geotechnical, hydrometallurgical, materials, and environmental challenge. The evidence supports an

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author-developed default decision logic in which water and alkali recovery are addressed early where reuse quality can be demonstrated, residue chemistry is conditioned to downstream requirements, technically plausible high-volume mineral fractions are matched to specification-compliant products and realistic regional demand, and high-value metals are recovered selectively only where the additional process intensity is justified. Site-specific mineralogy, infrastructure, energy and water conditions, regulation, and market geography may alter or invert this sequence.

Mechanical dewatering and dry placement materially improve water management and physical control, but they do not eliminate chemical liability. Dealkalization and rehabilitation can reduce that liability, yet endpoint pH is insufficient without long-term, service-condition-specific leaching and field evidence. Construction materials remain the largest technically plausible mass-scale class of applications, but technical incorporation capacity must be distinguished from realistic regional market absorption. Sc, REEs, Ti, V, and Ga offer value-density opportunities that are more sensitive to feed variability, impurity control, reagent recycle, and downstream purification. Pilot-scale Sc recovery provides stronger readiness evidence than many emerging solvent, biological, and integrated critical-metal routes, whose maturity remains predominantly laboratory or bench scale. The most credible industrial concepts are therefore site-optimized integrated cascades rather than single-product flowsheets.

Future progress depends on comparable feed characterization, mass-water-energy and element-specific closure, multicycle operation, product and regulatory qualification, and harmonized environmental and economic boundaries. Waste diversion alone should not be described as circularity: a defensible claim requires demonstrable virgin-material displacement, process-reagent recovery, a qualified secondary product, and/or verified reduction of long-term environmental liability within a complete system boundary. A technology should be considered mature only when it can handle realistic feed variability, produce an accepted product or service, control secondary residues and reuse-quality water, and demonstrate that total system risk and cost are lower than those of the relevant management alternative. The general decision principles may be transferable among refineries, but numerical process criteria and route ordering remain residue- and site-specific.

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Data Availability

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