v7.n9.2026

SCIENTIFIC JOURNAL - RECIMA21 ISSN 2675-6218

FROM MINE TO SALEABLE PRODUCT: A FEASIBILITY FRAMEWORK FOR ATMOSPHERIC LEACHING OF NICKEL LATERITES - A CRITICAL REVIEW

DA MINA AO PRODUTO COMERCIAL: UMA ESTRUTURA DE AVALIAÇÃO DA VIABILIDADE DA LIXIVIAÇÃO ATMOSFÉRICA DE LATERITAS NIQUELÍFERAS - UMA REVISÃO CRÍTICA

DE LA MINA AL PRODUCTO COMERCIALIZABLE: UN MARCO DE EVALUACIÓN DE LA VIABILIDAD DE LA LIXIVIACIÓN ATMOSFÉRICA DE LATERITAS DE NÍQUEL - UNA REVISIÓN CRÍTICA

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e798955
https://doi.org/10.47820/recima21.v7i9.8955

PUBLISHED: 09/2026

ABSTRACT

Atmospheric acid leaching of nickel laterites is frequently judged by reactor extraction, although investment decisions require an auditable boundary from ore definition to a saleable, on-spec product. This structured critical narrative review evaluates 100 references, centered on 2020–2026 and supplemented by foundational and downstream studies, to integrate mineralogy, mining and blending, beneficiation, leach chemistry, solid-liquid separation, purification, Ni-Co recovery, utilities, residues, capital and operating costs, and economic risk. Evidence was coded once by its primary engineering role; batch experiments accounted for 52% of the corpus, whereas no fully integrated continuous laboratory campaign was identified in the reviewed corpus. The principal contribution is the integration of established engineering relationships into a ten-step feasibility architecture supported by five compact synthesis tables and three decision figures. Feed selection is based on metallurgical and economic ore value rather than nickel grade alone. Overall Ni and Co recovery is calculated separately to a product-in-inventory accounting boundary, defined as saleable product physically present in inventory after finishing. Stoichiometric acid demand is distinguished from operational consumption, and project progression is controlled by evidence-maturity and decision gates. The framework is intended to prevent route selection from being driven by maximum extraction alone and to expose the ore, process, environmental, and economic conditions under which atmospheric leaching remains competitive.

KEYWORDS: *Nickel laterite. Atmospheric leaching. Techno-economic feasibility. Geometallurgy. Sulfuric acid consumption. Saleable product.*

RESUMO

A lixiviação ácida atmosférica de lateritas de níquel é frequentemente avaliada por meio de extração em reator, embora decisões de investimento exijam uma fronteira auditável, desde a definição do minério até o produto comercial conforme a especificação. Esta revisão crítica narrativa estruturada avalia 100 referências, concentradas em 2020–2026 e complementadas por estudos fundamentais e de etapas a jusante, para integrar mineralogia, lavra e mistura de minérios, beneficiamento, lixiviação, separação sólido-líquido, purificação, recuperação de Ni-Co, utilidades, resíduos, custos de capital e operação e risco econômico.

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Cada referência foi classificada uma única vez com base em sua função principal de engenharia; estudos em batelada representam 52% do corpus, enquanto nenhuma campanha laboratorial contínua e totalmente integrada foi identificada no corpus revisado. A principal contribuição é integrar as relações de engenharia estabelecidas em uma arquitetura de viabilidade em dez etapas, apoiada por cinco tabelas sintéticas compactas e três figuras decisórias. A alimentação é selecionada pelo valor metalúrgico-econômico do minério, e a recuperação global de Ni e Co é calculada separadamente até a fronteira de produto em estoque, definida como produto comercial conforme especificação e fisicamente disponível após o acabamento. A demanda estequiométrica de ácido é separada do consumo operacional, e o avanço do projeto é condicionado à maturidade das evidências e a portões decisórios. A estrutura evita que a seleção de rota seja determinada apenas pela máxima extração.

PALAVRAS-CHAVE: Laterita de níquel. Lixiviação atmosférica. Viabilidade técnico-econômica. Geometalurgia. Consumo de ácido sulfúrico. Produto comercial.

RESUMEN

La lixiviación ácida atmosférica de lateritas de níquel suele evaluarse por la extracción en el reactor, aunque las decisiones de inversión requieren un límite auditable desde la definición del mineral hasta un producto comercializable conforme a especificación. Esta revisión crítica narrativa estructurada evalúa 100 referencias, centradas en 2020–2026 y complementadas con estudios fundamentales y de etapas posteriores, para integrar mineralogía, minería y mezcla, beneficio, lixiviación, separación sólido-líquido, purificación, recuperación de Ni-Co, servicios, residuos, costos de capital y de operación, y riesgo económico. Cada referencia se clasificó una sola vez según su función principal de ingeniería; los estudios por lotes representan el 52% del corpus, mientras que no se identificó en el corpus revisado una campaña de laboratorio continua y totalmente integrada. La principal contribución consiste en integrar las relaciones de ingeniería establecidas en una arquitectura de viabilidad de diez etapas, apoyada por cinco tablas sintéticas compactas y tres figuras de decisión. La alimentación se selecciona por el valor metalúrgico-económico del mineral, y la recuperación global de Ni y Co se calcula por separado hasta el límite de producto en inventario, definido como producto comercializable conforme a especificación y físicamente disponible después del acabado. La demanda estequiométrica de ácido se separa del consumo operacional, y el avance del proyecto depende de la madurez de la evidencia y de portones de decisión. El marco evita seleccionar rutas únicamente por la máxima extracción.

PALABRAS CLAVE: *Laterita de níquel. Lixiviación atmosférica. Viabilidad técnico-económica. Geometalurgia. Consumo de ácido sulfúrico. Producto comercializable.*

INTRODUCTION

Nickel laterites comprise limonitic, transition, and saprolitic materials whose mineral hosts, gangue reactivity, moisture, texture, and product targets differ enough that no flowsheet is intrinsically optimal. Route selection increasingly connects orebody characteristics with product markets, project scale, energy and logistics, and strategic supply-chain conditions rather than with extraction alone. (Dalvi *et al.*, 2004; Mudd & Jowitt, 2022; Bradley *et al.*, 2025; Schodde & Guj,

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2025; Konewka *et al.*, 2026; Manurung *et al.*, 2025; Soamole & Mokodompit, 2025; Binnemans & Jones, 2025; Bonfu *et al.*, 2026).

Atmospheric sulfuric-acid leaching is attractive because it avoids autoclave pressure, but lower pressure does not automatically mean lower project cost. Reactive Mg-, Al-, Fe-, Ca-, and Si-bearing phases can increase acid use, dissolved impurities, neutralization, water demand, solid–liquid separation duties, residue mass, corrosion exposure, and equipment inventories. Comparative reviews therefore support conditional route selection among atmospheric leaching, HPAL, heap leaching, reduction–ammonia/Caron processing, RKEF/ferronickel, chloride systems, and hybrid routes. (McDonald & Whittington, 2008a, 2008b; Whittington & Muir, 2000; Caetano, Ostroski, *et al.*, 2025; Chi *et al.*, 2026; Msumange *et al.*, 2026; Pandey *et al.*, 2023; Stanković *et al.*, 2020, 2022; Suleimen *et al.*, 2026; Zevgolis & Daskalakis, 2021).

The problem addressed is the disconnect between reactor-centered testwork and investment-grade decisions. The general objective is to establish a structured feasibility framework linking resource definition, mining, beneficiation, atmospheric leaching, downstream recovery, utility and residue closure, CAPEX/OPEX, and risk. The specific objectives are to classify evidence maturity, formalize element-specific recovery to product inventory, integrate reactive-gangue penalties into ore value, define a transparent sequence of decision gates, and identify data gaps requiring continuous or pilot validation. In this article, saleable product refers to the commercial endpoint, whereas product-in-inventory is a deliberate accounting term for an on-spec, saleable product physically present in inventory after all losses from mining through finishing. This definition is used consistently as the terminal recovery boundary.

1. THEORETICAL FRAMEWORK

1.1. Laterite mineralogy and route dependence

Laterite processing behavior is controlled by mineral host rather than bulk Ni grade alone. Goethitic limonite, transition ores, serpentine-rich saprolite, clays, silica phases, and minor Mn/Cr-bearing minerals distribute Ni and Co differently and also determine acid reactivity, rheology, and impurity deportment. Process-mineralogical monitoring, beneficiation studies, and recent reviews show that ore domains should therefore be defined by mineralogy, texture, particle-size distribution, and reactive-gangue indicators in addition to assays. (König, 2021; Xu *et al.*, 2021; Acquah, Abaka-Wood, Addai-Mensah, *et al.*, 2025; Asadrokht & Zakeri, 2022; Mweene *et al.*, 2024; Zappala *et al.*, 2024).

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Beneficiation and pretreatment can create value when they preferentially reject acid consumers or change mineral reactivity, but benefits must be net of Ni/Co losses, energy, additional equipment, and downstream effects. Selective comminution, mechanical activation, thermal pretreatment, roasting, and alternative preparation routes illustrate both opportunity and transfer of burden between unit operations. (Acquah, Abaka-Wood, Skinner, *et al.*, 2026; Acquah, Spiridonov, Abaka-Wood, *et al.*, 2026; Borda & Torres, 2023; Dong *et al.*, 2023; Ribeiro *et al.*, 2021, 2022).

1.2. Atmospheric-leach chemistry, acid demand, and downstream burden

Atmospheric leaching responds jointly to acid dosage or free-acid target, solids concentration, temperature, residence time, particle size, redox potential, and agitation. Laboratory studies on ferruginous, limonitic, saprolitic, and pretreated laterites show that Ni and Co optima may diverge and that higher reagent intensity can also increase Fe and other impurity dissolution. (Abbasi Gharaei *et al.*, 2024; da Silva Ribeiro *et al.*, 2025; He *et al.*, 2023; Hosseini Nasab *et al.*, 2020; Jeong *et al.*, 2025; Kang *et al.*, 2026; Li *et al.*, 2025; Lucy *et al.*, 2023; Ma *et al.*, 2026; Prasetya *et al.*, 2025; Santos *et al.*, 2021; Yunita & Mubarok, 2021).

Pressure-leach and alternative-acid studies are useful as transferable evidence for acid intensity, mineral-host effects, scaling, staged addition, and impurity behavior, provided that pressure-specific performance is not treated as direct atmospheric design data. (Acquah, Ritch, *et al.*, 2025; Baking *et al.*, 2025; Bana *et al.*, 2025; Çoban & Baş, 2024; Dickson *et al.*, 2025, 2026; Duman & Can, 2022; Gultom & Sianipar, 2020; Komnitsas *et al.*, 2026; Shayakhmetova *et al.*, 2025; Top *et al.*, 2020).

The theoretical distinction that matters economically is between stoichiometric acid demand and operational acid consumption. Stoichiometric demand reflects reactions that actually proceed, whereas operational consumption also accounts for free acid maintained for kinetics/speciation, incomplete contact, entrainment, recycle, and secondary precipitation. Downstream neutralization and impurity removal then determine whether the reactor extract becomes a recoverable product. (da Silva *et al.*, 2022; Das & Li, 2023; Faris, Fischmann, *et al.*, 2021; Faris, White, *et al.*, 2021; Dwi *et al.*, 2025; Mystrioti *et al.*, 2022).

1.3. Product endpoints and feasibility criteria

MHP, MSP, nickel salts, and metallic products impose different requirements for purification, moisture, logistics, safety, and contracts. MHP can reduce primary-plant complexity

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while transferring impurity removal to refining; sulfate production internalizes more of the refining and quality-control duties. Recent studies on MHP leaching, solvent extraction, selective precipitation, and nickel-sulfate crystallization show that recovery and product specification must be evaluated together. (Andriyanto *et al.*, 2025; Demirel *et al.*, 2022; Ichlas *et al.*, 2020, 2026; Sahiruddin *et al.*, 2025).

Accordingly, viability is defined here by the ability of a specific orebody and flowsheet to deliver the specified product with acceptable recovery, cost, environmental burden, and risk. The individual accounting equations used later are established engineering identities; the scientific contribution claimed is their integration with evidence maturity, geometallurgical ore definition, and stage-gated route selection for atmospheric laterites rather than novelty of the underlying mass-balance or stoichiometric relationships.

2. METHODOLOGY

2.1. Search strategy, eligibility, and scope

The study was designed as a structured critical narrative review rather than a systematic review. Google Scholar was the principal discovery interface, with iterative searches and source-level verification through 18 August 2026. Search families combined nickel laterite/lateritic nickel with atmospheric or sulfuric-acid leaching; mineralogy, geometallurgy, beneficiation and pretreatment; acid consumption and reactive gangue; solid–liquid separation and washing; MHP/MSP, purification and nickel sulfate; CAPEX/OPEX, feasibility, LCA and economics; and competing HPAL, heap, Caron, RKEF, chloride, and hybrid routes.

Eligibility required direct or transferable relevance to route selection, engineering design, or mine-to-product economics. Peer-reviewed articles and reviews were prioritized; technically substantive conference papers were retained for pilot, project, construction, or industrial evidence. Preprints, theses/dissertations, duplicates, and papers in which the relevant operation was incidental were excluded. The final corpus contains 100 unique references: a predominantly 2020–2026 core supplemented by foundational laterite-process sources and targeted downstream-product literature.

2.2. Evidence coding, auditability, and limitations of the search design

Each source was coded once according to its primary evidentiary role to avoid double counting. The coding categories were industrial/project, pilot, continuous laboratory, batch experimental, mechanistic/modeling, techno-economic/LCA/system, and review/context. This

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taxonomy ranks design transferability rather than scientific quality. Source-by-source coding, scale, principal evidence role, and classification rationale are reported in Supplementary Table S1, enabling audit of the percentages used in the manuscript.

The coding was performed by a single author and was not independently replicated; multi-role papers were forced into a single dominant category. Original database hit counts and a prospective exclusion log were not retained during iterative curation, so they were not reconstructed retrospectively, and no claim of systematic-review exhaustiveness is made. Statements about missing evidence are therefore restricted to the reviewed corpus. These limitations are explicitly carried into the interpretation of Figure 1 and the research gap analysis.

3. RESULTS AND DISCUSSION

3.1. Evidence maturity and design implications

The corpus is strongly asymmetric. Batch experiments account for 52 references, while only two sources were classified as integrated pilot evidence and no fully integrated continuous laboratory atmospheric-leach campaign was identified within the reviewed corpus. Industrial/project evidence represents 8%, mechanistic/modeling work 4%, techno-economic/LCA/system studies 11%, and review/context sources 23%. This distribution supports laboratory interpretation of chemistry and kinetics but provides a weaker basis for steady-state recycle behavior, wash efficiency, residence-time distribution, impurity accumulation, and integrated product recovery (Table 1).

Table 1. Evidence hierarchy used for atmospheric-leaching feasibility assessment

Evidence class	Appropriate feasibility use	Main transfer limitation	n (%)
Industrial / project	Design validation, availability, consumables, execution benchmarking	Feed/site transfer remains project-specific	8 (8%)
Demonstration / pilot	Hydraulics, operability, integrated scale-up factors	Moderate scale and feed-transfer uncertainty	2 (2%)
Continuous laboratory	Steady-state balance, recycle response, feed changes	Not identified in reviewed corpus	0 (0%)
Batch experimental	Mechanisms, kinetics, screening and operating windows	High scale-up uncertainty	52 (52%)
Mechanistic / model	Speciation, sensitivity, hypothesis and scenario testing	Requires calibration	4 (4%)

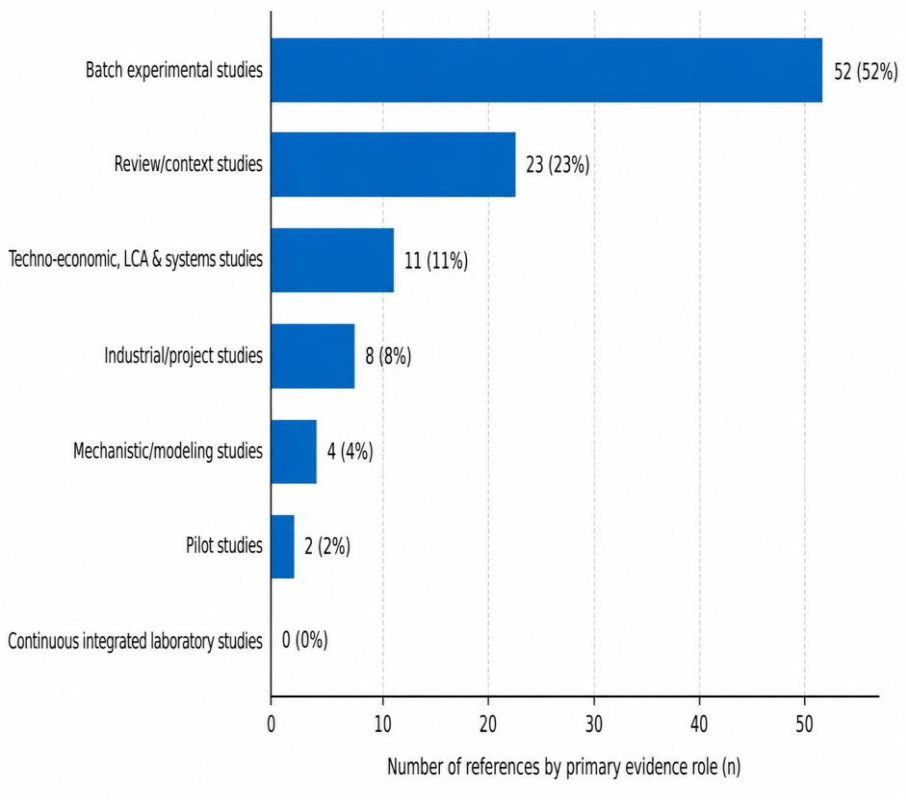
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Techno-economic / LCA / system	Cost, energy, emissions, supply and scenario framing	Assumption-dependent	11 (11%)
Review/context	Technology scope, maturity, historical and comparative context	Not direct design data	23 (23%)

Source: Prepared by the author from the primary-role coding of the 100-reference corpus; full audit trail in Supplementary Table S1.

The practical transfer rule is conservative: laboratory maxima are screening observations, not plant guarantees. Design values should reflect representative and adverse ore domains, residence-time distribution, slurry handling, washing, purification losses, product finishing, and availability. Pilot evidence is particularly valuable because it exposes hydraulic and operational constraints that batch work cannot reproduce. (Agatzini-Leonardou *et al.*, 2021; Nascimento *et al.*, 2026; Oxley *et al.*, 2025).

Figure 1. Distribution of the 100-reference corpus by primary evidentiary role



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Source: Prepared by the author from the audited primary-role coding reported in Table 1 and Supplementary Table S1.

3.2. Integrated ten-step feasibility framework

The review results were integrated into a ten-step architecture: (1) define product, capacity and battery limits; (2) build resource-to-feed domains; (3) establish mining, blending and beneficiation strategy; (4) define the leach operating window; (5) translate testwork into design values; (6) close the flowsheet and element-specific recovery; (7) close water, acid, energy and residue balances; (8) estimate CAPEX; (9) build OPEX; and (10) integrate economics and risk. The contribution lies in the decision sequence and the feedback among these steps; individual equations and unit-operation relationships remain conventional engineering tools.

3.3. Ore definition, geometallurgy, and feed strategy

A feasibility model should begin with geometallurgical domains rather than a single average assay. Similar Ni grades can have different acid demand and recoverability because Mg, Fe, Al, Ca, Si, clay/fines, and Ni/Co hosts differ in reactivity and separation behavior. Mining recovery, dilution, ore loss, stockpiling, moisture, and beneficiation must then be reconciled before laboratory extraction is converted to plant throughput. Table 2 condenses the ore and testwork variables that most directly translate into feasibility design criteria. (König, 2021; Mudd & Jowitt, 2022; Roskha *et al.*, 2024; Schodde & Guj, 2025; Xu *et al.*, 2021).

Table 2. Critical ore and testwork variables and their translation into feasibility design criteria

Variable / evidence	Metallurgical response	Engineering / economic consequence
Ni-Co grade and mineral host	Recoverability, dissolution kinetics, product ratio	Revenue potential cannot be inferred from grade alone; mineral host controls attainable recovery.
Reactive Mg and Ca	Acid consumption, sulfate loading, neutralization demand	Higher reagent, neutralization, recycle, scaling and residue burden.
Fe mineralogy	Dissolution/precipitation behavior and residue formation	Purification duty, solid generation and potential Ni-Co losses during impurity removal.
Al, clays and fines	Rheology, viscosity, settling and filtration response	Tankage, pumping, thickening, filtration and washing constraints.
Acid-temperature-time-redox window	Ni-Co extraction versus impurity dissolution	Reagent OPEX, residence time, corrosion/materials and downstream purification load.
Settling/filtration/washing tests	Flux, cake moisture, wash efficiency, soluble-metal loss	Thickener/filter sizing, water balance and correction from extraction to recoverable liquor.

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Continuous/pilot campaign	Recycle accumulation, RTD, operability, product quality	Scale-up basis, design margins and retirement of integration risk.

Source: Author synthesis from process mineralogy, beneficiation, atmospheric-leach, solid-liquid-separation, and scale-up literature (Acquah, Abaka-Wood, Addai-Mensah, *et al.*, 2025; König, 2021; Mweene *et al.*, 2024; Nascimento *et al.*, 2026; Pereira, 2026c; Xu *et al.*, 2021).

A screening-level net ore value, on a dry-ROM basis, can be written as NOV = Σm[10·GROM,m·RPII,m·Pm·Ym] − Ctotal, where m denotes payable metal, G is ROM grade in wt.%, RPII is element-specific recovery to product inventory, P is the metal-equivalent price, Y is contractual payability, and Ctotal includes mining, beneficiation, leaching, purification, utilities, residues, product finishing, and logistics on the same boundary. This equation is not proposed as a new valuation identity; its role is to force reactive-gangue and downstream penalties into the same decision basis as Ni grade.

Beneficiation is consequently justified by incremental value rather than grade upgrade alone. Rejecting mass is attractive when acid-reactive gangue falls faster than payable-metal recovery; conversely, a higher-grade concentrate can destroy value if Ni/Co losses, fine generation, or energy and separation penalties dominate. This feedback loop allows process economics to redefine ore, stockpiling, and blend strategy; a graphical version is provided as Supplementary Figure S5. (Acquah, Abaka-Wood, Addai-Mensah, *et al.*, 2025; Acquah, Abaka-Wood, Skinner, *et al.*, 2026; Asadrokht & Zakeri, 2022; Mweene *et al.*, 2024).

3.4. Leach chemistry, stoichiometric screening, and reactor design

Atmospheric-leach studies demonstrate a broad response window rather than a universal optimum. Table 3 retains four representative quantitative cases to make the heterogeneity visible without treating cross-study values as a meta-analytic optimum; ore mineralogy, pretreatment, acid expression, solids loading, redox conditions, and recovery basis differ materially among studies.

Table 3. Representative quantitative atmospheric sulfuric-acid leaching evidence

Study	Ore / representative conditions	Reported response	Feasibility interpretation
Hosseini Nasab *et al.* (2020)	Iron-rich laterite; calcined 500 °C for 2 h; 5 M H_2SO_4; S/L 0.1; 90 °C; 2 h; 370 rpm	Ni 65.9%; Co 63.1% recovery	Pretreatment and strong acid improve dissolution but add energy and reagent burden.

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da Silva Ribeiro *et al.* (2025)	Iron-rich laterite, Fe >35%; H_2SO_4 + ascorbic acid; optimized experimental design	Ni 51.8%; Co 80.6% recovery	Ni and Co optima need not coincide; additive cost and impurity load must be carried downstream.
Prasetya *et al.* (2025)	Limonitic laterite; 10 M H_2SO_4; 90 °C; S/L 0.1; 400 rpm	Ni 49.98%; Co 82.49% recovery	Aggressive acid conditions can favor Co relative to Ni and increase process severity.
Pereira (2026a)	Ferruginous laterite, ~1.08 wt.% Ni and ~33.53 wt.% Fe; 800 kg H_2SO_4/t; 300 min; ~95–100 °C	Ni 82.8% extraction; Fe 48.4% dissolution	A high-Ni extraction point may still impose substantial Fe-related purification and acid penalties.

Source: Values reported in the cited studies. They are used for comparative interpretation only and are not normalized across ores or proposed as universal design values.

For stoichiometric screening, the molar basis is explicit. If elemental Mg is treated as fully reactive MgO-equivalent material, $MgO + H_2SO_4 \rightarrow MgSO_4 + H_2O$; 98.079/24.305 = 4.035 kg H_2SO_4 per kg Mg, so 1 wt.% Mg in one dry tonne corresponds to approximately 40.4 kg H_2SO_4/t. For CaO-equivalent material, $CaO + H_2SO_4 \rightarrow CaSO_4 + H_2O$; 98.079/40.078 = 2.447 kg H_2SO_4 per kg Ca, so 1 wt.% Ca corresponds to approximately 24.5 kg H_2SO_4/t. These values are stoichiometric screening equivalents only; they are not predictions of operational acid consumption. Mineral host, accessibility, kinetics, precipitation, free-acid target, entrainment, and recycle determine the measured requirement.

The design criterion should therefore be a multi-response window that considers Ni and Co recovery, impurity dissolution, acid efficiency, rheology, solid–liquid separation, and residence time. Reactor volume scales approximately with $V_{reactor} \approx Q_{slurry} \cdot \tau \cdot F_{design}$; increasing extraction only by greatly increasing residence time can shift value into larger heated tankage, agitation power, inventory, and downstream separation. Recent atmospheric and HPAL studies reinforce the need to treat acid, solids loading, redox, temperature, and time as coupled variables. (Çoban & Baş, 2024; Dickson *et al.*, 2025; Duman & Can, 2022; Jeong *et al.*, 2025; Kang *et al.*, 2026; Pereira, 2026c, 2026d; Santos *et al.*, 2021; Surya *et al.*, 2026).

3.5. From testwork to an integrated design basis

A defensible program progresses from mineralogical characterization and batch screening to variability testing, solid–liquid separation, continuous operation, and pilot validation for the operations that control feasibility. High-Ni, high-Mg, high-Al/clay, high-Fe, transition, saprolitic-contamination, and fine-rich domains should be deliberately represented rather than

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averaged away. The laboratory optimum, the engineering design value, and the contractual guarantee should remain distinct. (Acquah, Skinner, Abaka-Wood, *et al.*, 2026; Acquah, Spiridonov, Abaka-Wood, *et al.*, 2026; Jeong *et al.*, 2025; Momberg & Marcus, 2025; Nascimento *et al.*, 2026).

Data models can support interpolation and uncertainty analysis, but their value depends on a physical and mineralogical data architecture. Machine-learning optimization and mine-level system-dynamics work demonstrate the availability of computational methods, yet no validated digital twin for an integrated atmospheric laterite circuit was identified in the reviewed corpus. Future datasets should connect block-model mineralogy, sample provenance, acid demand, kinetics, rheology, settling/filtration, recycle chemistry, product recovery, utilities, and cost with versioned uncertainty metadata, enabling probabilistic geometallurgical models to be updated as evidence matures. (Bradley *et al.*, 2025; Surya *et al.*, 2026).

3.6. Solid–liquid separation, purification, and element-specific overall recovery

Reactor extraction becomes commercial recovery only after dissolved metal is separated from residue, retained through impurity removal, recovered to the product stream, and finished on specification. Laterite slurries may contain fines, clays, precipitated Fe/Al phases, gypsum, and evolving surfaces that complicate thickening and filtration. HPAL CCD evidence is transferable as a warning that settling and washing can become dedicated design problems, but direct atmospheric scale-up data remain limited. (Keskin & Can, 2024; Tian *et al.*, 2023).

Purification can create substantial Ni/Co losses through coprecipitation, adsorption, occlusion, entrainment, or solvent-extraction co-loading. Iron precipitation, neutralization, alternative iron recovery, and solvent extraction therefore require recovery-retention data rather than assumed selectivity. (Caetano, Rodrigues, *et al.*, 2025; da Silva *et al.*, 2022; Das & Li, 2023; Dwi *et al.*, 2025; Faris, Fischmann, *et al.*, 2021; Faris, White, *et al.*, 2021; Mystrioti *et al.*, 2022).

For payable metal m (Ni or Co), overall recovery is expressed as $R_{PII,m} = R_{mine,m} \times R_{benef,m} \times X_{leach,m} \times RS\text{-}L_{,m} \times R_{purif,m} \times R_{product,m} \times R_{finish,m}$. Dilution is reconciled separately by ROM grade and throughput, rather than being hidden in a recovery factor. The multiplication itself is conventional; the contribution is to make the accounting element-specific and to enforce one terminal product-in-inventory boundary for route comparison. Table 4 links each stage to the corresponding recovery, cost, and risk consequence. (Andriyanto *et al.*, 2025; Demirel *et al.*, 2022; Ichlas *et al.*, 2020, 2026; Sahiruddin *et al.*, 2025).

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Table 4. Mine-to-product recovery, cost, and risk accounting framework

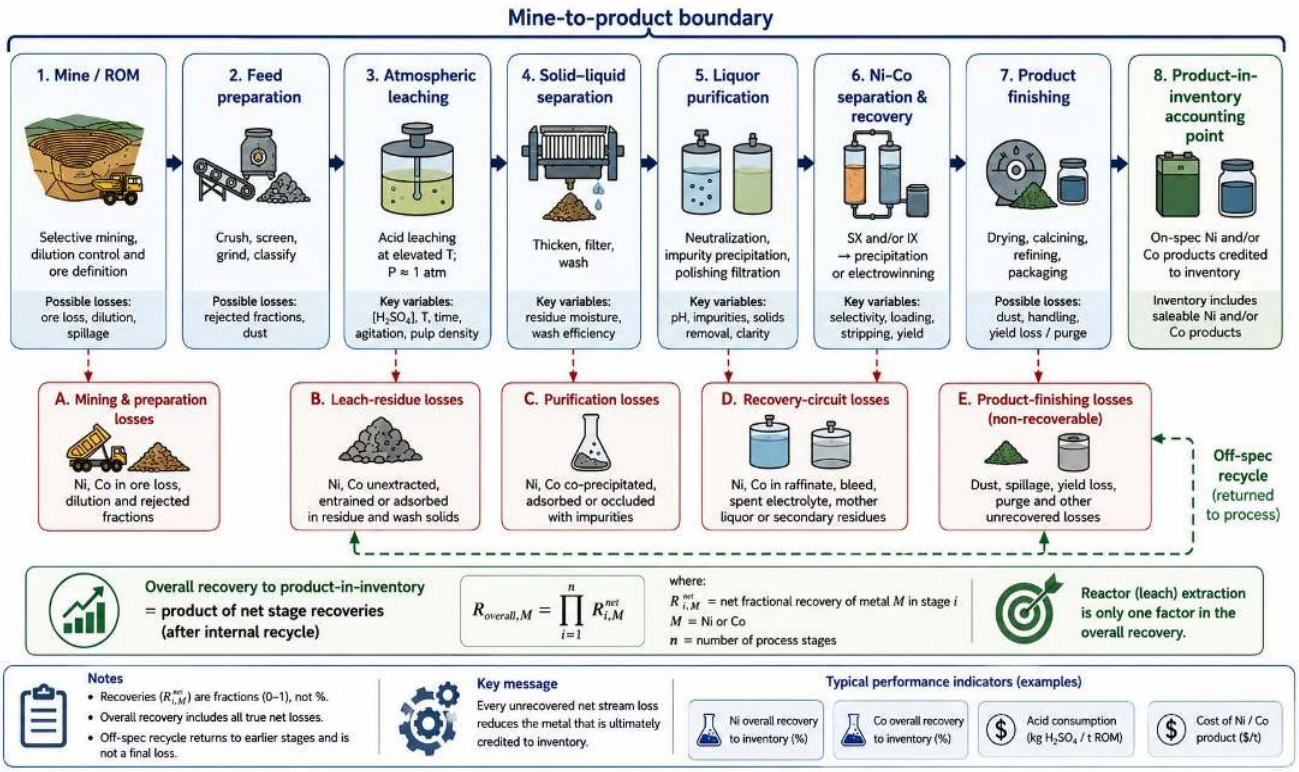
Stage	Principal metallurgical KPI	Main cost/design basis	Dominant feasibility risk
Mining / ROM	Rmine,m; dilution reconciled in ROM grade	Mining, haulage, rehandling, stockpiles	Selective test composite differs from mineable feed; reactive dilution.
Beneficiation/feed preparation	Rbenef,m; mass rejection; PSD/fines	Crushing, screening, scrubbing, grinding/desliming	Payable metal loss or the generation of fines can offset grade improvement.
Atmospheric leach	Xleach,m; acid efficiency; impurity dissolution	Acid, heat, agitation, tank volume, materials	High extraction may require excessive acid, residence time or impurity dissolution.
Solid-liquid separation / washing	RS-L,m; wash efficiency; cake moisture	Thickeners, filters, CCD/wash water, flocculant	Soluble Ni-Co loss, low flux, high moisture, water imbalance.
Purification	Rpurif,m; impurity removal/metal retention	Neutralization, SX/IX/precipitants, residue generation	Coprecipitation, adsorption or co-extraction of Ni-Co.
Product recovery/finishing	Rproduct,m × Rfinish,m; on-spec yield	Precipitation/crystallization, filtration, drying, packaging	Off-spec recycle, moisture, impurity penalties, payability.
Utilities/residues/logistics	Closed water-acid-energy balance; residue stability	Water/energy supply, acid logistics, residue facility, closure	Site-specific water/carbon exposure, recycle accumulation and long-term liability.

Source: Author integration of conventional stage recoveries and cost categories using laterite substance-flow, purification, product-recovery, construction, and environmental evidence (Connelly, 2025; Faris, Fischmann, *et al.*, 2021; Faris, White, *et al.*, 2021; Momberg & Marcus, 2025; Sahiruddin *et al.*, 2025; Tian *et al.*, 2023).

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The cumulative recovery concept is illustrated in Figure 2 by tracking nickel and cobalt from mine delivery through feed preparation, atmospheric leaching, solid–liquid separation, liquor purification, Ni–Co separation and recovery, product finishing, and final product-in-inventory accounting. Rather than treating reactor extraction as the dominant performance measure, the framework explicitly identifies metal losses at each stage—including mining and preparation losses, unextracted or entrained metal in leach residues, purification losses, recovery-circuit losses, and non-recoverable finishing losses—and shows how these losses multiply across the complete process chain. This representation provides the basis for calculating element-specific overall recovery and for linking metallurgical performance to acid consumption, product yield, and unit production cost.

Figure 2. Complete mine-to-product-in-inventory accounting boundary for atmospheric nickel-laterite processing



Source: Author-developed integration based on laterite substance-flow, purification, and product-recovery evidence, including da Silva *et al.* (2022), Faris, Fischmann, *et al.* (2021), Sahiruddin *et al.* (2025), and Tian *et al.* (2023).

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3.7. Water, acid, energy, carbon, and residue closure

Water closure should include ore moisture, slurry make-up, washing, reagent solutions, recycle, evaporation, product moisture, residue moisture, bleed streams, and treatment. Site water risk is inherently geographic: climate, make-up-water availability, discharge constraints, competing users, and residue-facility water management can alter the preferred route. The reviewed literature does not support a universal water-risk threshold, so project studies should report both specific water use and site-specific availability/restriction scenarios. (Bartzas & Komnitsas, 2024; Kinanti *et al.*, 2026; Roy *et al.*, 2025; Valencia *et al.*, 2025).

Acid closure must distinguish delivered acid, reaction demand, free-acid inventory, entrainment, neutralization, purge, and regenerated/recycled acid. Regeneration and mineral-carbonation concepts can reduce fresh reagent demand, but credits should be based on demonstrated recovery and compatibility with impurities, as recycling can accumulate Mg, sulfate, and minor elements. (Pereira, 2026e; Wang & Dreisinger, 2023; Zappala *et al.*, 2020).

Carbon accounting should include not only plant electricity and heat but also sulfuric acid production and transport where these contributions are material. The corpus provides life-cycle frameworks for nickel products but not a single defensible carbon factor for delivered acid across locations; consequently, acid-production technology, transport distance/mode, grid mix, fuel mix, and on-site heat integration should be treated as scenario inputs rather than generic constants. This is especially important when atmospheric leaching is compared with higher-pressure or thermal routes. (Bartzas & Komnitsas, 2024; Kinanti *et al.*, 2026; Roy *et al.*, 2025; Valencia *et al.*, 2025).

Residue evaluation should quantify solids mass, retained liquor, sulfate phases, neutralization products, soluble-metal losses, drainage chemistry, geochemical stability, water management, and closure liability. Near-zero-waste and by-product strategies can improve value, but marketability and long-term stability must be demonstrated. Scandium/chromite recovery, integrated valuable-metal recovery, and low-waste flowsheets illustrate possible credits without removing the need for conservative residue design. (Amador *et al.*, 2025; Li, Chen, *et al.*, 2023; O'Sullivan & Williams, 2025; Sun *et al.*, 2026).

3.8. CAPEX, OPEX, product specification, and economic risk

CAPEX must be estimated on the same mine-to-product boundary used for recovery: mining/ROM interfaces, feed preparation, leaching, solid–liquid separation, purification and Ni–Co recovery, product finishing, utilities and reagent storage, residue facilities, infrastructure,

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indirects, owner's costs, commissioning, contingency, and sustaining capital. Atmospheric operation may avoid autoclaves but can require large heated tankage, extensive washing/filtration, acid logistics, and residue infrastructure. Construction strategy, materials, modularization, and site logistics can therefore erase a simplistic pressure-based CAPEX comparison. (Connelly, 2025; Momberg & Marcus, 2025; Nikkhah, 2025).

OPEX should be reported both per tonne of ore and per unit of payable Ni (or Ni equivalent). Acid is a first-order variable but not a standalone cost: delivered acid, neutralization, energy, water, flocculants, purification reagents, labor, maintenance, analytical control, residue handling, product finishing, and logistics must be carried together. Remote-site acid transport and working capital can be material, and economic ore selection should therefore respond to site-specific acid price and reactive-gangue distribution. (Çoban & Baş, 2024; Roskha *et al.*, 2024; Pereira, 2026e).

Product specifications and payability can also change during the project life cycle. MHP impurity tolerance, refinery acceptance, and the quality requirements for nickel sulfate determine how much of the purification burden remains within the project boundary. Because future contractual specifications cannot be inferred from present laboratory purity alone, feasibility models should test payability and impurity-penalty scenarios while preserving flexibility for additional polishing or alternative product routing. (Andriyanto *et al.*, 2025; Demirel *et al.*, 2022; Ichlas *et al.*, 2026; Nikkhah, 2025; Sahiruddin *et al.*, 2025).

Economic robustness should be tested against uncertainty in Ni/Co prices, product payability, grade, reactive gangue, acid consumption, recovery, residence time, energy, CAPEX, schedule, and ramp-up. Nickel supply and downstream investment studies show that commodity cycles, policy, financing, and rapid capacity additions can materially affect project value. Deterministic base cases should therefore be complemented by coherent low/base/high scenarios and, where defensible distributions exist, probabilistic analysis. (Bradley *et al.*, 2025; Imami & Noveria, 2026; Kadir & Hakam, 2026; Schodde & Guj, 2025; Soamole & Mokodompit, 2025).

3.9. Route selection, decision gates, and research priorities

No route is universally superior. Atmospheric sulfuric-acid leaching, HPAL, heap leaching, Caron/reduction-ammonia, RKEF/ferronickel, and chloride/hybrid systems redistribute pressure, energy, reagent, kinetics, selectivity, solid-liquid separation, residue, and product risks. Table 5 normalizes these alternatives by feed/product fit and dominant feasibility penalties rather

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than by reactor extraction alone. (Agatzini-Leonardou *et al.*, 2021; Ilyas *et al.*, 2020; McDonald & Li, 2020; McDonald & Whittington, 2008a, 2008b; Oxley *et al.*, 2025; Pereira, 2026b; Shabanov *et al.*, 2026; Stanković *et al.*, 2022; Tauakelov *et al.*, 2025; Whittington & Muir, 2000; Zevgolis & Daskalakis, 2021).

Table 5. Normalized route-selection matrix for major nickel-laterite processing options

Route	Preferred feed/product context	Principal advantage	Dominant limitation/risk
Atmospheric H_2SO_4 leaching	Limonitic/ferruginous domains with acceptable acid efficiency; hydrometallurgical intermediates	Lower pressure containment; conventional tank-based equipment; modular testability	Acid consumption, long residence time, impurity dissolution, large slurry inventory and S-L burden.
HPAL	Limonites where high T/P materially improve kinetics/selectivity; MHP/MSP	High reaction intensity; short residence relative to atmospheric routes; established commercial base	Autoclave severity, materials, scaling, construction complexity, high CAPEX and ramp-up risk.
Heap leaching	Permeable/agglomeratable ore with acceptable long-cycle recovery	Low tankage and potentially lower energy intensity	Cycle time, permeability, solution distribution, wash/recovery losses, climate and pad management.
Caron / reduction-ammonia	Selected laterites compatible with reduction roasting and ammoniacal recovery	Different selectivity pathway; historical industrial precedent	Thermal energy demand, complex gas/reagent handling, generally lower persistence in modern project pipelines.
RKEF / ferronickel	Saprolitic/high-Mg feeds directed to stainless-steel value chain	Mature pyrometallurgical route; direct ferronickel/NPI product	Very high energy intensity; limited Co recovery; product not aligned with sulfate/battery route.
Chloride / hybrid routes	Feeds or residues where chloride selectivity/recycle or combined routes create value	Potential selectivity and alternative impurity control; route flexibility	Corrosion, chloride management/recycle, reagent recovery, materials and lower commercial maturity for many variants.

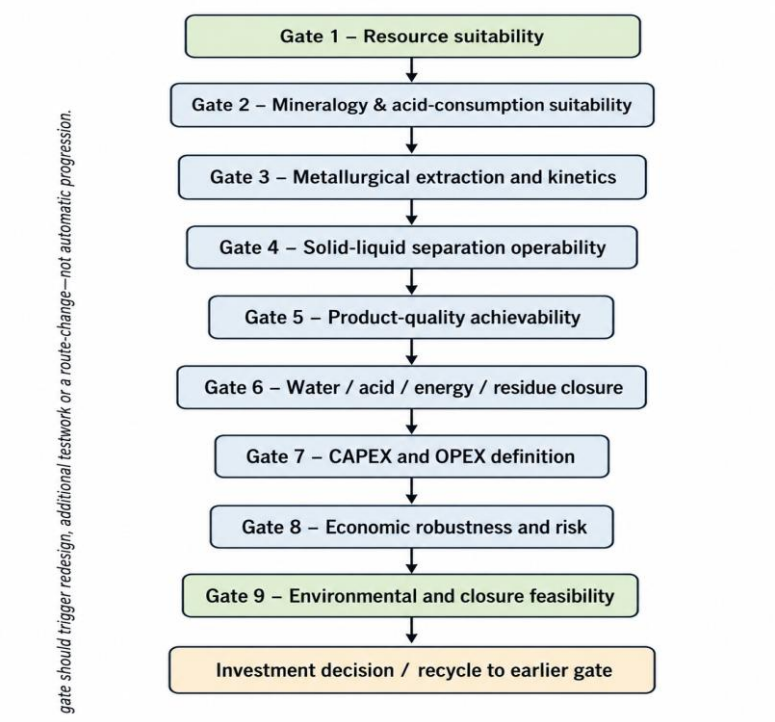
Source: Author synthesis from foundational and contemporary laterite route reviews, project evidence, and comparative studies cited in Section 3.9. The matrix is conditional and does not imply a universal ranking.

The stage-gate structure in Figure 3 converts this comparison into an iterative decision process. Failure at a gate is not necessarily project failure; it can trigger a new blend, additional

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testwork, a changed product, a modified purification/residue strategy, or a different route. This is where the framework differs from a linear testwork checklist: economic and environmental results feed back to ore definition and route selection.

Figure 3. Stage-gate feasibility decision framework for atmospheric leaching of nickel laterites



Source: Author-developed integration of the evidence hierarchy and mine-to-product framework; route-comparison context from Chi *et al.* (2026), Msumange *et al.* (2026), Pandey *et al.* (2023), and Stanković *et al.* (2020).

Priority research should therefore focus on integrated continuous campaigns; deliberate ore-variability programs; coupled acid/free-acid/neutralization balances; scale-up of settling, filtration, and washing; steady-state Mg/sulfate recycle behavior; site-specific water and carbon scenarios; product-specification/payability flexibility; residue geochemical stability; by-product recovery; and data architectures capable of supporting probabilistic geometallurgy and future digital twins. Alternative leachants, selective pretreatment, acid regeneration, and low-waste routes should be advanced when they reduce the total cost, environmental burden, or risk of producing the specified product—not merely when they raise dissolution in isolated tests. (Acquah, Spiridonov, Abaka-Wood, *et al.*, 2026; Li, Chen, *et al.*, 2023; Li *et al.*, 2025; O'Sullivan

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& Williams, 2025; Pereira, 2026e; Sun *et al.*, 2026; Wang & Dreisinger, 2023; Zappala *et al.*, 2020).

3.10. Limitations of the review

The review is narrative and structured, not systematic. Google Scholar was the principal discovery interface; original hit counts and exclusion logs were not retained; historical back-searching was selective; and the evidence categories were assigned by the single author without independent duplicate coding. The source-by-source audit in Supplementary Table S1 improves transparency but does not eliminate the need for classification judgment. The underlying studies remain heterogeneous in ore type, mineralogy, pretreatment, acid expression, solids loading, temperature, residence time, analytical basis, and product boundary. Downstream and solid–liquid-separation evidence is partly transferred from HPAL and refining because integrated atmospheric data are scarce. Quantitative examples are therefore comparative rather than meta-analytic, and the economic equations and decision boundaries require project-specific calibration.

4. FINAL CONSIDERATIONS

Atmospheric leaching of nickel laterites should be evaluated as an integrated mine-to-product-in-inventory system rather than as a reactor-extraction problem. Ore definition must incorporate mineral host, reactive gangue, dilution, beneficiation response, acid demand, downstream recovery, and site economics, not nickel grade alone.

Acid consumption is a first-order economic and environmental variable because reactive gangue propagates into neutralization, dissolved-impurity load, sulfate-rich residues, water demand, equipment duties, logistics, and potentially carbon intensity. Stoichiometric screening values are useful only when clearly separated from operational acid consumption.

The preferred metallurgical KPI is element-specific recovery to the defined product-in-inventory boundary. The economic optimum will not necessarily coincide with maximum extraction, maximum acid dosage, finest grinding, or longest residence time. Project economics, water/carbon constraints, product quality, and residue closure should feed back to the mine plan, blending strategy, and route decision.

The central contribution of the review is the integration of established engineering relationships into an auditable ten-step and stage-gated feasibility architecture. The current evidence base remains strongest for batch chemistry and weakest for integrated continuous

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atmospheric operation; consequently, continuous and pilot validation should increase as a project advances toward feasibility and execution.

DECLARATIONS

Funding: No external funding is declared for the preparation of this critical review.

Conflicts of interest: The author declares no known competing financial interests or personal relationships that could have appeared to influence the work.

Data availability: No new experimental dataset was generated. The review is based on the literature corpus cited in the manuscript; source-by-source evidence coding is provided in Supplementary Table S1.

Author contributions: Conceptualization, methodology, critical analysis, synthesis, writing—original draft, and writing—review and editing: author.

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