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# Aluminum Control and Selective Recovery from Ni–Co Laterite Leach Liquors: A Critical Review

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**Abstract**
Aluminum is simultaneously a process impurity and a potential secondary resource in hydrometallurgical treatment of nickel–cobalt laterites. The principal engineering problem is not simply removing dissolved aluminum but doing so without unacceptable nickel and cobalt losses, excessive neutralizing-agent consumption, or poorly manageable residues. This critical review examines ore mineralogy, acid leaching, aluminum complexation and hydrolysis, hydroxide precipitation, solvent extraction, ion exchange, membrane-assisted separations, and possible aluminum products. A thematic synthesis of a supplied bibliography of 145 records is used to compare thermodynamic feasibility with kinetic and operational constraints; because the compilation contains unverified metadata and heterogeneous evidence, no pooled recovery or cost estimate is claimed. The analysis identifies controlled neutralization as an established reference route whose selectivity depends on feed composition and solids management, while organic and adsorptive alternatives require more rigorous demonstrations with authentic laterite liquors. Aluminum valorization is justified only after specification-driven impurity control and a transparent water, reagent, residue, and energy balance. An integrated decision framework is proposed to guide comparative testing and process design.

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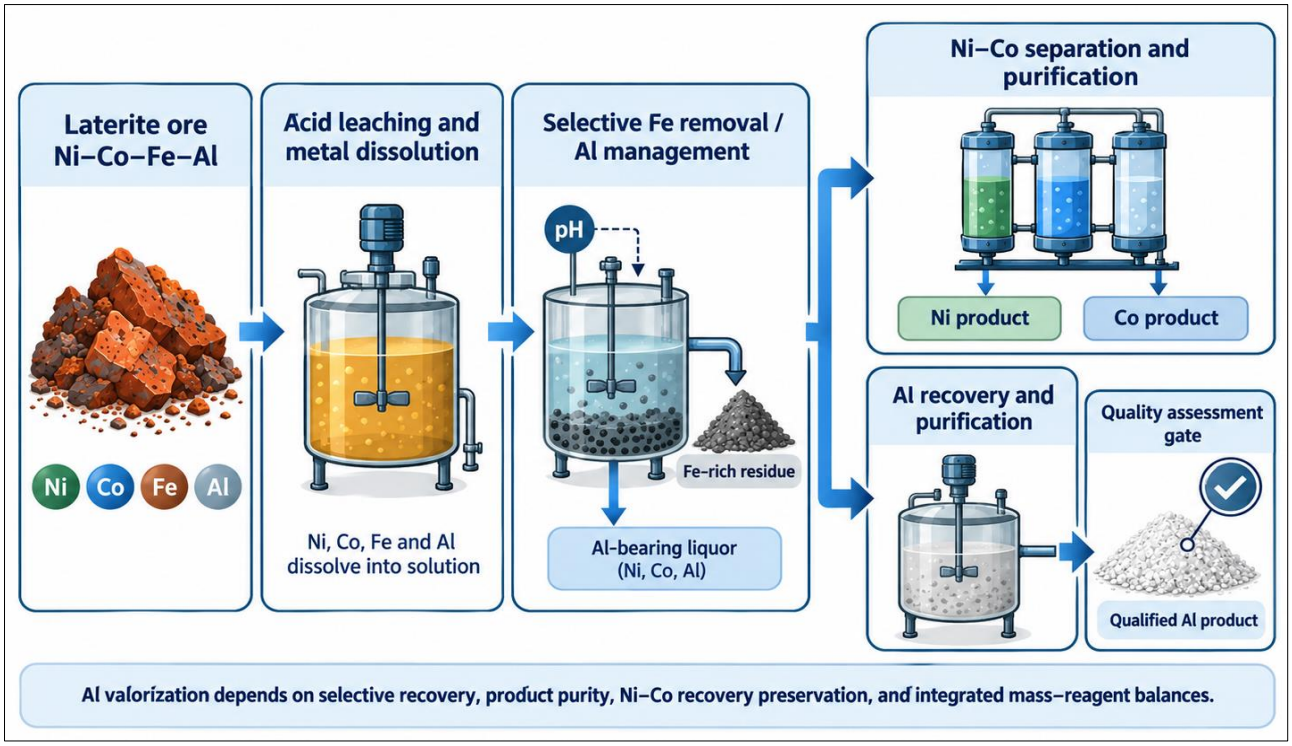
**Keywords:** nickel laterites, aluminum speciation, selective precipitation, solvent extraction, ion exchange, process integration

## 1. Introduction

Nickel–cobalt laterites combine substantial resource potential with heterogeneous mineralogical hosts and demanding impurity control. High-pressure acid leaching (HPAL), atmospheric acid leaching, and heap leaching produce liquors whose compositions depend strongly on the material processed and the dissolution history. Aluminum is an instructive case: substantial dissolution can increase neutralization demand, promote gelatinous precipitates, and entrain valuable metals, while a sufficiently pure isolated aluminum stream may have value. The literature spans mineralogical studies, leaching experiments, impurity neutralization, and downstream recovery but offers much less directly comparable evidence for aluminum-selective product manufacture (Abdollahi *et al*., 2024; Agatzini-Leonardou *et al*., 2021; Aiglsperger *et al*., 2016; Bartzas *et al*., 2024; Butt *et al*., 2013; Han *et al*., 2017) [1, 3, 4, 9, 13, 33].

This review asks which chemistry and unit operations can restrict aluminum transfer into nickel–cobalt products while permitting defensible aluminum valorization. Figure 1 traces ore-host variability, Figure 2 separates aqueous speciation from solids generation, Figure 3 locates prospective separation stages in an integrated circuit, and Figure 4 presents the decision criteria. Tables 1–3 summarize route-specific limitations and evidence requirements; these are frameworks, not new measurements.

**Graphical Abstract**




***Note.*** Original conceptual figure created for this review from the thematic synthesis of the supplied bibliography; no quantitative measurements are represented.

**Fig 1**

**Table 1:** Engineering comparison of aluminum-removal mechanisms

| Route | Potential advantage | Principal limitation / validation need |
|---|---|---|
| Staged neutralization | Simple integration with acid-leach circuits | Co-precipitation, gypsum, and filtration behavior |
| Seeded hydrolysis | Potential particle-size control | Seed stability and reproducible solid quality |
| Solvent extraction | Chemical partitioning without bulk solids formation | Fe interference, stripping, entrainment, and organic loss |
| Ion exchange | Polishing and modular operation | Breakthrough, competitive loading, and regeneration |
| Membrane hybrid | Possible fractionation and recycle | Fouling, osmotic loading, and long-term stability |

Note. Original critical synthesis; categorical assessments are conditional and are not numeric performance estimates.

**Table 2:** Minimum evidence for classification of an Al-bearing stream

| Classification | Evidence gate | Consequence |
|---|---|---|
| Process residue | Mass balance and safe management route | Disposal or treatment cost |
| Potential co-product | Reproducible enrichment and impurity characterization | Conditional downstream upgrading |
| Qualified product | Buyer-grade chemical and physical specification; market route | Defensible revenue sensitivity |

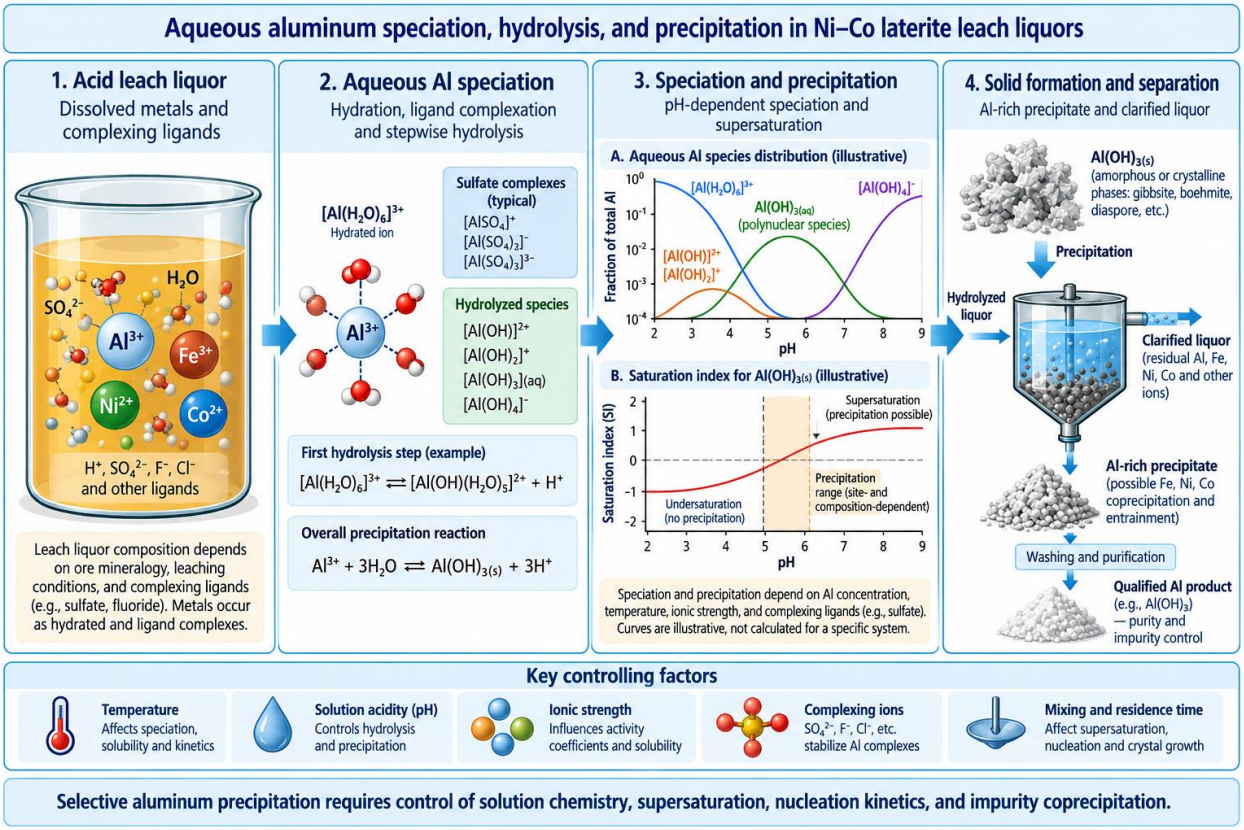
Note. Original critical synthesis; categorical assessments are conditional and are not numeric performance estimates.

The source bibliography contains 145 selected entries from an earlier compilation of 179 records and was assembled around 13 subject-specific Boolean searches. This is a critical narrative review rather than a systematic review: full-text eligibility, source-level measurements, and all bibliographic identifiers have not been independently confirmed. Accordingly, the comparison distinguishes chemistry-based reasoning from demonstrated performance and avoids pooled recoveries, cost estimates, or industrial-readiness claims. Bibliographic entries retained for provenance but not discussed in the analysis require source-level screening before journal submission.

## 2. Mineralogy and Geochemical Controls

Limonitic, transitional, and saprolitic zones differ in iron oxyhydroxide and magnesium silicate content, clay abundance, and the distribution of nickel, cobalt, aluminum, and accessory elements. Consequently, bulk Al grade does not predict dissolved Al independently of mineral hosts and lixiviant chemistry (Aiglsperger *et al*., 2016; Butt *et al*., 2013; Han *et al*., 2017; Kursunoglu, 2025; Li *et al*., 2011) [4, 13, 33, 43, 47].

Figure 1 represents the principal interpretive problem: an ore sample described simply as laterite may conceal different Al-host contributions. Mineralogy-resolved deportment and dissolution tests should precede claims of universal neutralization pH or recoverable Al yield.




*Note.* Original conceptual figure created for this review from the thematic synthesis of the supplied bibliography; no quantitative measurements are represented.

**Fig 2:** Conceptual progression from aluminum aqueous chemistry to solid-phase separation.

**Table 3:** Required dataset for a meaningful continuous-process comparison

| Dimension | Required measurement | Failure mode if omitted |
|---|---|---|
| Selectivity | Al removal and Ni/Co loss on consistent mass basis | Misleading recovery claim |
| Solution chemistry | Free acid, sulfate/chloride, Fe oxidation state, ionic strength | Unreliable speciation prediction |
| Solid handling | Particle size, settling, filtration, wash efficiency | Understated operating limitation |
| Organic/resin performance | Cycling, stripping, breakthrough, contaminant loading | Overstated reagent life |
| Utilities and environment | Reagent, energy, water, purge, and residues | Incomplete OPEX and LCA |
| Product qualification | Phase, grade, contaminants, buyer specification | Unjustified coproduct credit |

Note. Original critical synthesis; categorical assessments are conditional and are not numeric performance estimates.

## 3. Generation of Aluminum-Bearing Leach Liquors

The dissolution of Al varies with acid type, available free acidity, thermal regime, residence time, and the rates of dissolution or secondary-phase formation. HPAL conditions cannot be exchanged directly for those of ambient-pressure, heap, or chloride systems; comparison requires consistent definitions of extraction, solid–liquid ratio, liquor concentration, and reagent inventory (Abdollahi *et al*., 2024; Agatzini-Leonardou *et al*., 2021; Bartzas *et al*., 2024; Carpen *et al*., 2022; Dash *et al*., 2025; Garces-Granda *et al*., 2020; Gultom *et al*., 2020) [1, 3, 9, 16, 19, 28, 31].

Aluminum deportment must be closed across pregnant solution, residue, washings, and neutralization solids. A defensible process balance distinguishes initial release from subsequent reprecipitation and identifies losses of nickel and cobalt through the same sequence.

## 4. Aqueous Speciation and Thermodynamic Boundaries

Hydrated $Al^{3+}$ undergoes hydrolysis and participates in sulfate- and chloride-associated equilibria; the predominant dissolved species depends on temperature, activities, ionic strength, acid concentration, and competing ions. Simplified equilibrium plots are useful for framing hypotheses but insufficient to predict actual precipitation in concentrated industrial liquor (Alkarkhi *et al*., 2012; Schodde *et al*., 2025; Shi *et al*., 2021; Su *et al*., 2024; Wang *et al*., 2018; de Almeida Silva *et al*., 2019) [5, 98, 101, 108, 122].

Figure 2 distinguishes complexation, hydrolysis, nucleation, and particle capture. Solubility calculations must be coupled with mixing, local pH, and residence-time effects before they can explain measured selectivity.

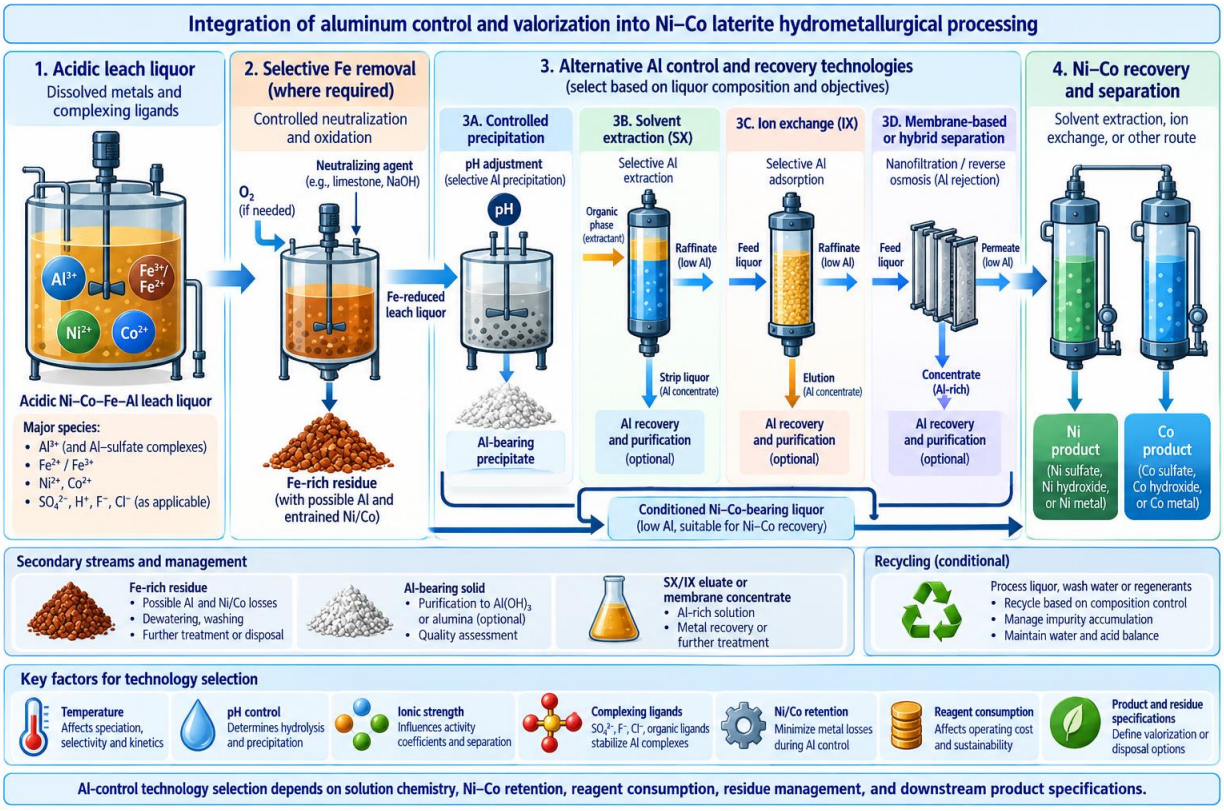
For the trivalent hydrolysis limit, $Al^{3+} + 3H_2O \rightleftharpoons Al(OH)_3(s) + 3H^+$ is a useful schematic relation, not a complete description of polymeric or sulfate-bearing species. Model parameterization should be checked against the actual liquor matrix.

## 5. Neutralization, Hydrolysis, and Selective Precipitation

Controlled neutralization with calcium carbonate, lime, sodium hydroxide, or magnesium oxide is a relevant process reference. However, apparent aluminum removal cannot by itself establish selectivity because ferric iron, chromium, silica, and precious nickel–cobalt inventory may co-

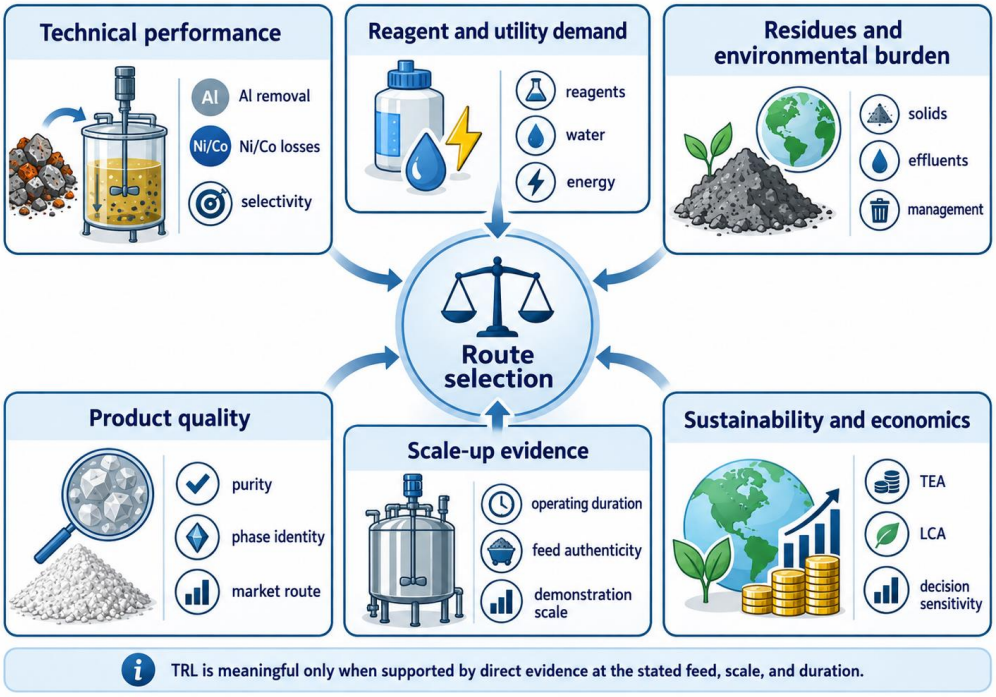
precipitate or be physically entrained (Mubarok *et al*., 2013; Wang *et al*., 2025) [63, 124].

The critical operating variables are reagent addition profile, pH gradient, solids loading, seeding, aging, and filterability. Equilibrium-centered comparisons without particle-size and filtration data are incomplete. Table 1 records the essential tradeoffs.



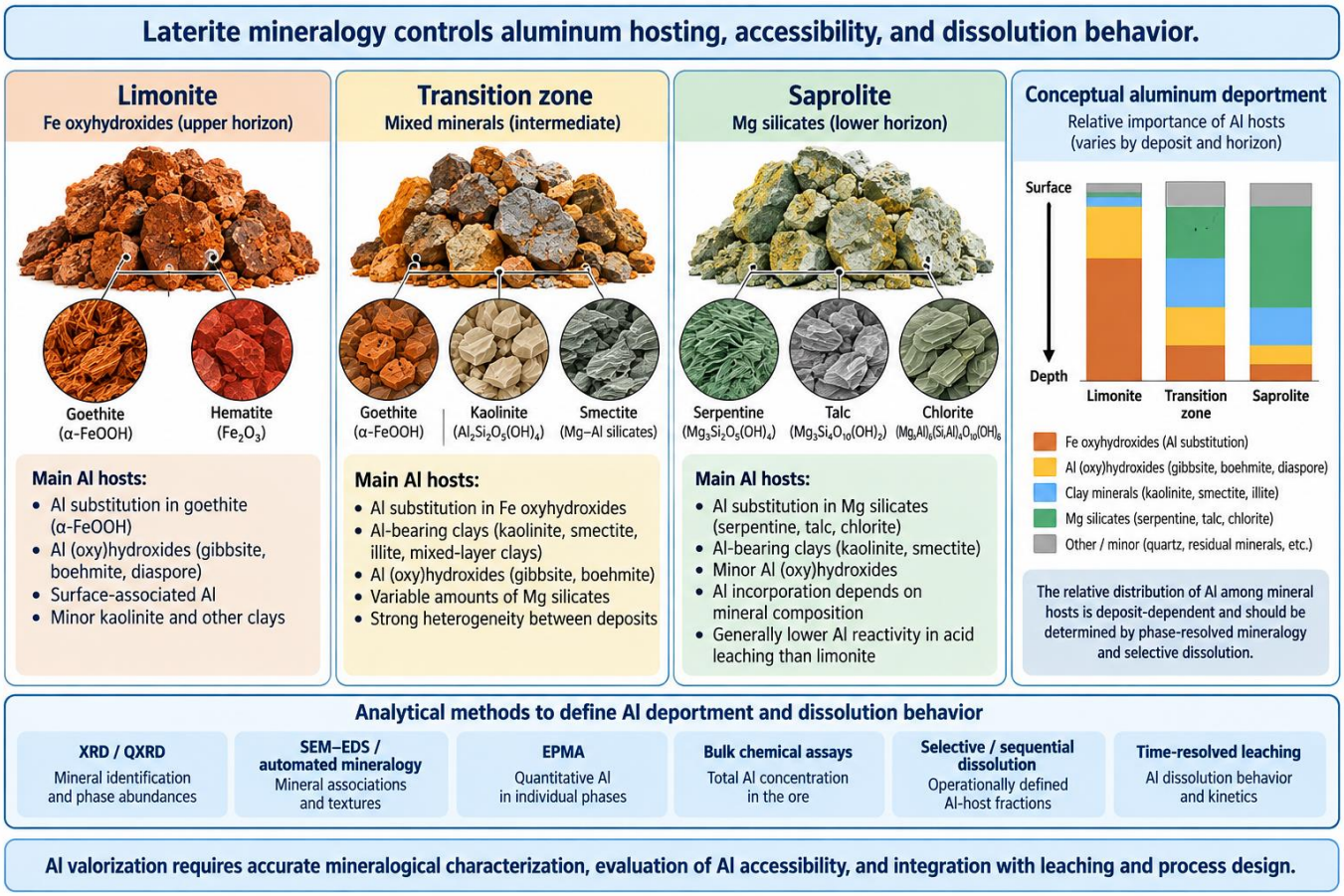

Note. Original conceptual figure created for this review from the thematic synthesis of the supplied bibliography; no quantitative measurements are represented.

**Fig 3:** Indicative integration of impurity removal with nickel and cobalt product purification.




*Note.* Original conceptual figure created for this review from the thematic synthesis of the supplied bibliography; no quantitative measurements are represented.

**Fig 4:** Linked technical, product-quality, and sustainability criteria for route selection.




*Note*. Original conceptual figure created for this review from the thematic synthesis of the supplied bibliography; no quantitative measurements are represented. A practical evaluation should link X-ray diffraction, quantitative mineralogy, bulk assays, and timed liquor analyses. This is a methodological recommendation rather than evidence that any particular ore responds uniformly.

**Fig 5:** Conceptual heterogeneity in aluminum-host environments across lateritic profiles.

The chief comparison is therefore not percent Al removed in isolation but the joint outcome of aluminum rejection, nickel and cobalt losses, precipitate filterability, and reagent consumption. If two tests start from different acidities or Fe(III) concentrations, an identical endpoint pH does not imply equal selectivity. Reported operating windows should be interpreted in the context of feed composition and sampling time, not transferred as universal set points.

No universal ranking follows from this table: the economically favored route must be determined using actual pregnant-leach-solution assays, continuous solids characterization, and nickel–cobalt accountability.

## 6. Solvent Extraction and Organic Reagents

Extraction chemistry can potentially separate dissolved aluminum from nickel and cobalt without creating a bulk hydroxide sludge. However, preferential loading cannot be inferred from reagent class alone. Fe(III) competition, sulfate complexation, pH-dependent loading, and organic-phase capacity must be established experimentally with the same laterite leach liquor. A credible claim of aluminum selectivity requires paired aqueous and organic assays for Al, Fe, Ni, and Co, with distribution ratios and phase-volume corrections reported for each metal.

A full SX assessment needs extraction isotherms, pH or acidity dependence, scrubbing and stripping steps, organic regeneration, crud propensity, and multicycle losses. Aluminum-selective SX should not be portrayed as industrially proven for lateritic liquors solely on the basis of metal extraction reported for related feedstocks.

For process integration, stripping is as consequential as extraction. A loaded organic phase is not an aluminum product, and metal partitioning across extraction, scrubbing, stripping, and recycle must be reconciled before claiming n*et al*uminum recovery. Without multi-cycle evidence, a solvent formulation is a screening candidate rather than a validated alternative to neutralization.

## 7. Ion Exchange and Adsorptive Separation

Chelating and conventional ion-exchange resins can be attractive for removal or polishing of selected metal ions, particularly when feed solids have already been eliminated. Comparison of functional groups should include competitive loading with Fe and Mn, breakthrough profiles, acid regeneration, and full resin mass balance (Botelho Junior *et al*., 2019; Pereira, 2026c) [12, 77].

Resin performance measured on synthetic single-ion solutions provides only screening evidence. Real-liquor trials should assess colloidal fouling, sulfate competition, irreversible adsorption, and recovery of aluminum from regeneration effluent before product-grade claims are made.

## 8. Membranes and Hybrid Treatment Trains

Nanofiltration, dialysis, electrodialysis, and membrane-assisted extraction are conceptually relevant to sulfate management or metal fractionation, but charge-based

transport and concentration polarization complicate extrapolation to strongly acidic multicomponent systems.

Membranes are most appropriately considered within hybrid trains after particulate control and with measured permeability, rejection, recovery, cleaning requirements, and membrane life. The absence of a demonstrated closed-loop nickel–cobalt laterite duty must be explicit rather than filled with generic membrane advantages.

## 9. Aluminum Recovery, Product Quality, and Residue Management

Precipitated aluminum hydroxide, hydrated alumina phases, aluminum sulfate, or related intermediates represent conditional potential products rather than automatic by-products of impurity removal. Residual Fe, Cr, Si, Ni, and Co constrain quality, while reagent-derived calcium or magnesium can alter both phase composition and treatment burden (Bartzas *et al*., 2021; Caetano *et al*., 2025; Duman *et al*., 2022; Luo *et al*., 2026; Ruan *et al*., 2024; Savinova *et al*., 2023; Schmidt *et al*., 2016) [10, 14, 21, 51, 93, 94, 96].

Product assessment should be defined backward from a buyer specification, validated solid assay, phase identity, washing and calcination needs, and marketable mass yield. Table 2 separates engineering feasibility from the unsupported assumption that any Al-bearing precipitate is saleable.

In particular, a hydroxide-rich filter cake can retain sulfate, gypsum, and sorbed nickel or cobalt. Washing may improve purity but transfer these constituents to a larger effluent volume. Any co-product credit therefore requires a complete upgrading route and analytical verification of the final material, not simply an elevated aluminum concentration in the precipitate.

The product classification may change across different feedstocks; an impurity solid from one operation is not a qualified alumina precursor by nomenclature alone.

## 10. Integration with Nickel–Cobalt Purification

Figure 3 organizes separation around the metal-product pathway rather than treating aluminum recovery as an independent objective. Early iron management can mitigate downstream contamination, but premature neutralization may also entrain nickel and cobalt. The preferred insertion point therefore depends on upstream acid consumption and downstream mixed-hydroxide, sulfide, or solution-product specifications (Acquah *et al*., 2026; Astuti *et al*., 2023; Bana *et al*., 2025; Berni *et al*., 2010; Cao *et al*., 2022; Chen *et al*., 2025; Dickson *et al*., 2025; Çoban *et al*., 2024) [2, 6, 8, 11, 15, 17, 18, 20].

The flowsheet is intentionally route-neutral. It does not prescribe a universal sequence of solids and solvent extraction operations; integration requires stream assays, recycle accounting, and decision thresholds for valuable-metal retention.

## 11. Scale-Up, Sustainability, and Comparative Decision Criteria

A process comparison should normalize the feed-basis, impurity removal efficiency, Ni/Co losses, reagent mass, water demand, energy use, solids generation, and treatment disposition. Life-cycle assessment (LCA) and techno-economic assessment (TEA) can reverse rankings obtained from apparent laboratory extraction alone (Bai *et al*., 2022; Golroudbary *et al*., 2023; Wahyono *et al*., 2024) [7, 29, 119].

Figure 4 brings the decision constraints together. Technology readiness level (TRL) is relevant only when independently supported by evidence of demonstration at the stated feed, operating duration, and scale; a published bench experiment does not establish industrial TRL.

Table 3 offers an evidence-based comparison template, with explicit missing values rather than speculative route yields or costs.

This framework is deliberately qualitative. A comparative score, predicted cost, or TRL designation should be introduced only after measurements and source verification permit it.

## 12. Research Priorities and Proposed Verification Framework

Priority experiments should begin with compositional and mineralogical characterization of representative laterite feeds and matched solution sampling through leaching and partial neutralization. Next, small-scale factorial comparisons should quantify simultaneous Al rejection and Ni/Co retention over pH, dose, time, and temperature while recording solids characteristics. More selective SX, IX, and membrane options should then be screened against the same real liquor rather than independent synthetic matrices.

Subsequent continuous trials must close multistage mass balances, quantify long-term reagent and membrane or resin stability, and recover enough solids for a preliminary product-specification audit. Only after these gates should integrated TEA/LCA and capacity scale-up be credible.

## 13. Conclusion

The controlling challenge is selective management of aluminum in a matrix that also contains valuable nickel and cobalt and competing iron, silicon, manganese, and other impurities. Dissolution depends on mineralogical host and leach conditions; subsequent aqueous speciation, hydrolysis, and the nucleation and separation of solids determine whether aluminum can be isolated without disproportionate metal losses. Controlled neutralization provides a practical benchmark, although its true performance is defined by solids handling and multimetal retention. Solvent extraction, ion exchange, membranes, and hybrid routes can be useful alternatives within defined service windows, but they require consistent real-liquor and closed-loop evidence before we can infer industrial readiness. Aluminum valorization requires chemistry confirmed by specifications, saleable physical characteristics, and full consideration of reagent, water, energy, and residual streams. Future work should prioritize comparative campaigns with authentic liquors, continuous balances, and transparent product qualification.

## Declarations

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## Conflict of Interest

Conflict-of-interest declaration to be confirmed by the author.

## Data Availability

This manuscript presents a qualitative synthesis of the supplied literature list; it reports no original experimental data. Bibliographic metadata and primary-source results require further verification.

**Author Contributions**

Authorship and contribution statement to be confirmed by the author prior to submission.

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