JIRRS
Journal International Review of Research Studies

Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Scandium Recovery from Primary and Secondary Resources: A Critical Review of Mineralogical Controls, Process Integration, and Separation Technologies

Antonio Clareti Pereira, Ph.D.
Department of Graduate Program in Materials Engineering
Federal University of Ouro Preto (UFOP)
Ouro Preto, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Scandium is a high-value, supply-constrained metal whose recovery is complicated less by absolute crustal scarcity than by extreme dispersion among Fe-, Al-, Ti-, and silicate-bearing host phases. Using a narrative critical-appraisal framework, this review evaluates scandium recovery from primary ores, nickel laterites, bauxite residue, titanium- and iron-processing residues, and other secondary streams by linking mineralogical occurrence to pre-concentration, thermal treatment, leaching, solution purification, and final product recovery. The central argument is that extraction yield alone is a poor metric for flowsheet selection; process-wide Sc recovery and impurity mass transferred per unit of recovered Sc must also be evaluated. A technically credible scandium circuit must also control impurity dissolution, preserve host-process economics, minimize acid and energy intensity, enable reagent recycling, and produce a high-purity product. Conventional physical beneficiation often fails because scandium is structurally incorporated or finely disseminated, although indirect upgrading through host-phase partitioning can help. Acid leaching remains dominant, but selective leaching, acid baking, alkaline–acid sequences, and integration with pressure leaching can reduce downstream impurity burdens. Solvent extraction remains the most mature purification route, while ion exchange, polymer inclusion membranes, ionic-liquid systems, and tailored sorbents are increasingly relevant for low-concentration streams. The review shows that the most attractive near-term opportunities lie in integrated by-product circuits tied to existing alumina, nickel–cobalt, and titanium value chains. Future progress depends on mineralogy-informed process selection, impurity-first flowsheet design, countercurrent validation, reagent and water recycling, and techno-economic assessment using realistic feed variability and product specifications.

Keywords: scandium; bauxite residue; nickel laterite; hydrometallurgy; solvent extraction; process integration

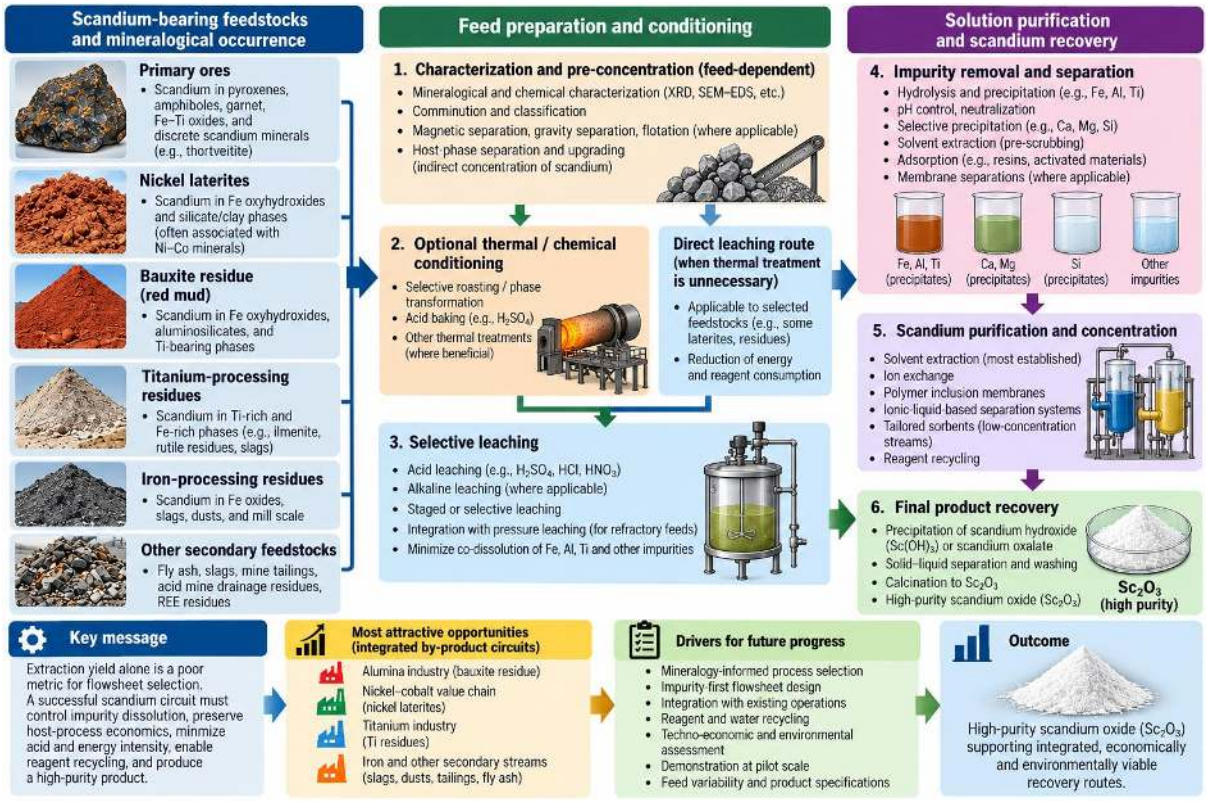
Highlights

- Scandium recovery is controlled by host mineralogy and impurity-to-Sc ratios, not by grade alone.
- Physical beneficiation is usually weak, whereas host-phase partitioning and selective leaching are more effective.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

- Fe and Al management determines the performance of downstream solvent extraction, ion exchange, and precipitation.
- Near-term viability favors integrated by-product circuits with realistic reagent recycle, product quality, and scale-up metrics.

Graphical abstract



1. Introduction

Scandium occupies an unusual position among critical metals. It is not exceptionally rare in the crust, yet it seldom forms large, high-grade ore bodies because Sc^{3+} substitutes into common Fe-, Al-, Mg-, and silicate minerals. The result is a resource base dominated by low concentrations, polymetallic associations, and process streams in which the mass of competing elements exceeds the scandium inventory by several orders of magnitude. This geological dispersion explains why the commercial question is rarely “Can scandium be leached?” and is more often “Can scandium be recovered selectively without destroying the economics of the host process?” (Botelho Junior et al., 2021; Wang et al., 2011).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

The strategic interest in scandium is driven primarily by Al–Sc alloys and solid oxide fuel cells, with additional uses in electronics and specialized alloys. The U.S. Geological Survey identifies aerospace alloys and solid oxide fuel cells among the principal uses and continues to characterize supply as highly concentrated and dependent on recovery from process streams rather than conventional stand-alone mines (U.S. Geological Survey, 2026). This market structure matters metallurgically: scandium recovery must normally be designed as an incremental circuit attached to alumina, nickel–cobalt, titanium, rare-earth, or other processing operations.

For the 2025 reporting year, the U.S. Geological Survey (2026) estimated global scandium oxide production at about 80 t, consumption at nearly 60 t, and production capacity above 90 t/y (Sc_2O_3-equivalent basis). The United States remained 100%reliant on net imports, and China remained the leading producer. Export controls introduced by China in 2025 further underscore supply-chain exposure. These estimates show that available capacity, actual production, and market absorption are distinct constraints, not interchangeable indicators of supply security.

The published literature on scandium recovery is extensive but fragmented. Mineralogical studies reveal the host phases, leaching studies optimize extraction, and separation studies report high distribution ratios or recoveries, yet these results are not always connected across the flowsheet. For example, an aggressive acid leach may maximize scandium extraction while simultaneously increasing Fe and Al dissolution, acid consumption, neutralization demand, solvent-extraction loading, and final residue mass. Conversely, a lower extraction with a much higher Sc/Fe selectivity can be superior at the plant scale. This review therefore treats selectivity, integration, and downstream burden as co-equal performance criteria rather than secondary considerations.

The objective is to critically connect source type, mineralogical deportment, beneficiation potential, thermal pretreatment, leaching chemistry, impurity control, selective separation, product finishing, techno-economics, and environmental performance. The review distinguishes unit-operation performance from flowsheet performance and asks which

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

combinations are most credible for industrial scale-up. Figure 1 illustrates the source-to-product logic, Figure 2 presents the feed-specific selection matrix, and Figure 3 shows the integrated circuit hierarchy. The evidence synthesis is organized around source characteristics (Table 1), leaching strategies (Table 2), purification technologies (Table 3), and scale-up metrics (Table 4); these diagrams and tables are interpretative syntheses rather than validated process designs.

The distinctive contribution of this review is not another catalog of Sc leachants or extractants. Botelho Junior et al. (2021) surveyed Sc recovery across feedstocks; Cao et al. (2025) emphasized resource availability and extraction/separation technologies; Jammulamadaka et al. (2025) and Kumaş et al. (2026) examined bauxite-residue routes; and Yoshida and Goto (2025) focused on solvent-extraction advances. In contrast, the present review connects phase-specific Sc deportment across primary and secondary feeds to an impurity-first, host-process-compatible flowsheet hierarchy. It evaluates the full chain from pre-treatment and real-liquor purification through reagent and water recycling, specification-grade Sc_2O_3, incremental economics, environmental system boundaries, and market absorption. This positioning is a conceptual integration, not a claim to experimental novelty.

2. Review scope and critical-appraisal approach

This article is a narrative critical review rather than a formal systematic review. It prioritizes peer-reviewed work that clarifies source mineralogy, selective extraction, impurity management, separation mechanisms, and integrated scandium recovery, with particular emphasis on literature published from 2018 onward and on representative earlier studies that remain foundational. The evidence base includes bauxite residue, lateritic nickel process streams, primary Sc-bearing occurrences, and industrial secondary resources, as well as solvent extraction, ion exchange, membrane transport, and product-recovery studies. Because no reproducible search strings, database retrieval dates, or independent screening log were documented for this manuscript, the coverage is not presented as exhaustive and no PRISMA-style completeness claim is made. We weighed studies based on whether they report feed characterization, scandium-specific recovery, competing-element balances, real-liquor

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

validation, and process integration. Work on related nickel, iron, or sulfate systems is labeled as analogous rather than direct scandium evidence.

The literature was evaluated by source domain, unit operation, measured scandium deportment, impurity inventories, and strength of process-scale evidence. Relevant search concepts included 'scandium recovery', 'bauxite residue/red mud', 'nickel laterite', 'titanium processing waste', 'acid baking', 'selective leaching', 'solvent extraction', 'ion exchange', and 'scandium oxide purity'. Bibliographic references and citation links informed the narrative synthesis, including foundational studies cited by the included reviews; however, individual platform search logs, language eligibility decisions, forward-citation screening records, and an auditable final retrieval date were not retained. Accordingly, no specific database coverage, absence of language restrictions, fixed search cut-off, reproducibility, or exhaustive inclusion is asserted. We discuss online-first 2026 studies where bibliographic details can be verified, and all claims remain limited to the scope of the cited source.

Direct Sc evidence is distinguished from analogous hydrometallurgical evidence throughout: Sc-specific extraction, deportment, distribution ratios, and product assays require measurements on Sc-bearing material, whereas work on Ni, Fe, sulfates, neutralization, or other adjacent systems informs only transferable mechanisms and potential boundary conditions. Such analogies are not treated as performance validation for scandium.

The appraisal framework uses six questions. First, where is scandium hosted, and how does that host control liberation or dissolution? Second, does a pretreatment increase scandium grade or merely transfer it into a more reactive phase? Third, what impurity mass enters solution per unit mass of scandium? Fourth, can the separation stage tolerate the resulting acidity and competing ions? Fifth, can the route recycle acid, extractant, water, and neutralizing reagents? Sixth, can the scandium circuit be inserted into the host operation without sacrificing recovery or quality of the principal product? These questions are used throughout the review to distinguish laboratory extraction from industrially meaningful recovery.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

3. Occurrence, source classes, and mineralogical controls

3.1 Primary and by-product geological sources

High-grade scandium minerals such as thorite are geologically uncommon and volumetrically limited, whereas larger scandium inventories are associated with laterites, bauxite systems, Ti-bearing ores, Fe oxides, and polymetallic deposits. In lateritic environments, weathering redistributes Sc and may enrich it through incorporation or sorption in Fe-bearing phases. Spectroscopic work on lateritic deposits shows that scandium can associate with Fe oxides and related weathering products, reinforcing the importance of host-phase chemistry over bulk grade (Chassé et al., 2017).

Bauxite and bauxite residue illustrate this principle particularly well. Microanalytical work on Greek material showed that hematite, goethite, and zircon can host most of the scandium inventory, with the Bayer process changing the modes of occurrence less than might be expected from the major-element transformation of the residue (Vind et al., 2018). Consequently, a route that dissolves only easily reactive minor phases may leave a substantial fraction of scandium locked in refractory Fe oxides or zircon.

The broader residue-valorization perspective is relevant to scandium only insofar as it clarifies the boundary conditions of a dedicated extraction circuit. Residue storage, major-element recovery, and the sequence of co-product operations can determine whether a scandium-bearing fraction is accessible at economically tolerable impurity loading (Pereira, 2026b).

3.2 Secondary and industrial sources

Secondary sources are attractive because host operations have already paid for mining and primary comminution, and scandium can concentrate in residues, neutralization precipitates, or waste liquors. Bauxite residue is prominent; Al-rich laterite residues, acidic titanium-industry streams, and other metallurgical by-products may be even better targets when scandium is already concentrated in less material or liquid. Reviews identify bauxite residue

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

and nickel laterites as leading candidates for integrated recovery (Botelho Junior et al., 2021; Wang et al., 2011; Zhang & Li, 2016).

The economic advantage of a secondary source is therefore conditional rather than universal. A low-grade residue can be attractive if it is already finely divided, available at large throughput, and located beside acid, utilities, and separation infrastructure. By contrast, a secondary stream that contains very high Fe, Al, Ca, or Si may impose a large neutralization and waste-treatment penalty. Feed grade must be interpreted together with host mineralogy, throughput, impurity inventory, and the point in the host flowsheet at which the scandium circuit is attached.

Table 1 summarizes the principal source domains and the metallurgical consequences of their typical scandium occurrence.

Table 1. Source classes, scandium occurrence, and implications for process selection

Source domain	Typical Sc occurrence	Main constraint/opportunity	Likely processing emphasis
Bauxite residue	Sc commonly associated with Fe oxides and accessory phases; very high Fe/Al/Ti matrix	Low selectivity in strong-acid leaching; physical separation usually weak	Selective leaching, acid baking/roasting, Fe control, SX/IX polishing
Ni–Co laterites and intermediates	Sc associated with limonite and may report to Fe/Al precipitates during pressure leaching	Opportunity to recover Sc without changing the main Ni–Co circuit	Precipitation/re-leach, alkaline Al removal, selective SX
Ti/Fe process residues and acidic waste streams	Sc may already be concentrated in a liquid or residue relative to the original ore	Potentially lower mining and comminution burden, but chemistry can be highly acidic	Direct purification, SX, IX, or tailored sorption
Primary Sc minerals / specialized deposits	Higher local Sc grade but limited tonnage and complex silicates	Potential direct resource but often lacks mature integrated infrastructure	Mineral-specific comminution, thermal activation, leaching, and purification
Other industrial wastes and tailings	Highly variable host phases and impurity inventories	Resource value depends on accumulated tonnage and pre-existing processing history	Site-specific mineralogy-first flowsheet design

Note. Generalized synthesis based on Botelho Junior et al. (2021), Chassé et al. (2017), Vind et al. (2018), Wang et al. (2011), and Zhang and Li (2016).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

3.3 Mineralogy as the first process-selection variable

The most transferable conclusion across source types is that scandium recovery should begin with deportment, not with reagent selection. Bulk chemical analysis cannot distinguish structurally substituted Sc from surface-bound Sc, nor can it show whether the recoverable fraction is located in fine goethite, massive hematite, accessory zircon, or a soluble process salt. These distinctions determine whether physical pre-concentration is plausible, whether roasting can improve reactivity, and whether selective leaching can exploit different dissolution kinetics.

This mineralogy-first perspective also explains why apparently similar residues can behave differently. Bauxite residues from different ores and Bayer conditions can have different Fe mineralogy, Ti phases, desilication products, and particle-size distributions. Laterite intermediates can likewise reflect different pressure-leach chemistries and neutralization sequences. Therefore, the most useful characterization package for process development combines bulk chemistry with X-ray diffraction, particle-size analysis, electron microscopy, and, where possible, phase-specific Sc measurements.

For limonitic feedstocks, interpret particle-size distributions as indicators of surface area, host-phase association, and leaching kinetics rather than evidence of scandium liberation. Nickel-laterite studies provide transferable methodological guidance, but they cannot establish scandium recovery without element-specific deportment measurements (Pereira, 2026h).

Geological investigations broaden the source-selection framework by documenting heterogeneous Sc associations in primary, lateritic, and weathered deposits. Nevertheless, occurrence data should be kept distinct from process evidence: site-specific host identification and phase-resolved balances are prerequisites for predicting recoverable Sc (Beland, 2023; Choudhary et al., 2024; Gentzmann et al., 2022; Gülyüz, 2024; Ignatov et al., 2023).

Studies of diverse mineral systems indicate that Sc concentration alone cannot establish beneficiation potential. Differences in substitution sites, weathering pathways, and grain-scale association determine whether dissolution is kinetically accessible or demands host-mineral

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

transformation (Liu et al., 2023; Liu et al., 2025; Qin et al., 2020; Qin et al., 2021; Shao et al., 2023).

Recent studies of specialized deposits and alteration products reinforce the need to resolve mineral-scale heterogeneity before selecting a route. Their strongest contribution is geological discrimination; without accompanying leach tests, direct inference of recovery or reagent demand would exceed the evidence (Supit et al., 2025; Wang et al., 2026; Wang et al., 2021; Xue et al., 2026; Yang et al., 2025).

Additional geological evidence further supports feed-specific characterization rather than extrapolation from nominally similar ore categories (Zhang et al., 2022).

4. Mineral processing and pre-concentration

4.1 Limits of conventional physical beneficiation

Gravity, magnetic separation, and flotation work well when the target element resides in a separable mineral phase, but scandium often violates that assumption. In bauxite residue and many laterites, Sc is distributed through Fe-rich phases or fine-grained matrices, so a physical concentrate may simply track hematite, goethite, or clay without generating a sufficiently large Sc upgrade. The recent red-mud literature explicitly notes that physical separation alone is often ineffective because the residue is fine and compositionally homogeneous at the scale relevant to conventional beneficiation (Jammulamadaka et al., 2025).

The implication is not that beneficiation has no role, but that its purpose should be reframed. Instead of expecting a direct scandium concentrate, physical operations can remove coarse inert phases, control particle size, improve solid–liquid separation, or partition a host phase for subsequent chemical treatment. For example, magnetic separation after reduction roasting may be useful because the thermal step changes the Fe phases and produces a separable metal- or magnetite-rich product, while scandium remains in a slag or residue. The value is therefore indirect enrichment and impurity rejection.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

4.2 Indirect upgrading and host-phase management

Indirect upgrading is particularly attractive when the host industry already creates a scandium-enriched intermediate. In laterite processing, carefully selected neutralization or precipitation conditions can transfer Sc into an Al-rich or Fe-rich precipitate that represents only a small fraction of the original ore mass. Subsequent re-leaching and solvent extraction can then operate on a more concentrated stream. Zhou et al. (2022b) demonstrated this logic for high-pressure sulfuric-acid leach liquor, while Zhou et al. (2022a) treated a Sc-bearing Al residue through selective alkaline leaching, acid re-leaching, and solvent extraction.

Figure 1 shows the source-to-product logic adopted in this review. The key feature is that we evaluate physical or thermal pretreatment by its effect on downstream impurity burden, not by scandium upgrade ratio alone.

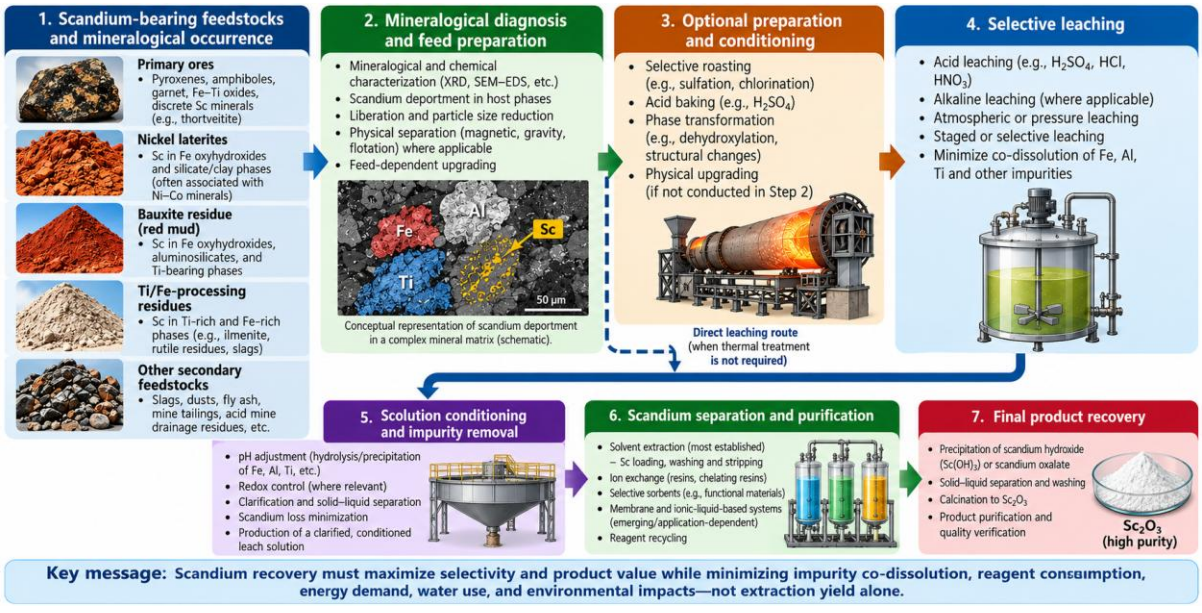


Figure 1. Source-to-product logic for scandium recovery from primary and secondary resources
Note. Original synthesis by the author based on the literature discussed in this review.

Interpret the conceptual diagram as a decision framework rather than a validated industrial flowsheet; site-specific phase balances, reagent consumption, and product specifications remain necessary before selecting a route.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Physical upgrading studies show that separation can be useful when scandium follows a discrete or transformable host phase. Assess reported magnetic- or density-based approaches using Sc deportment and whole-circuit mass recovery, because removing iron alone does not prove scandium enrichment (Kallio et al., 2021; Pan et al., 2020; Sauber et al., 2026).

5. Pyrometallurgical and thermal pretreatments

5.1 Smelting and slag enrichment

Pyrometallurgical treatment is justified when the objective is to restructure a difficult matrix while recovering a major co-product. Reduction smelting of Fe-rich residues can transfer iron to a metal phase while retaining scandium in an oxide-rich slag. This improves the Sc/Fe ratio before hydrometallurgy and can reduce the solvent-extraction burden. The penalty is high-temperature energy consumption, refractory wear, gas handling, and the need for a downstream slag-leaching circuit. Accordingly, smelting is most defensible where Fe recovery or integration with an existing furnace contributes independent value.

5.2 Roasting, sulfation, and acid baking

Lower-temperature roasting and acid-baking approaches can alter mineral reactivity without complete melting. The recent red-mud literature highlights reduction roasting followed by acid baking and water leaching, ball-mill-assisted acid-baking routes, and staged acid baking as ways to break Fe-hosted structures while attempting to control Fe dissolution (Jammulamadaka et al., 2025). Their advantage is the ability to decouple phase transformation from the final aqueous leach. Their disadvantage is that the full process balance must include acid addition, off-gas management, heat recovery, corrosion, and solid handling.

Selective sulfation offers an instructive comparison across Fe-rich matrices. The rationale developed for bauxite residue focuses on sulfate formation and decomposition windows, whereas ferruginous nickel-laterite work emphasizes acid dosage, particle-size response, and iron rejection. Both offer analogous process-design evidence, not direct proof of scandium selectivity for a particular feed (Pereira, 2026e, 2026m).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

A rigorous comparison should therefore report more than scandium extraction. Relevant metrics include acid dosage per kilogram of dry feed, mass loss during roasting, Fe and Al transfer to solution, water demand during leaching and washing, residual acidity, and the amount and quality of any Fe-rich co-product. Thermal activation becomes attractive when it sharply improves selectivity or enables saleable co-products; it is less attractive when it merely shifts acid consumption from the leach reactor to an upstream baking step.

Thermal studies encompass sulfation followed by water leaching, acid baking, reductive conversion, and slag conditioning. A reliable comparison must normalize reagent input, temperature, phase transformations, and iron partitioning; otherwise, differences in feed chemistry dominate apparent recovery advantages (Agrawal, 2021; Anawati, 2022; Cao et al., 2020; Cunningham et al., 2026; Falah et al., 2026).

Investigations of roasting and acid-baking strategies illustrate the tension between disrupting resistant host phases and controlling the soluble Fe inventory. Feed composition and the amount of acid consumed should therefore accompany any claimed improvement in Sc extraction (Kallio et al., 2022; Kallio et al., 2022b; Kim, 2020; Li et al., 2024; Li et al., 2025).

Further thermal studies raise questions about the stability of new sulfate phases, thermal energy recovery, and downstream leachability. Their results are best treated as process-specific evidence rather than interchangeable estimates of scandium extraction efficiency (Mao et al., 2025; Meng et al., 2020; Pan et al., 2021; Pereira, 2026l; Shao et al., 2024).

The design implication is to close the combined roast–leach mass balance, including off-gas and wash streams, before recommending heat-intensive pretreatment (Xiao et al., 2020).

6. Hydrometallurgical extraction

6.0 Reporting boundar$_i$es and quantitative definitions. All recovery values should identify their feed, target stream, analytical basis, and included unit operations. Stage recovery is $R_{Sc,k}$ (%) = 100 × m(Sc in target stream k)/m(Sc in stage feed). For sequential stages without recycle, overall feed-to-product recovery is $R_{Sc,overall}$ (%) = 100 × $\Pi(i=1\ldots n)$ r_i,

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

where r_i denotes each stage's fractional Sc recovery and all relevant loss streams are included. With interconnected recycle loops, recovery must instead be calculated from a closed external-input/external-output Sc balance, avoiding double counting internal circulation.

For impurity j, define impurity intensity I_j = m(j entering the specified recovery or purification boundary)/m(Sc recovered at the same boundary), expressed as kg j/kg Sc; a comparison must disclose both absolute masses and analytical uncertainty. A supplementary selectivity index $S_{Sc/j} = R_{Sc}/R_j$ may be reported only where recoveries share consistent boundaries and $R_j > 0$. Neither a large selectivity ratio nor a high Sc extraction fraction substitutes for the impurity inventory. For beneficiation, report $D_{Sc,k}$ (%) = 100 × m(Sc in fraction k)/m(Sc in original feed), mass pull MP_k (%) = 100 × m(fraction k)/m(original feed), and concentration factor CF_k = grade(Sc in fraction k)/grade(Sc in feed). Complete fraction balances are essential.

Normalize acid and alkali demands to both feed and saleable product: A_f = kg acid/t dry feed; A_p = kg acid/kg specification-grade Sc2O3; B_f = kg fresh alkali/t dry feed; B_p = kg fresh alkali/kg specification-grade Sc2O3. Explicitly distinguish gross addition, chemically consumed reagent, recovered reagent, makeup, neutralization demand, and bleed. For thermally activated routes, report specific thermal energy in kWh_{th}/t feed and kWh_{th}/kg final Sc2O3, accounting for coproduct allocation separately. Close water, washing, evaporation, recycle, bleed, and Fe/Al/Ti/Ca/Si/Zr material inventories whenever a route-level comparison is claimed.

6.1 Acid leaching: high extraction versus high impurity loading

Sulfuric, hydrochloric, and nitric acid systems dominate scandium leaching because Sc^{3+} can be mobilized effectively under acidic conditions. The central limitation is non-selective dissolution. In Fe- and Al-rich feeds, stronger acidity often increases scandium extraction but also raises concentrations of Fe^{3+}, Al^{3+}, Ti species, Ca, and other components that must later be removed. This trade-off has been recognized in red-mud reviews for more than a decade and remains the central constraint on direct strong-acid leaching (Zhang & Li, 2016).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Selective acid leaching attempts to exploit kinetic or thermodynamic differences rather than maximize total dissolution. Shoppert, Loginova, Napol'skikh, and Valeev (2022) showed that diluted acid with $MgSO_4$could extract more than 63% of Sc from bauxite residue at pH 4 and 80 °C while suppressing Fe extraction to a very low level; lower pH increased Sc recovery but also increased Fe dissolution. The importance of this result is the selectivity trend, not the specific batch condition: moderate scandium extraction with minimal Fe transfer may reduce total downstream reagent consumption.

Results on atmospheric sulfuric-acid leaching of ferruginous nickel laterites also underscore the coupled dependence of acid dosage, residence time, and iron transfer on apparent extraction performance. Such nickel-centered datasets can guide controlled-experiment design, but scandium-specific extraction and solution inventories must be measured separately before applying these trade-offs to a scandium flowsheet (Pereira, 2026a).

Alkali-fusion or alkali-assisted pretreatment can similarly create a residue that is more amenable to selective acid leaching. Shoppert et al. (2022) reported selective Sc extraction from alkali-fusion bauxite residue using dilute HNO_3under conditions designed to limit Fe dissolution. Such routes are promising when caustic can be recycled or when the host process already contains an alkaline circuit; otherwise, the additional reagent loop must be justified against direct acid routes.

6.2 Alkaline leaching and sequential alkaline–acid routes

Direct alkaline leaching is not universally selective for scandium, but alkaline chemistry can be powerful when the primary purpose is to remove Al or another amphoteric impurity before an acid Sc leach. In a Sc-bearing Al residue from laterite processing, Zhou et al. (2022a) separated most Al by NaOH leaching while retaining most Sc in the solid, then acid-leached the Sc-rich residue and recovered Sc by synergistic solvent extraction. Yu et al. (2024) further developed this process logic, using NaOH to separate Al, acid to dissolve Sc, and a P204–N1923 system for selective extraction and product preparation.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

These sequential routes illustrate a broader design principle: the best first leach may intentionally leave scandium in the solid if it selectively removes a dominant impurity. The objective is to increase the Sc-to-impurity ratio of the stream entering the expensive separation stage.

6.3 Pressure leaching and integration with nickel laterite circuits

High-pressure acid leaching (HPAL) and related pressure-leach routes already exist at industrial scale for Ni–Co laterites, which makes them natural hosts for scandium recovery. The challenge is to collect scandium without compromising Ni and Co recovery or introducing excessive neutralization costs. Zhou et al. (2022b) proposed staged precipitation from HPAL liquor to remove Fe and enrich Sc before re-leaching and synergistic extraction. This is more industrially relevant than treating the whole ore solely for scandium because it uses an existing high-throughput leach and inserts the Sc circuit after the main dissolution step.

A separate evaluation of nickel-laterite process feasibility provides a useful systems-level counterpoint: the incremental scandium circuit must be assessed against main-metal throughput, cost allocation, residence-time constraints, and the host operation's operating window. These are analogical economic considerations rather than demonstrated scandium process economics (Pereira, 2026g, 2026k).

Table 2 compares representative hydrometallurgical route logics. The table deliberately emphasizes selectivity and downstream burden rather than presenting extraction percentages as directly comparable performance rankings.

Table 2. Critical comparison of representative scandium leaching strategies

Route	Strength	Primary penalty	Best-fit context
Direct strong-acid leach	Simple flowsheet; high Sc extraction can be obtained	High Fe/Al/Ti dissolution; acid and neutralization demand	When feed is already pre-enriched or impurity inventory is moderate
Selective dilute-acid leach	Lower impurity loading; improved Sc/Fe selectivity	May sacrifice some Sc extraction; kinetics can be slower	Fe-rich bauxite residues where downstream

JIRRS Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

			purification dominates cost
Acid baking/roasting + water leach	Phase transformation can unlock refractory Sc and control Fe behavior	Thermal energy, acid handling, off-gas, and solid handling	Fe-rich residues where direct leaching is unselective
Alkaline impurity removal + acid Sc leach	Can separate Al before Sc dissolution; enables reagent-loop integration	Two reagent circuits and extra solid–liquid separation	Al-rich laterite intermediates and amphoteric impurity systems
Pressure-leach integration + precipitation/re-leach	Uses existing Ni–Co leach infrastructure; Sc can be recovered as a by-product	Sc must be captured without disturbing host metal recovery	Large laterite operations with existing HPAL/NAPL circuits

Note. Representative evidence includes Shoppert et al. (2022), Shoppert, Loginova, Napol'skikh, and Valeev (2022), Zhou et al. (2022b, 2022a), Yu et al. (2024), Zhang and Li (2016), and Jammulamadaka et al. (2025).

Additional extraction studies cover different acidic, alkaline, pressure-assisted, and staged routes. Because host mineralogy and solution composition vary markedly between feeds, their reported yields do not support an unqualified global ranking of leachants (Botelho Junior et al., 2021a; Cao et al., 2026; Chen et al., 2025; Ding et al., 2023; Grigorieva et al., 2025).

Studies of mixed and secondary feeds emphasize the need to measure Fe, Al, and Ti transfer alongside Sc, acid intensity, filtration, and wash losses. A high one-stage leach yield is an intermediate result, not proof of integrated circuit performance (Ichlas et al., 2022; Kanekaputra, 2023; Mostajeran et al., 2021; Salman et al., 2022; Shoppert et al., 2024).

A second group of extraction studies extends the possible range of chemical activation and aqueous separation conditions. Their transferability depends on demonstration with relevant mineral phases and comparably defined feed-to-product recovery boundaries (Tian et al., 2021; Xiao et al., 2021; Xiong et al., 2024; Yan et al., 2024; Yüksekdağ et al., 2022).

7. Separation, purification, and product finishing

7.0 Comparable separation and product-recovery metrics. For solvent extraction at a specified aqueous chemistry and temperature, $D_{Sc} = [Sc]_{org}/[Sc]_{aq}$ and $D_M = [M]_{org}/[M]_{aq}$, each at equilibrium and expressed on a consistent volumetric concentration basis. The oriented separation factor is $\beta_{Sc/M} = D_{Sc}/D_M$; report the two distribution ratios alongside β,

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

since a high factor alone can coexist with insignificant Sc transfer. Also report phase ratio, loading, number and efficiency of extraction, scrub, and strip stages, phase-disengagement time, crud generation, entrainment, organic solubility/degradation losses, and makeup. Stripping efficiency is η_{strip} (%) = 100 × m(Sc in strip liquor)/m(Sc in loaded organic entering stripping), with a stated circuit boundary. Countercurrent and repeated-cycle results are preferred to single-contact synthetic-solution experiments.

For ion exchange, document dynamic working capacity at a defined breakthrough criterion (rather than batch-equilibrium uptake alone), feed composition, superficial velocity, bed volumes treated, breakthrough curves, pressure drop, regeneration and eluent use, and cyclic capacity retention CR_n (%) = 100 × q_n/q_1 using the same loading protocol. For membranes, report Sc flux (mass/area/time), permeability under stated driving force, impurity selectivity, membrane area, fouling, carrier loss and lifetime over repeated cycles. Ionic-liquid systems require reporting viscosity, transfer rate, aqueous loss, solvent make-up, closed-loop regeneration, and synthesis burden. These indicators are prospective reporting requirements, not measured values for every cited study.

For precipitation and calcination, report Sc yield from strip liquor to precipitate, mother-liquor and wash losses, cake handling, co-precipitated Fe/Al/Ti/Zr/REEs, calcination energy, and final assay. The appropriate functional unit is 1 kg of Sc_2O_3meeting a stated grade and trace-impurity specification; purity cannot be inferred from extraction or precipitation yield. Particle morphology should be reported where a particular customer qualification actually demands it.

7.1 Solvent extraction as the mature reference technology

Solvent extraction (SX) remains the reference technology for scandium purification because it is scalable, compatible with continuous countercurrent operation, and capable of high selectivity when acidity and extractant chemistry are controlled. Acidic organophosphorus extractants such as D2EHPA/P204 and related reagents have a long history in scandium recovery, while neutral extractants, amines, carboxylic acids, synergistic mixtures, and newer

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

ionic-liquid systems expand the available selectivity window (Wang & Cheng, 2011; Yoshida & Goto, 2025).

The recurring problem is that an extractant with high affinity for Sc may also co-extract Fe, Ti, Zr, or other trivalent and tetravalent ions or may require harsh stripping conditions. Therefore, the best SX circuit is rarely determined by extraction percentage alone. Scrubbing, stripping, phase disengagement, organic loss, crud formation, and extractant degradation are equally important. For example, Salman et al. (2022) demonstrated high Sc extraction from a real red-mud leachate using D2EHPA and TBP systems, but the process logic also depended on controlling Fe chemistry, stripping conditions, and leachate composition.

In laterite intermediates, synergistic systems can improve selectivity after upstream impurity removal. Zhou et al. (2022b) used P204 and TBP after staged precipitation and re-leaching, while Yu et al. (2024) reported high Sc extraction with a P204–N1923 combination after separating most Al in an alkaline step. These results reinforce a fundamental point: SX performance is strongly conditioned by upstream solution preparation.

7.2 Ion exchange and tailored sorbents

Ion exchange (IX) and chelating resins are attractive for dilute streams because they can concentrate scandium without circulating large organic-phase inventories. Their practical limitations include resin capacity, competition from abundant ions, fouling, elution efficiency, and the need for stable performance over many cycles. Toli et al. (2023) evaluated ion-exchange resins for sulfuric-acid leach solutions and showed that resin choice and solution composition strongly control scandium uptake. IX is therefore particularly relevant as a polishing or pre-concentration step after major impurities have been removed.

General reviews of conventional ion-exchange and chelating resins stress that equilibrium selectivity alone is insufficient; breakthrough curves, competing-ion loading, regeneration efficiency, and cyclic capacity loss govern practical operation. These principles directly inform the choice of a Sc-polishing stage, although quantitative performance must be validated with scandium-bearing liquor (Pereira, 2026d).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

7.3 Membranes, ionic liquids, and emerging separation media

Polymer inclusion membranes (PIMs) combine selective carrier chemistry with membrane transport and can reduce the inventory of organic diluent. Yoshida et al. (2019) demonstrated selective transport of Sc from sulfate media using amic-acid carriers and showed that Fe transport could be kinetically differentiated from Sc. The challenge for industrialization is maintaining flux, membrane stability, and selectivity in real high-ionic-strength liquors over long operating periods.

Ionic liquids provide another route to tune solvent polarity, extractant environment, and safety characteristics. Zhang et al. (2024) reported an ionic-liquid-based extraction strategy using phenylphosphinic acid for selective Sc recovery from acidic media. Such systems are scientifically promising, but a credible scale-up comparison must include solvent cost, viscosity, mass-transfer rate, loss to the aqueous phase, regeneration, and life-cycle burden. “Green solvent” claims should not be accepted without a closed-loop solvent-recovery analysis.

7.4 Precipitation, crystallization, and final Sc_2O_3 production

Precipitation remains a practical product-finishing step because Sc can be recovered as hydroxide or oxalate and converted to Sc_2O_3 by calcination. However, direct precipitation from impure leach liquor is rarely selective enough for high-purity product specifications. The role of precipitation is therefore usually downstream of SX or IX, where the Sc concentration is higher and competing ions have been reduced. Yu et al. (2024) demonstrated this integrated sequence by combining selective extraction, stripping, oxalate/hydroxide precipitation, and calcination to obtain a high-purity Sc_2O_3 product.

In product-finishing circuits, uncontrolled co-precipitation can compromise purity and generate voluminous hydroxide solids. Process-oriented studies of coprecipitation and hydroxide filterability provide useful design criteria—reagent addition rate, hydrolysis conditions, residence time, settling, and filtration—but their transfer to scandium requires experimental confirmation of Sc losses and contamination (Pereira, 2026c, 2026i).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Table 3 summarizes the main separation technologies and the scale-up questions that should be reported in a critical review.

Table 3. Separation and purification technologies for scandium-bearing liquors

Technology	Main strength	Main limitation	Scale-up metrics
Solvent extraction	High capacity; continuous countercurrent scalability; mature equipment	Co-extraction, stripping severity, organic loss, phase disengagement	Distribution ratio, separation factor, scrub/strip efficiency, organic recycle
Ion exchange / chelating resin	Good for dilute solutions and polishing; compact equipment	Capacity, fouling, competing ions, elution and resin lifetime	Breakthrough capacity, selectivity, cycle stability, eluent consumption
Polymer inclusion membrane	Low carrier inventory; extraction and transport combined	Flux, long-term stability, scale-up area, membrane replacement	Permeability/flux, selectivity, cycle life, real-liquor stability
Ionic-liquid extraction	Highly tunable solvent environment; potential low volatility	Viscosity, cost, solvent loss, regeneration, uncertain large-scale EHS profile	Mass transfer, solvent recovery, phase behavior, life-cycle inventory
Precipitation / crystallization	Simple equipment; direct solid product	Impurity co-precipitation; poor selectivity in raw liquors	Product purity, particle filtration, reagent consumption, calcination demand

Note. Synthesized from Wang and Cheng (2011), Toli et al. (2023), Yoshida et al. (2019), Yoshida and Goto (2025), Zhang et al. (2024), and Yu et al. (2024).

The expanded separation literature spans organophosphorus reagents, synergistic extractants, resins, and alternative extraction media. Mechanistic selectivity data can support carrier selection, but evaluation of actual leach liquors is essential to establish capacity under competing-ion loading (Babain et al., 2026; Botelho Junior et al., 2021b; Cao et al., 2024; Chen et al., 2021; Gangadari et al., 2025).

For sorption and solvent-based separations, reported equilibrium selectivity must be complemented by kinetics, impurity saturation, elution behavior, and regeneration. Such operating descriptors are needed to relate laboratory uptake to cyclic plant performance (Hajmohammadi et al., 2020; Hedwig et al., 2022; Koller et al., 2023; Lin et al., 2026; Madhavi et al., 2026).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Membrane and resin investigations offer potential advantages in dilute solutions, but fouling, membrane lifetime, ionic-strength sensitivity, and consumable losses can outweigh nominal selectivity. Comparative assessments should explicitly state these unknowns rather than presume direct replacement of solvent extraction (Mikeli et al., 2021; Mikeli et al., 2022; Napol'skikh et al., 2024; Rout, 2022; Smyshlyaev et al., 2022).

Emerging studies of extraction chemistry and transport broaden the available selective-separation toolkit. Their practical value remains conditional on verified selectivity in multicomponent liquors and repeated recovery and regeneration cycles (Tian et al., 2026; Wang et al., 2026; Watanabe et al., 2024; Watanabe et al., 2026; Xiao et al., 2023).

Other process investigations highlight the importance of integrated scrubbing, stripping, organic inventory, and impurity recycle. Apparent high scandium loading is insufficient if the same chemistry compromises stripping or creates unmanageable spent streams (Zhang et al., 2026; Zhou et al., 2021; Zhou et al., 2020; Zhu et al., 2020; Zou et al., 2022).

A review of alternative extractant strategies likewise supports using closed-loop recovery and product specification as the final comparison criteria, rather than equilibrium distribution ratios in isolation (Zou et al., 2020).

8. Impurity management and solution chemistry

Fe, Al, and Ti dominate the impurity problem because their concentrations are typically far greater than those of Sc and because they affect both leaching and separation. Fe is especially problematic in bauxite residue, where scandium may be hosted in Fe oxides and where dissolving the host can release the very impurity that later competes most strongly in extraction. Al is especially important in laterite intermediates, where selective alkaline dissolution can be used to create a Sc-rich residue. Ti, Zr, Ca, Si, and rare-earth elements can also influence extraction, phase separation, precipitation, and final product purity depending on the source.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

The correct design variable is therefore the impurity-to-Sc ratio in the process stream, not simply the impurity concentration in the original solid. A pretreatment that removes 90% of the Fe before leaching or transfers Sc to a small intermediate stream can reduce SX stages, scrub demand, and organic loading more than a modest increase in leach extraction. Conversely, a leach that dissolves nearly all Sc and tens of kilograms of Fe per gram of Sc may create an uneconomic purification problem.

Figure 2 summarizes a matrix-driven decision logic. The diagram is intentionally qualitative because exact pH and reagent windows are feed-specific; its purpose is to show that Fe-rich, Al-rich, and pre-enriched streams should not be forced into the same generic flowsheet.

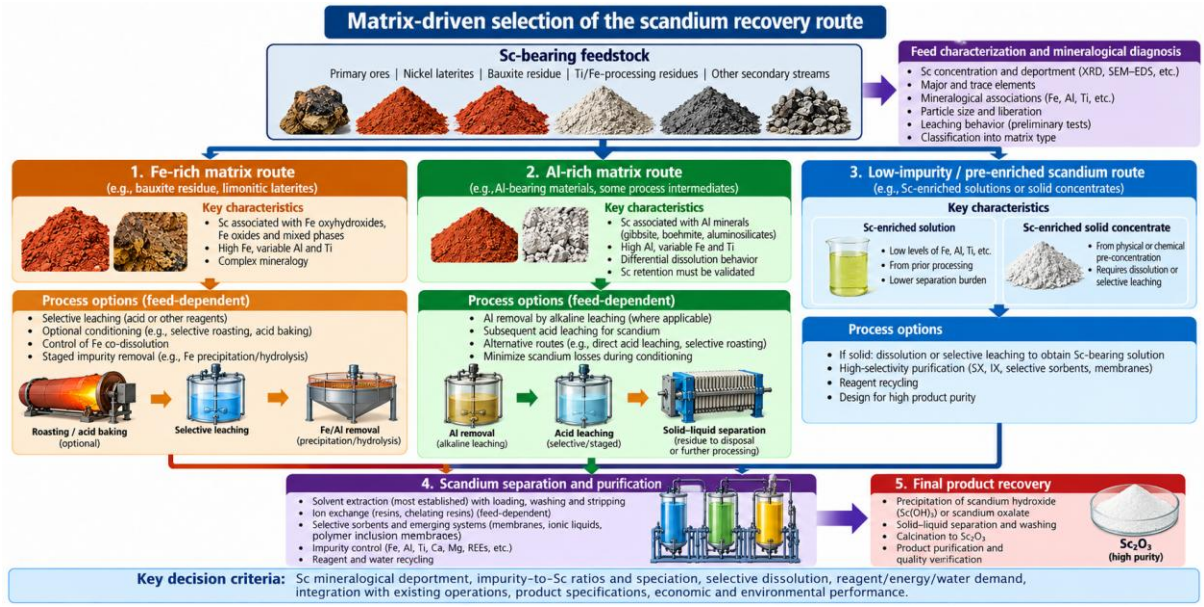


Figure 2. Matrix-driven selection of scandium recovery and purification routes
Note. Original synthesis by the author based on the literature discussed in this review.

Speciation also matters. Sulfate, chloride, nitrate, and phosphate media can change extraction equilibria and stripping behavior, while hydrolysis and polymeric Fe species can change both separation and filtration. For this reason, treat results from synthetic single-metal solutions as mechanism studies rather than direct evidence of plant performance. Industrial process comparison requires real or realistically simulated multi-component liquors, repeated cycles, and mass balances that close across extraction, scrub, strip, precipitation, and recycle.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Interpreting acid–base conditions also requires distinguishing between free acidity and measured pH, particularly in concentrated metal-sulfate liquors that can hydrolyze or buffer during conditioning. Similarly, jarosite precipitation can remove Fe but raises questions about entrainment, contaminant deportment, wash-water demand, and residue stability. These are relevant mechanistic analogs rather than validated scandium-removal factors (Pereira, 2026f, 2026j).

Several studies explicitly address co-recovery or rejection of iron, aluminum, and titanium during scandium concentration and product finishing. They confirm the importance of selecting the location of each impurity-removal step and tracking scandium entrainment through precipitation, washing, and residue handling (Bu et al., 2026; Cao et al., 2025; Gao et al., 2024; Habibi et al., 2023; Hu et al., 2020).

Studies of oxide production and purification clarify that product purity must be established by the final material assay, not inferred from leach or extraction recovery. Precipitation chemistry and calcination introduce additional routes for impurity carryover (Bu et al., 2026; Cao et al., 2025; Gao et al., 2024; Habibi et al., 2023; Hu et al., 2020).

Studies of oxide finishing, crystal formation, and impurity rejection establish separate quality-control requirements that leach extraction alone cannot infer. Product assays should specify both total purity and critical trace contaminants (Wang et al., 2025; Xiao et al., 2024; Zhang et al., 2021; Zhang et al., 2026; Zhou et al., 2021).

Complementary scandium-recovery studies further reinforce the distinction between a high-purity isolated product and a demonstrated process-wide yield: the latter requires reporting losses at every separation, wash, and finishing step (Zhou et al., 2022).

9. Process integration and flowsheet design

A scandium circuit should be designed around the host plant. In alumina operations, this means locating the circuit where Sc is enriched but before residue chemistry becomes unnecessarily complex. In Ni–Co laterite processing, it means recovering Sc from HPAL/NAPL liquors or intermediate precipitates without reducing Ni and Co recovery. In Ti

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

or Fe operations, it means using existing acid, roasting, smelting, or waste-treatment infrastructure where possible. This integration perspective is the main reason by-product recovery can be more credible than a stand-alone scandium plant even when the original feed grade is low.

The flowsheet must also preserve optionality. For example, Fe removal can occur before leaching through reduction/smelting, during leaching through selective conditions, or after leaching through precipitation or solvent extraction. Each location changes acid consumption, energy demand, residue mass, and process complexity. A critical review should therefore compare where an impurity is removed, not merely whether it is removed.

An integrated acid balance should consider not only fresh reagent addition but also acid bound in neutralization precipitates, dissolved sulfate, wash streams, and opportunities for regeneration. Nickel-laterite sulfuric-acid regeneration literature provides a process-integration framework relevant to proposed scandium circuits, but it does not, by itself, demonstrate commercial acid-recycle performance for scandium (Pereira, 2026n).

Figure 3 shows an integration hierarchy and the five metrics to report when comparing scandium flowsheets: recovery, selectivity, resource intensity, operability, and circularity.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

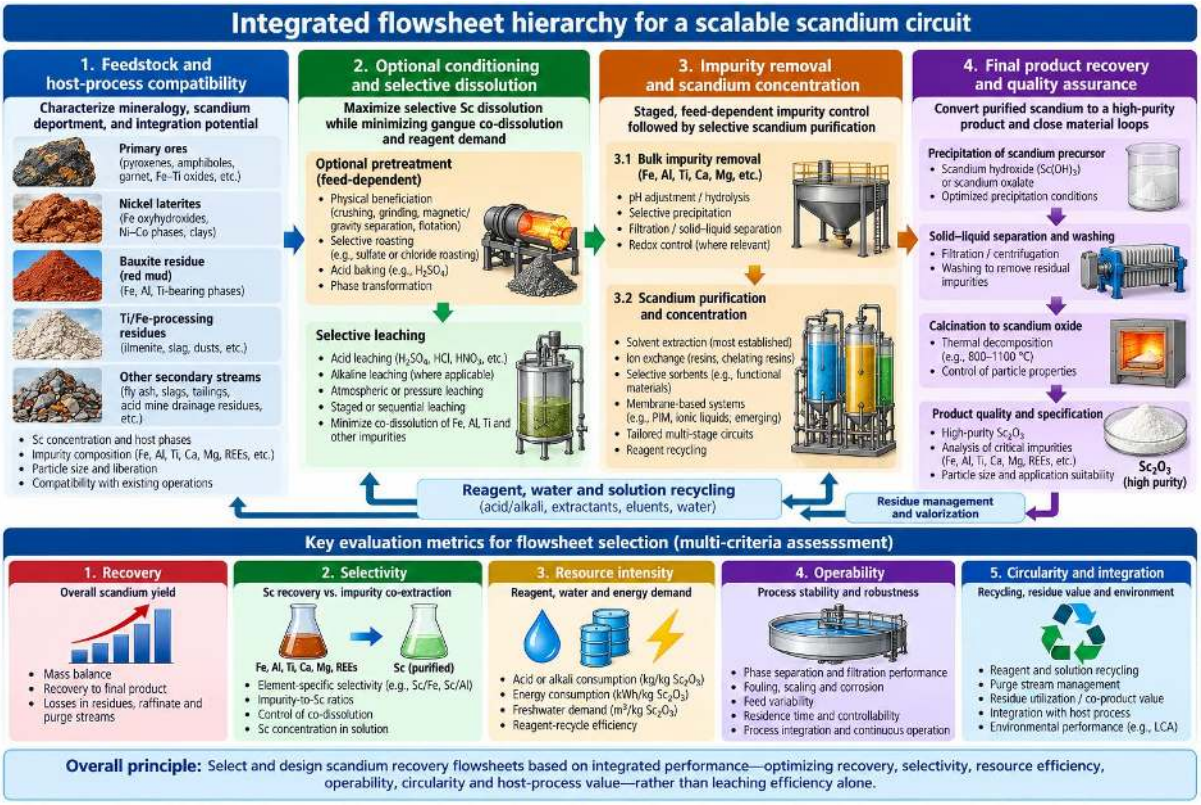


Figure 3. Integrated flowsheet hierarchy and scale-up metrics for scandium recovery
Note. Original synthesis by the author based on the literature discussed in this review.

The hierarchy also clarifies why a flowsheet with a lower single-stage extraction can outperform one with a higher extraction. If the selective route reduces acid use, Fe transfer, organic loading, neutralization sludge, and stripping severity, the overall plant recovery and cost may be superior after recycle streams are included. This is the distinction between optimizing a reactor and optimizing a value chain.

Process-integration and scale-up reports increasingly combine leaching, liquor conditioning, selective extraction, and product preparation or test circuits at larger scale. Such reports carry stronger engineering relevance than disconnected batch optimizations, particularly when coupled to an existing alumina, nickel, or titanium operation (Davris et al., 2021; Hatzilyberis et al., 2020; Hedwig et al., 2023; Rychkov et al., 2021).

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

10. Techno-economic and scale-up assessment

The original argument that scandium is "only viable as a by-product" is directionally useful but too absolute. The economic advantage of by-product recovery arises because the host process supplies ore mining, primary size reduction, utilities, residue handling, and often the first extraction step. However, stand-alone opportunities may still be possible where ore grade, mineralogy, jurisdiction, and product value justify dedicated infrastructure. The defensible conclusion is that current near-term scale-up is strongly favored by integrated recovery from existing high-throughput operations.

Techno-economic analysis (TEA) should distinguish fixed infrastructure from incremental scandium-circuit costs. For red mud, major cost drivers include drying or dewatering, acid or roasting reagents, heating, filtration, Fe/Al control, SX inventory, stripping, precipitation, calcination, and treatment of secondary residues. For laterite intermediates, the key question is whether Sc can be captured from a small stream with minimal effect on the main Ni–Co circuit. In both cases, reagent recycle and saleable co-products can dominate the economics.

Scandium markets are small relative to bulk-metal markets, which creates an additional scale-up constraint: a technically successful process can oversupply the market if deployed at very large host-plant throughput. Current commodity information continues to describe scandium as a relatively small-volume market with production linked to by-product streams (U.S. Geological Survey, 2026). Therefore, economic models should include market absorption, ramp-up scenarios, and product qualification rather than assuming that all recovered Sc_2O_3can be sold at a single long-term price.

For host-integrated recovery, incremental CAPEX and OPEX must be distinguished from existing shared/sunk infrastructure, with explicit allocation of utilities, waste treatment, and any host-plant throughput effects. Measure the changes in primary Ni and Co recoveries and host-product quality before crediting the Sc circuit. Market scenarios should include customer qualification delays, ramp-up, price sensitivity, off-take uncertainty, and throttled saleable output rather than assigning one fixed price to all theoretical production. The

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

economic functional unit should be one kilogram of qualified Sc_2O_3, with host-plant boundary assumptions reported (U.S. Geological Survey, 2026).

Table 4 lists the minimum scale-up metrics that should accompany a credible process claim.

Table 4. Minimum technical and economic metrics for evaluating scandium flowsheets

Metric family	What should be reported	Why it matters
Feed variability	Sc grade, mineralogy, moisture, Fe/Al/Ti/Ca/Si, particle size	Determines reagent demand and process robustness
Extraction and selectivity	Sc recovery plus Sc/Fe and Sc/Al rejection	Prevents misleading ranking by extraction alone
Reagent intensity	kg acid/alkali per t feed and per kg Sc product; extractant losses	Direct OPEX and environmental burden
Water and solids handling	L/t feed, wash ratio, filtration rate, residue moisture	Often controls practical throughput and tailings load
Energy intensity	Roasting/smelting duty, pressure-leach duty, calcination	Major OPEX and carbon driver
Separation performance	Stage count, phase ratio, scrub/strip efficiency, resin cycles	Translates equilibrium data into circuit size
Product quality	Sc_2O_3purity, impurity specification, morphology	Controls saleability and qualification
Integration impact	Effect on Al, Ni, Co, Ti, or Fe recovery and product quality	Protects host-plant economics
Recycle closure	Acid, alkali, water, solvent, and bleed streams	Determines steady-state accumulation and waste generation
Market basis	Recoverable annual Sc relative to realistic market uptake	Avoids overvaluing large theoretical production
Overall product recovery	Feed-to-qualified Sc_2O_3recovery; stagewise losses and recycle-adjusted balance	Report % overall and stage-level boundaries

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Impurity intensity	Fe, Al, Ti, Ca, Si, Zr and relevant REEs entering purification per recovered Sc	kg impurity/kg recovered Sc; disclose inventories
Recycle stability	Acid/alkali/water recycle, SX/IX cycle retention, solvent/eluent loss and bleed	Make-up, purge and recoverable fraction by cycle
Product qualification	Final Sc_2O_3assay, critical impurities, stability and customer acceptance	Defined assay and trace-element limits

Note. The table is a reviewer-oriented scale-up checklist intended to prevent unit-operation metrics from being mistaken for industrial viability.

Demand, material-flow, and end-use investigations place an independent boundary on technically feasible scandium production. Oxide, alloy, or fuel-cell applications may define product specifications, but they alone do not establish market absorption for a new high-throughput recovery circuit (Arifin et al., 2023; Córdova González et al., 2020; Li et al., 2026; Phoung et al., 2023; Sverdrup, 2024).

For supply scenarios, forecast assumptions, qualification times, and price sensitivity should be treated explicitly. Downstream functional-material studies establish possible uses rather than extractive-metallurgy evidence (Zakaria, 2021; Zhigachev et al., 2021).

11. Environmental performance and circularity

Recovering scandium from waste does not automatically make a process environmentally superior. The environmental benefit depends on whether recovery reduces long-term residue liability without creating disproportionate acid consumption, neutralization sludge, high-temperature energy demand, solvent losses, or contaminated secondary residues. Circularity must therefore be evaluated as a mass-balance property rather than as a feed-source label.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Bauxite residue is a strong circular-economy candidate because it is already accumulated at large scale and contains multiple potentially valuable components. Nevertheless, aggressive selective metal recovery can leave a residue that is more acidic, salt-rich, or harder to reuse. A better strategy is to sequence recovery so that Fe, Al, Ti, rare earths, and construction-material uses remain compatible where possible. The same principle applies to laterite operations: scandium should add value without increasing Ni–Co residue risk or consuming excessive neutralization reagents.

Emerging solvent systems should be assessed with the same discipline. Ionic liquids and membrane systems can reduce volatility or organic-phase inventory, but they may introduce high embodied energy, complex synthesis, difficult regeneration, or specialized waste streams. Environmental performance should therefore include solvent manufacture, recovery efficiency, lifetime, and end-of-life treatment, not only extraction selectivity.

Environmental assessment contributes a second independent screening dimension, including energy use, acids and neutralizing agents, waste treatment, and the consequences of secondary-residue generation. Comparative studies need equivalent system boundaries and co-product allocation before impact differences can be interpreted (Cao et al., 2025; Hengevoss et al., 2024; Wang et al., 2020).

For comparable life-cycle results, report the same functional unit and system boundary across options, disclose allocation of shared host-process burdens and coproduct credits, and avoid double counting avoided disposal and product credit. Include acid and alkali production, solvent/resin/membrane replacement, thermal energy, water treatment, neutralization sludge, purge, and secondary-residue management. Circularity claims require quantitative material balances rather than classification of the feed as waste.

12. Research gaps and a decision framework for future development

Four research gaps are especially important. First, mineralogical data and hydrometallurgical data are still too often generated in separate studies. Phase-specific scandium deportment should be measured before and after each major process step so that

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

extraction can be attributed to host-phase transformation rather than only to bulk dissolution. Second, real-liquor separation data remain less common than synthetic-solution data, especially for long-term resin, membrane, and solvent systems. Third, pilot-scale studies need stronger closure of water, acid, alkali, organic, and impurity recycle loops. Fourth, techno-economic and environmental analyses should be based on steady-state flowsheets rather than batch reagent consumption.

A practical decision framework follows from these gaps. If Sc is structurally dispersed in Fe oxides, the first question is whether Fe should be removed thermally, selectively left undissolved, or precipitated after leaching. If Sc is concentrated in an Al-rich intermediate, selective alkaline Al removal may be preferable before an acid Sc leach. If Sc is already present in a relatively clean process liquor, direct SX, IX, or membrane polishing becomes more attractive. The route should then be screened against host-process compatibility, impurity rejection, reagent recycle, and final Sc_2O_3specification.

The most valuable future studies will therefore not necessarily report the highest scandium extraction. They will report a lower-uncertainty process: representative feed variability, phase-specific mineralogy, countercurrent separation, repeated recycle, realistic solid–liquid ratios, stable filtration, complete product analysis, and a transparent mass and energy balance. These data are what allow a laboratory result to move from chemical feasibility to process credibility.

Additional investigations of scandium recovery illuminate specialized processing possibilities and unresolved mechanisms. Their applicability depends on the feed, solution chemistry, and demonstrated compatibility with upstream and downstream operations (Gentzmann et al., 2021; Kallio et al., 2022a; Kumaş et al., 2026; Wang et al., 2025; Zhao et al., 2024).

13. Conclusions

Scandium recovery is fundamentally a problem of dispersion, impurity management, and process integration. High extraction is achievable from many primary and secondary

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

resources, but extraction alone does not establish a viable flowsheet. The decisive question is whether scandium can be transferred into a manageable stream while Fe, Al, Ti, Ca, Si, and other competing elements are rejected at the lowest overall cost in acid, alkali, energy, water, and separation capacity.

Physical beneficiation has a limited direct role when scandium is structurally incorporated or finely disseminated, but indirect pre-concentration through host-phase partitioning can be valuable. Thermal pretreatment, selective acid leaching, alkaline impurity removal, and integration with pressure leaching are best viewed as tools for controlling the impurity-to-Sc ratio entering purification. Solvent extraction remains the most mature large-scale separation method, while ion exchange, membranes, tailored sorbents, and ionic-liquid systems broaden the options for dilute or difficult streams.

The strongest near-term opportunities are integrated by-product circuits associated with existing alumina, nickel–cobalt, and titanium value chains. Future scale-up should prioritize mineralogy-informed flowsheet selection, real-liquor countercurrent testing, reagent recycle, product qualification, and techno-economic analysis at steady state. A successful scandium process will be the one that creates the highest value from the entire host stream, not the one that reports the highest isolated extraction percentage.

Declarations

Funding: This work received no external funding.

Conflicts of interest: The author declares no conflict of interest.

Data availability: No new experimental datasets were generated. The review is based on published literature.

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

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

References

Agrawal, S., & Dhawan, N. (2021). Microwave acid baking of red mud for extraction of titanium and scandium values. Hydrometallurgy, 204, 105704. https://doi.org/10.1016/j.hydromet.2021.105704.

Alguacil, F. J., & Robla, J. I. (2023). Recent work on the recovery of rare earths using ionic liquids and deep eutectic solvents. Minerals, 13(10), 1288. https://doi.org/10.3390/min13101288

Anawati, J., & Azimi, G. (2022). Integrated carbothermic smelting–acid baking–water leaching process for extraction of scandium, aluminum, and iron from bauxite residue. Journal of Cleaner Production, 330, 129905. https://doi.org/10.1016/j.jclepro.2021.129905.

Arifin, N. A., Afifi, A. A., Samreen, A., Hafriz, R. S. R. M., & Muchtar, A. (2023). Characteristic and challenges of scandia stabilized zirconia as solid oxide fuel cell material—In depth review. Solid State Ionics, 399, 116302. https://doi.org/10.1016/j.ssi.2023.116302.

Babain, V., Kazanina, D., Alyapyshev, M., Kenf, E., Tkachenko, L., Nechaev, A., Porsev, V., Evarestov, R., Gurzhiy, V., & Kirsanov, D. (2026). Extraction of scandium and lanthanides with N,O-hybrid ligands. Hydrometallurgy, 245, 106867. https://doi.org/10.1016/j.hydromet.2026.106867.

Beland, C. M. J., & Williams-Jones, A. E. (2023). The genesis of a potential scandium ore deposit at Crater Lake, Canada. Chemical Geology, 615, 121223. https://doi.org/10.1016/j.chemgeo.2022.121223.

Botelho Junior, A. B., Espinosa, D. C. R., & Tenório, J. A. S. (2021a). Characterization of bauxite residue from a press filter system: Comparative study and challenges for scandium extraction. Mining, Metallurgy & Exploration, 38(1), 161–176. https://doi.org/10.1007/s42461-020-00333-3.

Botelho Junior, A. B., Espinosa, D. C. R., & Tenório, J. A. S. (2021b). Selective separation of Sc(III) and Zr(IV) from the leaching of bauxite residue using trialkylphosphine acids, tertiary amine, tri-butyl phosphate and their mixtures. Separation and Purification Technology, 279, 119798. https://doi.org/10.1016/j.seppur.2021.119798.

Botelho Junior, A. B., Espinosa, D. C. R., Vaughan, J., & Tenório, J. A. S. (2021). Recovery of scandium from various sources: A critical review of the state of the art and future prospects. Minerals Engineering, 172, 107148. https://doi.org/10.1016/j.mineng.2021.107148

Bu, Y., Sun, A., Deng, X., Yin, Z., Guan, Q., Zhou, S., Wang, W., Zhang, H., & Zhang, C. (2026). Mechanistic study on the extraction of rare earth element scandium from sulfate process-based titanium dioxide sulfuric acid wastewater. Minerals Engineering, 247, 110484. https://doi.org/10.1016/j.mineng.2026.110484.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Cao, W., Hua, J., Jin, X., He, M., Xin, Y., & Liu, W. (2024). Efficient extraction and separation of scandium from scandium-bearing solid waste and acid by synergistically leaching followed by solvent extraction. Molecules, 29(19), 4766. https://doi.org/10.3390/molecules29194766.

Cao, W., Liu, W., Yang, Z., He, M., Qin, Z., Jiang, Y., Liu, Q., Xin, Y., Lv, X., & Xie, H. (2026). Extraction of scandium from waste-acid leachate using D2EHPA–HEHEHP system: Process optimization and mechanistic insights. Hydrometallurgy, 242, 106673. https://doi.org/10.1016/j.hydromet.2026.106673.

Cao, W., Yang, Z., Rohani, S., He, M., Gao, Y., Jin, X., Qin, Z., Jiang, Y., Liu, Q., Lv, X., Xin, Y., & Liu, W. (2025). Towards sustainable scandium production: Advances in extraction and solvent extraction technologies. Separation and Purification Technology, 375, 133795. https://doi.org/10.1016/j.seppur.2025.133795.

Cao, X., Zhang, T.-A., Zhang, W., & Lv, G. (2020). Solvent extraction of Sc(III) by D2EHPA/TBP from the leaching solution of vanadium slag. Metals, 10(6), 790. https://doi.org/10.3390/met10060790.

Cao, Y., Sun, B., Jin, B., Yang, J., Xu, X., Wang, F., Zhang, Y., Chen, Q., He, L., & Zhong, X. (2025). Extraction behaviors of aluminum and scandium from Sc-bearing aluminum residue by cascade leaching in NaOH and HNO_3aqueous solution. Process Safety and Environmental Protection, 198, 107165. https://doi.org/10.1016/j.psep.2025.107165.

Chassé, M., Griffin, W. L., O'Reilly, S. Y., & Calas, G. (2017). Scandium speciation in a world-class lateritic deposit. Geochemical Perspectives Letters, 3, 105–114. https://doi.org/10.7185/geochemlet.1711

Chen, Y., Ma, S., Ning, S., Zhong, Y., Wang, X., Fujita, T., & Wei, Y. (2021). Highly efficient recovery and purification of scandium from the waste sulfuric acid solution from titanium dioxide production by solvent extraction. Journal of Environmental Chemical Engineering, 9(5), 106226. https://doi.org/10.1016/j.jece.2021.106226.

Chen, Y., Wu, H., Xu, B., & Zhang, W. (2025). Selective extraction process of scandium from nickel laterite waste through hydrometallurgy. RSC Advances, 15, 2250–2259. https://doi.org/10.1039/D4RA07520J.

Choudhary, A. K. S., Kumar, S., & Maity, S. (2024). A study on speciation and enrichment of rare earth elements (REE) by sequential extraction from a potential coal fly ash resource and its role in REE extractability. Hydrometallurgy, 224, 106256. https://doi.org/10.1016/j.hydromet.2023.106256.

Córdova González, L., Bor, T., de Smit, M., Carmignato, S., Campos Gómez, M., & Tinga, T. (2020). Effects of powder reuse on the microstructure and mechanical behaviour of Al-Mg-Sc-Zr alloy processed by LPBF. Additive Manufacturing, 36, 101625. https://doi.org/10.1016/j.addma.2020.101625.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Cunningham, S., Sauber, M. E., & Azimi, G. (2026). Integrated caustic cracking and supercritical CO_2extraction for scandium and rare earths recovery from refractory silicate ores. Minerals Engineering, 240, 110160. https://doi.org/10.1016/j.mineng.2026.110160.

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

Ding, W., Bao, S., Zhang, Y., & Xiao, J. (2023). Efficient selective extraction of scandium from red mud. Mineral Processing and Extractive Metallurgy Review, 44(4), 304–312. https://doi.org/10.1080/08827508.2022.2047044.

Falah, F. N., Kurniawan, K., Ichlas, Z. T., & Mubarok, M. Z. (2026). Recovery of scandium from bauxite residue using sulfation roasting-assisted water leaching process. Mineral Processing and Extractive Metallurgy Review, 47(2), 211–225. https://doi.org/10.1080/08827508.2025.2454694.

Gangadari, T., Rezaee, M., & Pisupati, S. V. (2025). A critical review on selective separation of scandium and iron from aqueous solutions. Hydrometallurgy, 236, 106514. https://doi.org/10.1016/j.hydromet.2025.106514.

Gao, S., Song, B., Wang, S., Vaughan, J., Zhu, Z., & Peng, H. (2024). A low-cost process for complete utilization of bauxite residue. Journal of Environmental Management, 356, 120751. https://doi.org/10.1016/j.jenvman.2024.120751.

Gentzmann, M. C., Paul, A., Serrano, J., & Adam, C. (2022). Understanding scandium leaching from bauxite residues of different geological backgrounds using statistical design of experiments. Journal of Geochemical Exploration, 240, 107041. https://doi.org/10.1016/j.gexplo.2022.107041.

Gentzmann, M. C., Schraut, K., Vogel, C., Gäbler, H.-E., Huthwelker, T., & Adam, C. (2021). Investigation of scandium in bauxite residues of different origin. Applied Geochemistry, 126, 104898. https://doi.org/10.1016/j.apgeochem.2021.104898.

Grigorieva, N. A., Fleitlikh, I. Yu., Logutenko, O. A., Ivanenko, T. Yu., & Novikova, S. A. (2025). Scandium extraction from sulfate media with di-(2-ethylhexyl) phosphoric acid in decane or toluene mixed with proton-donor additives. Hydrometallurgy, 232, 106435. https://doi.org/10.1016/j.hydromet.2024.106435.

Gülyüz, N. (2024). Preliminary study of scandium enrichment in Çaldağ-Manisa lateritic Ni-Co Deposit, Western Anatolia. Yerbilimleri, 45(3), 185–206. https://doi.org/10.17824/yerbilimleri.1491285.

Habibi, H., Mokmeli, M., Shakibania, S., Pirouzan, D., & Pourkarimi, Z. (2023). Separation and recovery of titanium and scandium from the red mud. Separation and Purification Technology, 317, 123882. https://doi.org/10.1016/j.seppur.2023.123882.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Hajmohammadi, H., Jafari, A. H., & Eskandari Nasab, M. (2020). Scandium recovery from raffinate copper leach solution as potential new source with ion exchange method. Transactions of Nonferrous Metals Society of China, 30(11), 3103–3113. https://doi.org/10.1016/S1003-6326(20)65446-2.

Hatzilyberis, K., Tsakanika, L.-A., Lymperopoulou, T., Georgiou, P., Kiskira, K., Tsopelas, F., Ochsenkühn, K.-M., & Ochsenkühn-Petropoulou, M. (2020). Design of an advanced hydrometallurgy process for the intensified and optimized industrial recovery of scandium from bauxite residue. Chemical Engineering and Processing: Process Intensification, 155, 108015. https://doi.org/10.1016/j.cep.2020.108015.

Hedwig, S., Yagmurlu, B., Huang, D., von Arx, O., Dittrich, C., Constable, E. C., Friedrich, B., & Lenz, M. (2022). Nanofiltration-enhanced solvent extraction of scandium from TiO_2acid waste. ACS Sustainable Chemistry & Engineering, 10, 6063–6071. https://doi.org/10.1021/acssuschemeng.2c01056.

Hedwig, S., Yagmurlu, B., Peters, E. M., Misev, V., Hengevoss, D., Dittrich, C., Forsberg, K., Constable, E. C., & Lenz, M. (2023). From trace to pure: Pilot-scale scandium recovery from TiO_2acid waste. ACS Sustainable Chemistry & Engineering, 11, 5883–5894. https://doi.org/10.1021/acssuschemeng.2c06979.

Hengevoss, D., Misev, V., Feigl, V., Fekete-Kertész, I., Molnár, M., Balomenos, E., Davris, P., Hugi, C., & Lenz, M. (2024). Life cycle assessment of a novel production route for scandium recovery from bauxite residues. Cleaner Waste Systems, 7, 100129. https://doi.org/10.1016/j.clwas.2024.100129.

Hu, J., Zou, D., Chen, J., & Li, D. (2020). A novel synergistic extraction system for the recovery of scandium(III) by Cyanex 272 and Cyanex 923 in sulfuric acid medium. Separation and Purification Technology, 233, 115977. https://doi.org/10.1016/j.seppur.2019.115977.

Ichlas, Z. T., Jones, S. A., Ibana, D. C., Lee, G.-G., & Alorro, R. D. (2022). Technospheric mining of scandium from hydrometallurgical tailings of nickel laterite processing: Selection of lixiviant and optimization of leaching variables. Minerals Engineering, 179, 107436. https://doi.org/10.1016/j.mineng.2022.107436.

Ignatov, P. A., Eremenko, R. U., Tolstov, A. V., & Ovchinnikov, I. M. (2023). Scandium ore occurrences in the ancient weathering crust in the Nakyn Kimberlite Field of Yakutia. Geology of Ore Deposits, 65(6), 579–588. https://doi.org/10.31857/S0016777023060059.

Jammulamadaka, H. S., Rezaee, M., & Pisupati, S. V. (2025). Unlocking scandium from red mud: A critical review of challenges, opportunities, and recovery methods. Hydrometallurgy, 236, 106522. https://doi.org/10.1016/j.hydromet.2025.106522

Kallio, R., Lassi, U., Kauppinen, T., Holappa, E., Christophliemk, M., Luukkanen, S., Tanskanen, P., & Fabritius, T. (2022). Leaching characteristics of Sc-enriched, Fe-

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

depleted acidic slags. Minerals Engineering, 189, 107901. https://doi.org/10.1016/j.mineng.2022.107901.

Kallio, R., Tanskanen, P., & Luukkanen, S. (2021). Magnetic preconcentration and process mineralogical study of the Kiviniemi Sc-enriched ferrodiorite, eastern Finland. Minerals, 11(9), 966. https://doi.org/10.3390/min11090966.

Kallio, R., Tanskanen, P., Heikkinen, E.-P., Kokkonen, T., Luukkanen, S., & Fabritius, T. (2022a). Reduction characteristics of Kiviniemi ferrous scandium concentrate. Minerals Engineering, 177, 107369. https://doi.org/10.1016/j.mineng.2021.107369.

Kallio, R., Tanskanen, P., Heikkinen, E.-P., Kokkonen, T., Luukkanen, S., & Fabritius, T. (2022b). Slag modification in reduction of Kiviniemi ferrous scandium concentrates. Metals, 12(5), 709. https://doi.org/10.3390/met12050709.

Kanekaputra, M. R., & Mubarok, M. Z. (2023). Extraction of scandium from bauxite residue by high-pressure leaching in sulfuric acid solution. Heliyon, 9(3), e14652. https://doi.org/10.1016/j.heliyon.2023.e14652.

Kim, J., & Azimi, G. (2020). Recovery of scandium and neodymium from blast furnace slag using acid baking–water leaching. RSC Advances, 10, 31936–31946. https://doi.org/10.1039/D0RA05797E.

Koller, A. J., Wang, L., Deluca, M., Glaser, O., Robis, M. J., Mixdorf, J. C., Chernysheva, M. N., Guzei, I. A., Aluicio-Sarduy, E., Barnhart, T. E., Engle, J. W., & Boros, E. (2023). De novo approaches to the solid-phase separation of titanium(IV) and scandium(III). Inorganic Chemistry, 62(50), 20655–20665. https://doi.org/10.1021/acs.inorgchem.3c01493.

Kumaş, C., Prasetia, H., Astuti, W., Sumardi, S., Mufakhir, F. R., & Fasya, M. R. F. (2026). Red mud as a source of scandium: A review. Journal of Rare Earths, 44(6), 1693–1708. https://doi.org/10.1016/j.jre.2025.08.008.

Lei, Q., He, D., Zhou, K., Zhang, X., Peng, C., & Chen, W. (2021). Separation and recovery of scandium and titanium from red mud leaching liquor through a neutralization precipitation–acid leaching approach. Journal of Rare Earths, 39(9), 1126–1132. https://doi.org/10.1016/j.jre.2020.07.030.

Li, C., Ramasamy, D. L., Sillanpää, M., & Repo, E. (2021). Separation and concentration of rare earth elements from wastewater using electrodialysis technology. Separation and Purification Technology, 254, 117442. https://doi.org/10.1016/j.seppur.2020.117442.

Li, F., Li, X., Shi, L., Li, X., Liang, D., Wei, Y., & Fujita, T. (2024). Solvent extraction of scandium from leaching solution of red mud roasted with ammonium sulfate using D2EHPA/TBP. Journal of Rare Earths, 42(10), 1943–1949. https://doi.org/10.1016/j.jre.2023.12.010.

Li, Q.-F., Wu, Y.-D., Wang, L., Lai, D., Guo, Q.-M., Shi, Z.-B., Zhao, S., Wang, Q.-Q., & Chen, W.-Q. (2026). Global material flow analysis of scandium from 2000 to 2024:

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Insights into supply, stocks, and circularity gaps. Resources, Conservation and Recycling, 232, 108986. https://doi.org/10.1016/j.resconrec.2026.108986.

Li, W., Zhou, M.-F., Wang, N., & Gu, H. (2025). Selective extraction of scandium from bauxite residue (red mud) utilizing iron sulfate roasting followed by water leaching. Separation and Purification Technology, 359, 130634. https://doi.org/10.1016/j.seppur.2024.130634.

Lin, P.-X., Atayde, E. C., Wu, P.-H., Li, Y.-P., Chen, P.-J., & Wu, K. C.-W. (2026). Mechanistic insights into the selective recovery of aqueous scandium using iron-based metal–organic frameworks. Journal of Environmental Chemical Engineering, 14(5), 124417. https://doi.org/10.1016/j.jece.2026.124417.

Liu, S., Fan, H.-R., Santosh, M., Liu, X., Wang, Q.-W., & Butcher, A. R. (2023). Geological resources of scandium: A review from a Chinese perspective. International Geology Review, 65, 3065–3086. https://doi.org/10.1080/00206814.2023.2169842.

Liu, S.-L., Liu, X., Fan, H.-R., Butcher, A. R., Lahaye, Y., Michallik, R. M., Jolis, E. M., Lukkari, S., Yang, K.-F., Wang, Q.-W., Qiu, Z.-J., & She, H.-D. (2025). Scandium distribution in the Bayan Obo REE-Nb-Fe deposit, China: A multi-scale geochemical perspective. Ore Geology Reviews, 177, 106466. https://doi.org/10.1016/j.oregeorev.2025.106466.

Madhavi, K., Shekhar, R., Sai Krishna, D., & Dash, K. (2026). Development of an extraction method for scandium from secondary resources using a synthesized deep eutectic solvent for industrial waste valorization. Hydrometallurgy, 244, 106813. https://doi.org/10.1016/j.hydromet.2026.106813.

Mao, S., Huang, K., Lu, Y., Shan, X., Dong, H., Zhai, R., & Zhou, T. (2025). Selectively recovering scandium from red mud by a combination process of sulfation roasting and water leaching. Minerals Engineering, 228, 109357. https://doi.org/10.1016/j.mineng.2025.109357.

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

Mikeli, E., Balomenos, E., & Panias, D. (2021). Utilizing recyclable task-specific ionic liquid for selective leaching and refining of scandium from bauxite residue. Molecules, 26(4), 818. https://doi.org/10.3390/molecules26040818.

Mikeli, E., Marinos, D., Toli, A., Pilichou, A., Balomenos, E., & Panias, D. (2022). Use of ion-exchange resins to adsorb scandium from titanium industry's chloride acidic solution. Metals, 12(5), 864. https://doi.org/10.3390/met12050864.

Mostajeran, M., Bondy, J.-M., Reynier, N., & Cameron, R. (2021). Mining value from waste: Scandium and rare earth elements selective recovery from coal fly ash leach solutions. Minerals Engineering, 173, 107091. https://doi.org/10.1016/j.mineng.2021.107091.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Napol'skikh, J., Shoppert, A., Loginova, I., Kirillov, S., & Valeev, D. (2024). Selective recovery of scandium from sulfate solution of bauxite residue leaching using Purolite MTS9580 ion-exchange sorption. Metals, 14(2), 234. https://doi.org/10.3390/met14020234.

Pan, J., Nie, T., Vaziri Hassas, B., Rezaee, M., Wen, Z., & Zhou, C. (2020). Recovery of rare earth elements from coal fly ash by integrated physical separation and acid leaching. Chemosphere, 248, 126112. https://doi.org/10.1016/j.chemosphere.2020.126112.

Pan, J., Vaziri Hassas, B., Rezaee, M., Zhou, C., & Pisupati, S. V. (2021). Recovery of rare earth elements from coal fly ash through sequential chemical roasting, water leaching, and acid leaching processes. Journal of Cleaner Production, 284, 124725. https://doi.org/10.1016/j.jclepro.2020.124725.

Peng, X., Li, L., Zhang, M., Cui, Y., Jiang, X., & Sun, G. (2023). Preparation of ultra-high pure scandium oxide with crude product from titanium white waste acid. Journal of Rare Earths, 41(5), 764–770. https://doi.org/10.1016/j.jre.2022.04.006.

Pereira, A. C. (2026a). Balancing nickel recovery, iron dissolution, acid dosage, and residence time in atmospheric sulfuric acid leaching of a ferruginous lateritic nickel ore. Journal International Review of Research Studies, 1(9), 1–30. https://doi.org/10.66104/dempc459

Pereira, A. C. (2026b). Bauxite Residue (Red Mud) from the Bayer Process: A Critical Review of Management, Safe Storage, Valorization, Critical-Metal Recovery, and Industrial Integration. Journal International Review of Research Studies, 1(10 - October), 1–46. https://doi.org/10.66104/90twks68

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

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

Pereira, A. C. (2026e). Engineering Sulfate Stability for Metal Recovery from Bauxite Residue: A Critical Review of Selective Sulfation, Roasting, Water Leaching, and Process Integration. Nexus Science Review, 1(05 - October), 1-47. https://doi.org/10.66104/x41pvm52

Pereira, A. C. (2026f). Free acidity in hydrometallurgy is not pH: A critical review of measurement methods, errors, and process consequences. International Journal of Current Science Research and Review, 9(3), 1233–1260. https://doi.org/10.47191/ijcsrr/V9-i3-14

Pereira, A. C. (2026g). From mine to saleable product: A feasibility framework for atmospheric leaching of nickel laterites—A critical review. RECIMA21 – Revista

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Científica Multidisciplinar, 7(9), e798955. https://doi.org/10.47820/recima21.v7i9.8955

Pereira, A. C. (2026h). From mineralogy to process design: The role of particle size distribution on nickel extraction kinetics and hydrometallurgical route selection in a limonitic laterite. IKR Journal of Engineering and Technology, 2, 1–17. https://doi.org/10.5281/zenodo.21209619

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

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

Pereira, A. C. (2026k). Linking empirical nickel laterite leaching responses to preliminary economic performance: Trade-offs among Ni–Co extraction, acid dosage, Fe dissolution, and residence time. International Journal of Current Science Research and Review, 9(7), 3865–3879. https://doi.org/10.47191/ijcsrr/V9-i7-27

Pereira, A. C. (2026l). Mechanical activation in metallurgical processing: Mechanisms, applications and industrial perspectives. IKR Journal of Engineering and Technology, 2, 1–34.

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

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

Phoung, S., Williams, E., Gaustad, G., & Gupta, A. (2023). Exploring global supply and demand of scandium oxide in 2030. Journal of Cleaner Production, 401, 136673. https://doi.org/10.1016/j.jclepro.2023.136673.

Qin, H.-B., Yang, S., Tanaka, M., Sanematsu, K., Arcilla, C., & Takahashi, Y. (2020). Chemical speciation of scandium and yttrium in laterites: New insights into the control of their partitioning behaviors. Chemical Geology, 552, 119771. https://doi.org/10.1016/j.chemgeo.2020.119771.

Qin, H.-B., Yang, S., Tanaka, M., Sanematsu, K., Arcilla, C., & Takahashi, Y. (2021). Scandium immobilization by goethite: Surface adsorption versus structural incorporation. Geochimica et Cosmochimica Acta, 294, 255–272. https://doi.org/10.1016/j.gca.2020.11.020.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Rout, P. C., & Sarangi, K. (2022). A systematic study on extraction and separation of scandium using phosphinic acid by both solvent extraction and hollow fibre membrane. Mineral Processing and Extractive Metallurgy, 131(2), 166–176. https://doi.org/10.1080/25726641.2021.1908079.

Rychkov, V., Botalov, M., Kirillov, E., Kirillov, S., Semenishchev, V., Bunkov, G., & Smyshlyaev, D. (2021). Intensification of carbonate scandium leaching from red mud (bauxite residue). Hydrometallurgy, 199, 105524. https://doi.org/10.1016/j.hydromet.2020.105524.

Salman, A. D., Juzsakova, T., Jalhoom, M. G., Abdullah, T. A., Le, P.-C., Viktor, S., Domokos, E., Nguyen, X. C., La, D. D., Nadda, A. K., & Nguyen, D. D. (2022). A selective hydrometallurgical method for scandium recovery from a real red mud leachate: A comparative study. Environmental Pollution, 308, 119596. https://doi.org/10.1016/j.envpol.2022.119596

Salman, A. D., Juzsakova, T., Mohsen, S., Abdullah, T. A., Le, P.-C., Sebestyen, V., Sluser, B., & Cretescu, I. (2022). Scandium recovery methods from mining, metallurgical extractive industries, and industrial wastes. Materials, 15(7), 2376. https://doi.org/10.3390/ma15072376.

Sauber, M., Kravtsov, Y., & Di Feo, A. (2026). Enhanced scandium recovery from Crater Lake ore sample by dense media and magnetic separation. Canadian Metallurgical Quarterly. Advance online publication. https://doi.org/10.1080/00084433.2026.2635269.

Shao, D., Du, X., Yan, Z., Yu, H., & Qi, T. (2024). Recovery of scandium from Sc-bearing aegirine by Na_2CO_3roasting–water washing–H_2SO_4leaching process. Journal of Environmental Chemical Engineering, 12(4), 113146. https://doi.org/10.1016/j.jece.2024.113146.

Shao, D., Song, J., Du, X., Deng, Y., Xue, Z., Yu, H., & Qi, T. (2023). Leaching characteristics and kinetics of scandium from Sc-concentrate of Bayan Obo rare earth tailings in sulfuric acid solution. Journal of Environmental Chemical Engineering, 11(5), 111037. https://doi.org/10.1016/j.jece.2023.111037.

Shoppert, A., Loginova, I., Napol'skikh, J., & Valeev, D. (2022). High-selective extraction of scandium (Sc) from bauxite residue (red mud) by acid leaching with $MgSO_4$. Materials, 15(4), 1343. https://doi.org/10.3390/ma15041343

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

Shoppert, A., Valeev, D., Diallo, M. M., Napol'skikh, J., & Loginova, I. (2024). Reductive leaching of bauxite residue and subsequent scandium extraction by sulphuric acid

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

leaching—Preliminary evaluation. Hydrometallurgy, 226, 106315. https://doi.org/10.1016/j.hydromet.2024.106315.

Smyshlyaev, D., Kirillov, E., Kirillov, S., Bunkov, G., Rychkov, V., Botalov, M., Taukin, A., Yuldashbaeva, A., & Malyshev, A. (2022). Recovery and separation of Sc, Zr, and Ti from acidic sulfate solutions for high-purity scandium oxide production: Laboratory and pilot study. Hydrometallurgy, 211, 105889. https://doi.org/10.1016/j.hydromet.2022.105889.

Strnad, C., Lechner, M., Flachberger, H., & Gerold, E. (2026). Selective recovery of scandium from titanium ores in complex multi-metal systems. BHM Berg- und Hüttenmännische Monatshefte, 171, 323–329. https://doi.org/10.1007/s00501-026-01733-6.

Supit, J. M., Idrus, A., Petrus, H. T. B. M., Sukadana, I. G., & Pratiwi, F. (2025). Nickel and scandium-bearing minerals associated with limonitic laterite zone of the Lameruru Deposit in Southeast Sulawesi, Indonesia. Indonesian Journal on Geoscience, 12(2), 175–197. https://doi.org/10.17014/ijog.12.2.175-197.

Sverdrup, H. U., & Sverdrup, A. E. (2024). On the supply dynamics of scandium, global resources, production, oxide and metal price, a prospective modelling study using WORLD7. Biophysical Economics and Sustainability, 9, Article 2. https://doi.org/10.1007/s41247-024-00118-y.

Tian, C., Zhang, G., Liu, Q., Wang, M., Zhang, G., Li, Q., Guan, W., Wu, S., & Wu, X. (2026). Scandium recovery from post-demulsification organic phase. Journal of Sustainable Metallurgy, 12(4), 3363–3377. https://doi.org/10.1007/s40831-026-01504-0.

Tian, Q., Dong, B., Guo, X., Xu, Z., Wang, Q., Li, D., & Yu, D. (2021). Comparative atmospheric leaching characteristics of scandium in two different types of laterite nickel ore from Indonesia. Minerals Engineering, 173, 107212. https://doi.org/10.1016/j.mineng.2021.107212.

Toli, A., Mikeli, E., Marinos, D., Balomenos, E., & Panias, D. (2023). Assessing the efficiency of ion exchange resins for the recovery of scandium from sulfuric acid leaching solutions. Separations, 10(7), 366. https://doi.org/10.3390/separations10070366

Tonn, J., Fuchs, A. R., Libuda, L., & Jupke, A. (2024). Controlling crystal growth of a rare earth element scandium salt in antisolvent crystallization. Crystals, 14(1), 94. https://doi.org/10.3390/cryst14010094.

U.S. Geological Survey. (2026). Mineral commodity summaries 2026 (Version 1.3). U.S. Geological Survey. https://doi.org/10.3133/mcs2026

Vind, J., Malfliet, A., Bonomi, C., Paiste, P., Sajó, I. E., Blanpain, B., Tkaczyk, A. H., Vassiliadou, V., & Panias, D. (2018). Modes of occurrences of scandium in Greek

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

bauxite and bauxite residue. Minerals Engineering, 123, 35–48. https://doi.org/10.1016/j.mineng.2018.04.025

Wang, J.-X., Williams-Jones, A. E., Zhang, X.-N., & Yuan, S.-D. (2025). Are scandium sulfate complexes effective in mobilizing scandium? Geochimica et Cosmochimica Acta, 406, 90–100. https://doi.org/10.1016/j.gca.2025.01.038.

Wang, L. J., Luo, J. W., Cui, L., Yan, K. Z., Guo, Y. X., & Cheng, F. Q. (2025). The stepwise extraction strategy for selective recovery of scandium from hydrochloric acid leachate of bauxite residue. Separation and Purification Technology, 353, 128214. https://doi.org/10.1016/j.seppur.2024.128214.

Wang, L., Wang, P., Chen, W.-Q., Wang, Q.-Q., & Lu, H.-S. (2020). Environmental impacts of scandium oxide production from rare earths tailings of Bayan Obo Mine. Journal of Cleaner Production, 270, 122464. https://doi.org/10.1016/j.jclepro.2020.122464.

Wang, W., & Cheng, C. Y. (2011). Separation and purification of scandium by solvent extraction and related technologies: A review. Journal of Chemical Technology & Biotechnology, 86(10), 1237–1246. https://doi.org/10.1002/jctb.2655

Wang, W., Pranolo, Y., & Cheng, C. Y. (2011). Metallurgical processes for scandium recovery from various resources: A review. Hydrometallurgy, 108(1–2), 100–108. https://doi.org/10.1016/j.hydromet.2011.03.001

Wang, X., Yang, R., Cheng, W., Chen, R., Chen, J., & Li, X. (2026). Leaching of scandium from a basalt weathering crust-type scandium deposit: An alkali-acid combined treatment method. Minerals Engineering, 248, 110581. https://doi.org/10.1016/j.mineng.2026.110581.

Wang, Z., Zhang, W., Cao, X., Li, Y., Chen, Y., Zheng, X., & Jiang, X. (2026). Selective and efficient separation of scandium(III) from titanium dioxide waste acid by synergistic extraction. Hydrometallurgy, 245, 106871. https://doi.org/10.1016/j.hydromet.2026.106871.

Wang, Z.-C., Li, M. Y. H., Liu, Z., & Zhou, M.-F. (2021). Scandium: Ore deposits, the pivotal role of magmatic enrichment and future exploration. Ore Geology Reviews, 128, 103906. https://doi.org/10.1016/j.oregeorev.2020.103906.

Watanabe, H., Asano, S., & Murase, K. (2024). Kinetics study of adsorption behaviors of scandium onto chelating resin in sulfuric acid solution. Materials Transactions, 65(1), 61–70. https://doi.org/10.2320/matertrans.M-M2023813.

Watanabe, H., Asano, S., Kirishima, A., & Murase, K. (2026). Thermodynamic parameter estimation for the adsorption of scandium onto chelating resin in sulfuric acid solution. Materials Transactions, 67(3), 267–275. https://doi.org/10.2320/matertrans.M-M2025805.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Xiao, J., Peng, Y., Ding, W., Chen, T., Zou, K., & Wang, Z. (2020). Recovering scandium from scandium rough concentrate using roasting-hydrolysis-leaching process. Processes, 8(3), 365. https://doi.org/10.3390/pr8030365.

Xiao, J., Zhong, N., Cheng, R., Deng, B., & Zhang, J. (2024). New insights on scandium separation from scandium concentrate with titanium dioxide wastewater. Environmental Science and Pollution Research, 31(10), 15837–15850. https://doi.org/10.1007/s11356-024-32237-w.

Xiao, J., Zou, K., Chen, T., Peng, Y., Ding, W., Chen, J., Deng, B., Li, H., & Wang, Z. (2021). Extraction of Sc from Sc-bearing V–Ti magnetite tailings. JOM, 73(6), 1836–1844. https://doi.org/10.1007/s11837-021-04665-3.

Xiao, J., Zou, K., Zhong, N., & Gao, D. (2023). Selective separation of iron and scandium from Bayer Sc-bearing red mud. Journal of Rare Earths, 41(7), 1099–1107. https://doi.org/10.1016/j.jre.2022.06.003.

Xiong, X., Ma, B., Li, X., Yu, J., Shi, L., Wang, C., & Chen, Y. (2024). Hydrometallurgical process and recovery of valuable elements for limonitic laterite: A review. Chinese Journal of Chemical Engineering, 73, 189–201. https://doi.org/10.1016/j.cjche.2024.05.011.

Xue, S., Song, W., Xu, C., Zhang, T., Huang, X., Chen, Q., Xu, D., & Zhu, X. (2026). Origin of Sc mineralization in the Bayan Obo deposit, China: Constraints from mineralogy, geochemistry, and geochronology. Lithos, 532–533, 108508. https://doi.org/10.1016/j.lithos.2026.108508.

Yan, P., Chen, X., Gao, L., & Yang, B. (2024). Recovery of scandium from silicate minerals by high-pressure leaching in sulfuric acid. Journal of Rare Earths, 42(7), 1375–1384. https://doi.org/10.1016/j.jre.2023.02.021.

Yang, Z.-S., Huang, X.-W., & Meng, Y.-M. (2025). Distribution and enrichment of scandium in minerals of the Bayan Obo REE-Nb-Fe deposit, Inner Mongolia, north China. Journal of Asian Earth Sciences, 291, 106705. https://doi.org/10.1016/j.jseaes.2025.106705.

Yoshida, W., & Goto, M. (2025). Recent advances in solvent extraction for the efficient recovery of scandium: A review. Solvent Extraction and Ion Exchange, 43(1), 108–143. https://doi.org/10.1080/07366299.2024.2447483

Yoshida, W., Kubota, F., Baba, Y., Kolev, S. D., & Goto, M. (2019). Separation and recovery of scandium from sulfate media by solvent extraction and polymer inclusion membranes with amic acid extractants. ACS Omega, 4(25), 21122–21130. https://doi.org/10.1021/acsomega.9b02540

Yu, J., Ma, B., Cao, Z., Liu, Y., Shi, L., Wang, C., & Chen, Y. (2024). Recovery of scandium from laterite ore intermediate products: Efficient separation, selective extraction, and product preparation. Journal of Cleaner Production, 485, 144379. https://doi.org/10.1016/j.jclepro.2024.144379

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Yüksekdağ, A., Köse-Mutlu, B., Siddiqui, A. F., Wiesner, M. R., & Koyuncu, I. (2022). A holistic approach for the recovery of rare earth elements and scandium from secondary sources under a circular economy framework—A review. Chemosphere, 293, 133620. https://doi.org/10.1016/j.chemosphere.2022.133620.

Zakaria, Z., & Kamarudin, S. K. (2021). Advanced modification of scandia-stabilized zirconia electrolytes for solid oxide fuel cells application—A review. International Journal of Energy Research, 45, 4871–4887. https://doi.org/10.1002/er.6206.

Zhang, B., Xue, X., & Yang, H. (2022). A novel process for recovery of scandium, rare earth and niobium from Bayan Obo tailings. Minerals Engineering, 178, 107401. https://doi.org/10.1016/j.mineng.2022.107401.

Zhang, G., Zhang, W., Wang, Y., Zhang, L., Cao, X., Li, Y., Chen, Y., & Wang, Y. (2026). Green separation of scandium and titanium using citric acid and hydrogen peroxide scrubbing. Separations, 13(7), 203. https://doi.org/10.3390/separations13070203.

Zhang, L., Zhang, T.-A., Lv, G., Zhang, W., Li, T., & Cao, X. (2021). Separation and extraction of scandium from titanium dioxide waste acid. JOM, 73, 1301–1309. https://doi.org/10.1007/s11837-021-04629-7.

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

Zhang, S., Yan, Y., Zhou, Q., & Fan, Y. (2024). Ionic liquid-based extraction strategy for the efficient and selective recovery of scandium. Molecules, 29(17), 4007. https://doi.org/10.3390/molecules29174007

Zhang, Y., Yuan, S., Cao, Y., Yang, J., Chen, Q., & Jin, B. (2026). Recovery of scandium from nitric acid leachate of scandium-bearing aluminum residue by D2EHPA-TBP synergistic extraction system. JOM, 78(9), 8417–8426. https://doi.org/10.1007/s11837-026-08567-0.

Zhao, X., Rangel Guillen, T., Graham, T. R., Chen, P., Zhao, Y., Mergelsberg, S. T., Zhu, Z., Wang, Z., Rosso, K. M., Guo, X., & Zhang, X. (2024). Incorporation of rare earth elements Sc, Y and La into gibbsite. Chemical Engineering Journal, 485, 149809. https://doi.org/10.1016/j.cej.2024.149809.

Zhigachev, A. O., Rodaev, V. V., Zhigacheva, D. V., Lyskov, N. V., & Shchukina, M. A. (2021). Doping of scandia-stabilized zirconia electrolytes for intermediate-temperature solid oxide fuel cell: A review. Ceramics International, 47, 32490–32504. https://doi.org/10.1016/j.ceramint.2021.08.285.

Zhou, J., Ma, S., Chen, Y., Ning, S., Wei, Y., & Fujita, T. (2021). Recovery of scandium from red mud by leaching with titanium white waste acid and solvent extraction with P204. Hydrometallurgy, 204, 105724. https://doi.org/10.1016/j.hydromet.2021.105724.

JIRRS
Journal International Review of Research Studies
Received: 22/07/2026 - **Accepted:** 21/10/2026
Vol: 1.01
DOI: 10.66104/cm9aw838
Pages: 1-45

Zhou, J., Ning, S., Meng, J., Zhang, S., Zhang, W., Wang, S., Chen, Y., Wang, X., & Wei, Y. (2021). Purification of scandium from concentrate generated from titanium pigments production waste. Journal of Rare Earths, 39(2), 194–200. https://doi.org/10.1016/j.jre.2020.02.008.

Zhou, J., Yu, Q., Huang, Y., Meng, J., Chen, Y., Ning, S., Wang, X., Wei, Y., Yin, X., & Liang, J. (2020). Recovery of scandium from white waste acid generated from the titanium sulphate process using solvent extraction with TRPO. Hydrometallurgy, 195, 105398. https://doi.org/10.1016/j.hydromet.2020.105398.

Zhou, Z., Ma, B., Wang, C., Chen, Y., & Wang, L. (2022a). Recovery of scandium and aluminum from limonitic laterite intermediate product. Minerals Engineering, 188, 107844. https://doi.org/10.1016/j.mineng.2022.107844

Zhou, Z., Ma, B., Wang, C., Chen, Y., & Wang, L. (2022b). Separation and recovery of scandium from high pressure sulfuric acid leach liquor of limonitic laterite. Process Safety and Environmental Protection, 165, 161–172. https://doi.org/10.1016/j.psep.2022.06.028

Zhou, Z., Ma, B., Wang, C., Chen, Y., Zhang, W., & Huang, K. (2022). Enrichment of scandium and aluminum from limonitic laterite during the nitric acid pressure leaching process. Hydrometallurgy, 208, 105819. https://doi.org/10.1016/j.hydromet.2022.105819.

Zhu, X., Li, W., Xing, B., & Zhang, Y. (2020). Scandium extraction from a refractory nickel laterite ore by HCl leaching and P507 solvent extraction. Journal of Rare Earths, 38(9), 1003–1008. https://doi.org/10.1016/j.jre.2019.12.001.

Zou, D., Deng, Y., Chen, J., & Li, D. (2022). A review on solvent extraction of scandium. Journal of Rare Earths, 40(10), 1499–1508. https://doi.org/10.1016/j.jre.2021.12.009.

Zou, D., Li, H., Chen, J., & Li, D. (2020). Recovery of scandium from spent sulfuric acid solution in titanium dioxide production using synergistic solvent extraction with D2EHPA and primary amine N1923. Hydrometallurgy, 197, 105463. https://doi.org/10.1016/j.hydromet.2020.105463