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The Caron Process for Nickel Laterites: A Critical Review of Recent Developments, Limitations, and Research Gaps

Antonio Clareti Pereira*

PhD in Chemical Engineering, Federal University of Minas Gerais – UFMG, Department of Chemical Engineering Belo Horizonte – MG – Brazil. https://orcid.org/0000-0001-8115-4279

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ABSTRACT

Original Research Article

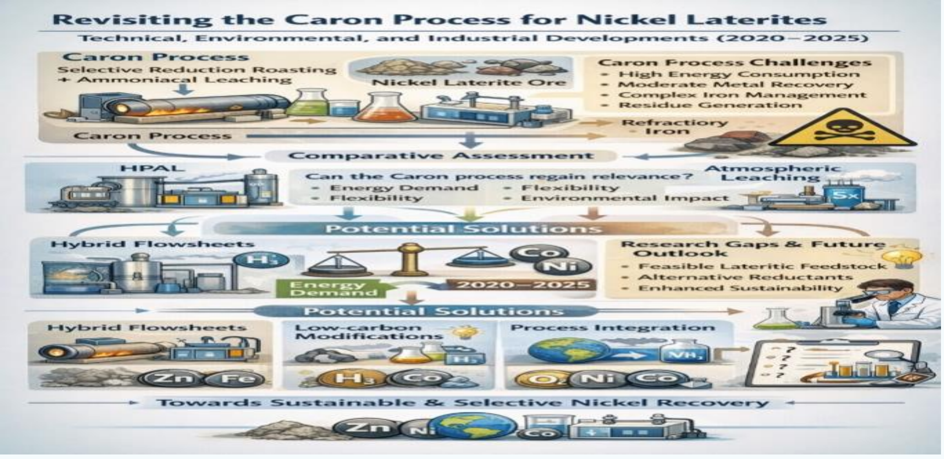
The Caron process is among the earliest hydrometallurgical technologies for processing nickel laterite, combining selective reduction roasting with ammoniacal leaching to recover nickel and cobalt. Although historically significant, the process has gradually lost industrial relevance due to high energy consumption, moderate recoveries, and competition from high-pressure acid leaching (HPAL) and atmospheric leaching. This critical review reassesses the Caron process based on literature published between 2020 and 2025, with emphasis on feedstock characteristics, reduction thermochemistry, ammoniacal leaching mechanisms, metal recovery efficiency, and environmental performance. Mineralogical constraints associated with iron-rich laterites, selectivity challenges during reduction, and reagent recycling limitations are systematically analyzed. Recent efforts involving process intensification, hybrid flowsheets, and low-carbon modifications, including alternative reducing agents and improved heat integration, are critically evaluated. A comparative assessment indicates that while the classical Caron process remains disadvantaged in terms of energy intensity and iron management, selected improvements may enhance its competitiveness for specific low-grade or high-iron laterites. The review identifies key research gaps and defines the technical, environmental, and economic conditions under which the Caron process could regain relevance in future sustainable nickel supply chains. Rather than positioning Caron as a universal alternative, this review defines its conditional and niche relevance.

Keywords: Caron process, Nickel laterites, Ammoniacal leaching, Selective reduction, Sustainable nickel processing, Hydrometallurgy, Life cycle assessment.

Highlights

- Critical reassessment of the Caron process based on literature from 2020–2025
- Analysis of mineralogical and thermochemical constraints affecting nickel recovery
- Comparison of Caron performance with HPAL and atmospheric leaching routes
- Evaluation of energy demand, reagent recycling, and environmental impacts
- Identification of niches and research pathways for low-carbon Caron-based flowsheets

Graphical abstract



*Corresponding author: Antonio Clareti Pereira
PhD in Chemical Engineering, Federal University of Minas Gerais – UFMG, Department of Chemical Engineering Belo Horizonte – MG – Brazil

1. Introduction

Nickel laterite ores make up about 55–60% of the world’s nickel resources and are increasingly important due to rising demand in stainless steel, superalloys, and battery materials for energy storage and electric vehicles (Kalungi et al., 2024; Sun et al., 2024). As sulfide deposits decline or face environmental and economic barriers, lateritic ores—particularly limonitic, saprolitic, and transitional types—are becoming dominant in the global nickel supply (Pandey et al., 2023; Bartzas et al., 2021).

Nickel laterites are abundant but pose metallurgical challenges due to their complex mineralogy, high iron content, variable nickel grades, and association with silicate and oxide phases (Chen et al., 2021; Kaczan et al., 2021). These issues lead to diverse processing routes: pyrometallurgical, hydrometallurgical, and hybrid pyro-hydrometallurgical methods (ChuanYu et al., 2024; Moats & Davenport, 2024; Caetano et al., 2025).

The Caron process, combining reduction roasting and ammoniacal leaching, is one of the earliest hybrid technologies for laterite processing. Developed in the mid-20th century, it selectively reduces nickel and cobalt oxides in limonitic and transitional ores, minimizing iron dissolution (Stanković et al., 2020; Ilyas et al., 2020). Although its industrial use has declined due to high energy costs and modest recoveries, it remains of academic and industrial interest as a benchmark and a platform for process improvements with additives, reductants, and modified strategies (Angulo-Palma et al., 2024; Chen et al., 2021).

Pyrometallurgical such as the RKEF process, dominate for saprolitic laterites, producing ferronickel for stainless steel (Tian et al., 2021; Vahed et al., 2021). However, RKEF is capital- and energy-intensive, unsuitable for low-grade limonitic ores, leading to renewed interest in alternative hydrometallurgical methods, including high-pressure acid leaching (HPAL), atmospheric leaching, bioleaching, and hybrids like reduction–leaching (Çoban & Baş, 2024; Abdollahi et al., 2024; Hariyanto et al., 2023).

Recent years have seen increased focus on process sustainability, including energy efficiency, greenhouse gas emissions, waste valorization, and the production of battery intermediates such as mixed hydroxide precipitates (MHP) and nickel sulfate (Valencia et al., 2025; Astuti et al., 2023). Laterite processing is being reevaluated for metallurgical performance, environmental impact, and integration into the circular economy (Bartzas et al., 2021; Kirimli, 2023).

The objective of this review is to critically analyze and compare the Caron process with alternative pyrometallurgical and hydrometallurgical routes for nickel laterite processing, with an emphasis on:

a) fundamental process chemistry and mineralogical selectivity.
b) technological evolution and process modifications reported between 2020 and 2025.
c) suitability of each route for different laterite types (limonite, saprolite, and transitional ores); and
d) emerging requirements related to sustainability and battery-grade nickel production.

By synthesizing experimental studies, industrial reports, and recent review articles, this work aims to clarify the current and future role of the Caron process in the broader landscape of nickel laterite metallurgy and to identify research gaps and development opportunities.

To achieve these objectives in a structured and reproducible manner, the following section outlines the methodology for the literature review, including database selection, keyword strategy, time window definition, inclusion and exclusion criteria, and the thematic classification of the analyzed studies.

2. Methodology

This study is a critical narrative review with systematic elements, reported in accordance with the PRISMA 2020 guidelines (Page et al., 2021). The review compares major nickel laterite processing routes, with an emphasis on the Caron process relative to RKEF, high-pressure acid leaching (HPAL), atmospheric leaching, selective reduction–leaching, and bioleaching technologies.

A structured literature search was conducted in Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, MDPI, and Google Scholar, prioritizing publications from 2020 to 2025. Earlier references were included selectively to provide context for the technological fundamentals. Search terms included combinations of nickel laterite, Caron process, reduction roasting, ammoniacal leaching, RKEF, HPAL, selective reduction, and bioleaching.

Eligible documents comprised peer-reviewed articles, books or book chapters, conference proceedings, theses, and institutional reports. Studies were included if they reported or enabled comparisons of operating conditions, Ni/Co recovery and selectivity relative to iron, and/or energy and reagent demand. Irrelevant studies, preprints, and works lacking process relevance were excluded.

For each selected study, data were extracted on ore type, processing route, key operating parameters, metallurgical performance, and sustainability indicators, when available. Evidence was synthesized using route-specific thematic clustering, and discrepancies were interpreted in terms of ore mineralogy, selective reduction windows, and coupling between thermal and leaching stages. In total, 113 references were consolidated and critically assessed.

To ensure transparency and reproducibility in the literature selection process, the identification, screening, eligibility, and inclusion of studies were conducted following the PRISMA 2020 framework. Figure 1 summarizes the systematic flow of records throughout the review process, from initial database identification to the final qualitative synthesis.

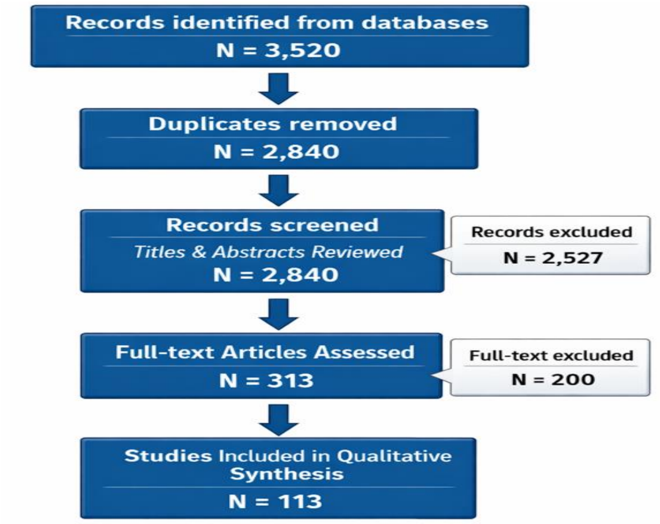


Figure 1. PRISMA 2020 flow diagram of the literature review process. Adapted from Page et al. (2021).

As shown in Figure 1, an initial set of 3,520 records was identified across multiple scientific databases. After removing duplicates and screening by titles, abstracts, and full texts, 113 studies met the inclusion criteria for qualitative synthesis. The selection focused on studies reporting metallurgical performance, operating conditions, and energy or reagent demand, enabling comparison between the Caron process and other nickel laterite routes.

3. Overview of the caron process

3.1. General description of the classical flowsheet

The Caron process is a hybrid pyro-hydrometallurgical method that recovers nickel and cobalt from lateritic ores, particularly limonitic and transitional types, through thermal pre-treatment, reduction roasting, and ammoniacal leaching. Although largely replaced by RKEF and HPAL in industrial practice, it remains a key benchmark for understanding selective reduction and alkaline leaching in laterites (Stanković et al., 2020; Moats & Davenport, 2024).

Figure 2 shows the classical Caron process flowsheet, highlighting the sequence of drying/calcination, selective reduction roasting, ammoniacal leaching, and downstream solution processing for nickel and cobalt recovery.

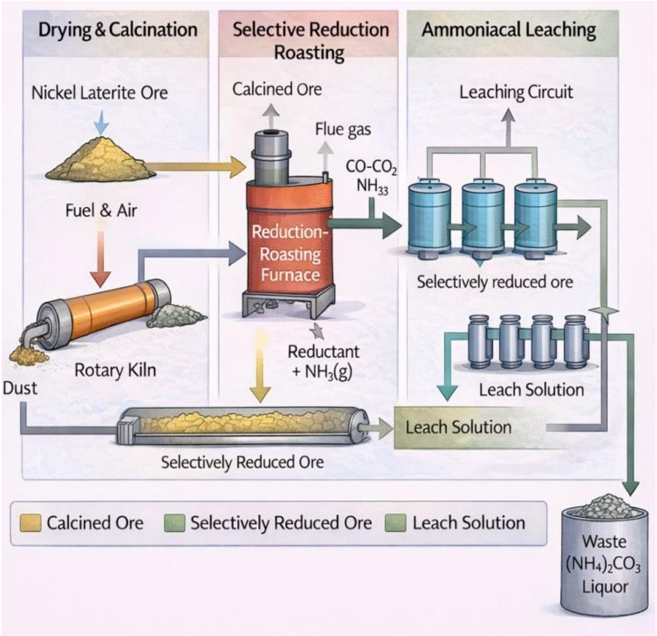


Figure 2. Classical Caron process flowsheet for nickel laterite processing. Adapted from Stanković et al. (2020), Moats and Davenport (2024), and Caetano et al. (2025).

As shown in Figure 2, the Caron process relies on solid-state transformations to convert nickel and cobalt oxides into metallic or low-valence forms before leaching, while iron is preferentially retained in the solid phase. This selectivity underpins both the strengths and limitations of the process across different laterite mineralogies (Pandey et al., 2023).

3.2. Drying and calcination

The first stage dries and calcines the laterite ore at 700–900 °C to remove water and decompose goethite into hematite, increasing porosity and preparing for reduction during roasting (Chen et al., 2021; Hosseini Nasab et al., 2020).

Calcination is particularly critical for limonitic ores, where high hydroxyl content would otherwise hinder reduction kinetics and gas–solid contact. Inadequate calcination has been shown to reduce nickel recovery and energy efficiency (Bhaskar & Bhoi, 2021).

3.3. Selective reduction roasting (NiO/CoO → Ni/Co)

After calcination, the ore undergoes selective reduction roasting, typically in a rotary kiln at 750–850 °C under a controlled reducing atmosphere ($CO–CO_2$ or H_2-based). The objective is to reduce NiO and CoO to metallic Ni and Co while minimizing the reduction of iron oxides (Chen et al., 2021; Ilyas et al., 2020).

The key reactions may be simplified as:

- $NiO + CO \rightarrow Ni + CO_2$
- $CoO + CO \rightarrow Co + CO_2$

Iron oxides are ideally retained as Fe_2O_3 or Fe_3O_4, thereby limiting iron dissolution during leaching. Recent studies show that additives such as coal–oil mixtures, sulfur-bearing compounds, or alkali salts can enhance selectivity and kinetics, albeit at the expense of increased process complexity (Angulo-Palma et al., 2024; Angulo-Palma et al., 2025).

Table 1 highlights representative operating windows reported for selective reduction roasting in the Caron process.

Table 1. Typical operating conditions for selective reduction roasting in the Caron process. Adapted from Chen et al. (2021), Ilyas et al. (2020), and Angulo-Palma et al. (2024)

Parameter	Typical range / condition	Technical relevance
Reduction temperature (°C)	650 – 850	Controls NiO/CoO reduction while suppressing Fe metallization
Heating device	Rotary kiln / shaft furnace	Enables controlled gas–solid contact and residence time
Residence time (min)	30 – 120	Influences extent of Ni/Co metallization and calcine porosity
Reducing atmosphere	$CO–CO_2$, $H_2–H_2O$, or mixed gases	Determines reduction potential and selectivity window
Reductant source	Coal, CO gas, H_2, coal–oil mixtures	Affects kinetics, heat balance, and Fe reduction tendency
CO concentration (vol.%)	5 – 30	Higher values increase Ni reduction but risk Fe metallization
H_2 concentration (vol.%)	5 – 20	Promotes fast reduction; requires strict temperature control
Oxygen partial pressure (pO_2)	$10^{-15} – 10^{-18}$ atm	Selectivity window for Ni/Co vs. Fe oxides
Calcine mineralogy	Hematite + dispersed Ni/Co metal	Favors ammoniacal leachability
Additives (optional)	Na_2SO_4, sulfur compounds, coal–oil blends	Improve selectivity and metal particle growth
Target Ni metallization (%)	70 – 90	Required for efficient ammoniacal leaching
Target Fe metallization (%)	< 10	Excess Fe increases NH_3 consumption and losses

The data in Table 1 highlights the narrow balance among temperature, reductant potential, and residence time required to maximize Ni/Co reduction while suppressing iron metallization, a key challenge that has historically constrained Caron process performance.

3.4. Ammoniacal leaching (NH_3–$(NH_4)_2CO_3$)

The reduced calcine is leached with an ammoniacal carbonate solution (NH_3–$(NH_4)_2CO_3$) at atmospheric pressure. Metallic nickel and cobalt dissolve by forming stable ammine complexes, whereas iron remains largely insoluble as oxide or hydroxide phases (Ilyas et al., 2020; Hu et al., 2022).

Representative dissolution reactions include:

- $Ni + 6NH_3 \rightarrow [Ni(NH_3)_6]^{2+}$
- $Co + 6NH_3 \rightarrow [Co(NH_3)_6]^{2+}$

This step provides the core selectivity advantage of the Caron process. However, incomplete reduction, low calcine porosity, or excessive iron metallization can significantly reduce leaching efficiency (Stanković et al., 2020; Borda & Torres, 2023).

3.5. Suitable laterite ore types: limonite vs. saprolite

The Caron process is best suited to limonitic and transitional laterites, characterized by high iron content and nickel hosted primarily in oxide phases. In contrast, saprolitic ores, where nickel is structurally bound in magnesium silicates, exhibit poor response to selective reduction and ammoniacal leaching (Kaczan et al., 2021; Tian et al., 2021).

Mineralogical classification, particularly the presence of garnierite and serpentine phases, remains a decisive criterion for selecting appropriate laterite processing routes (Husain et al., 2021).

To contextualize ore suitability, a schematic comparison of laterite types and preferred processing routes is shown in Figure 3.

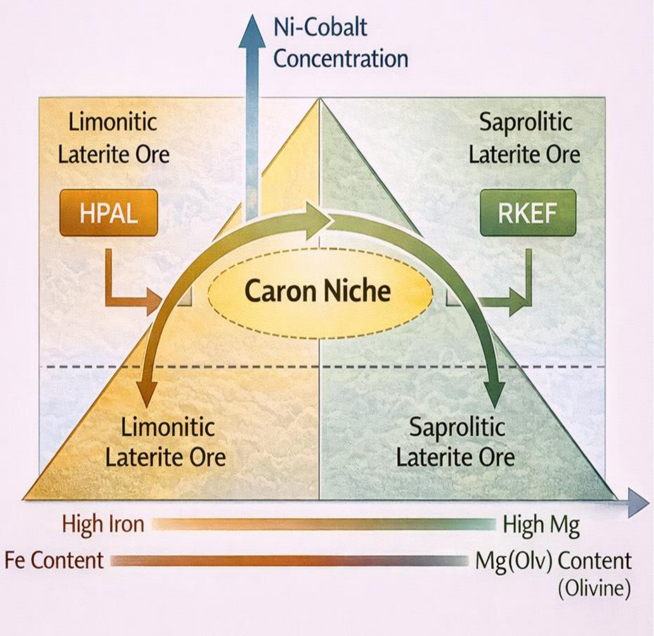


Figure 3. Schematic relationship between laterite ore type and preferred processing route, highlighting the niche applicability of the Caron process. Adapted from Pandey et al. (2023), Caetano et al. (2025), and Moats and Davenport (2024

Figure 3 shows that the declining industrial use of the Caron process is primarily tied to feedstock availability and energy intensity rather than fundamental chemical limitations, underscoring its continued relevance in laboratory-scale and process-modification studies.

4. Feedstock characteristics and mineralogical constraints

4.1. Typical chemical composition of laterites processed by the Caron route

Nickel laterites treated by the Caron process are mainly limonitic or transitional ores with high Fe (30–55 wt.% Fe_2O_3), moderate to low Ni (0.8–1.5 wt.% Ni), and variable MgO, Al_2O_3, MnO, and Cr_2O_3. These differ from saprolitic laterites, richer in Mg-silicates and unsuitable for ammoniacal leaching.

Table 2 illustrates representative chemical compositions reported for lateritic ores that have been historically and recently evaluated for the Caron process.

Table 2. Typical chemical composition (wt.%) of lateritic ores evaluated for the Caron process.Adapted from Pandey et al. (2023), Kaczan et al. (2021), and Domínguez-Carretero et al. (2024).

Component (wt.%)	Limonitic laterite	Transitional laterite	Saprolitic laterite	Process relevance (Caron)
Ni	0.8 – 1.5	1.0 – 1.8	1.5 – 2.5	Target metal; best liberated from goethitic hosts
Co	0.05 – 0.15	0.05 – 0.12	< 0.05	Co commonly enriched in limonites
Fe_2O_3	30 – 55	20 – 40	10 – 20	High Fe favors Caron but risks Fe metallization
MgO	1 – 5	5 – 15	20 – 35	High Mg inhibits selective reduction and leaching
Al_2O_3	3 – 10	5 – 15	2 – 8	Influences slagging and sintering behavior
SiO_2	5 – 15	15 – 30	30 – 45	Associated with silicates; hampers Caron efficiency
MnO	0.5 – 3.0	0.5 – 2.0	< 1.0	May partially dissolve; affects solution chemistry
Cr_2O_3	0.5 – 2.0	0.5 – 1.5	0.5 – 1.0	Forms refractory spinels during roasting
CaO	0.1 – 1.0	0.2 – 2.0	0.1 – 1.5	Minor fluxing effect
Loss on ignition (LOI)	8 – 15	5 – 10	3 – 8	Reflects hydroxyl content and calcination demand

The data in Table 2 shows that iron is the dominant component of Caron feedstocks, underscoring the need for selective reduction strategies that minimize Fe metallization while enabling efficient recovery of Ni and Co.

4.2. Role of Fe, Mg, Al, Mn, and Cr on process performance

Iron (Fe) plays a dual role in the Caron process: a high Fe content suppresses nickel smelting and favors reduction–leaching, but excess Fe promotes metallic iron formation, catalyzing ammonia decomposition and increasing reagent use. Iron-rich matrices can also trap Ni particles, limiting leaching (Ilyas et al., 2020; Borda & Torres, 2023).

Magnesium (Mg), commonly associated with serpentine and chlorite phases, is particularly detrimental. Mg-bearing silicates inhibit selective reduction by stabilizing nickel in the silicate lattice and reducing calcine porosity, leading to poor Ni recoveries under ammoniacal conditions (Chen et al., 2021; Tian et al., 2021).

Aluminum (Al), typically present as gibbsite or incorporated into goethite, increases slag viscosity during roasting and can hinder gas diffusion. Although Al does not dissolve during ammoniacal leaching, its indirect effects on thermal behavior and particle sintering are non-negligible (Bhaskar & Bhoi, 2021).

Manganese (Mn) and chromium (Cr) are present at low levels but affect processing. Mn can partially dissolve during leaching, complicating purification, while Cr remains inert but promotes refractory spinel formation during roasting (Grimsey et al., 2020; Makovskaya & Bryantseva, 2021).

4.3. Influence of mineralogy: goethite, hematite, serpentine, and chlorite

The mineralogical host of nickel affects Caron process efficiency. In limonitic ores, nickel mainly binds with goethite, substituting Fe^{3+} in the lattice. Calcination turns goethite into hematite, releasing nickel into more reducible oxides (Chen et al., 2021; Hosseini Nasab et al., 2020). Variations in grinding overburden, saprolite, and mixed feeds complicate feed preparation and laterite processing (Correa-Cala et al., 2025).

In contrast, saprolitic ores are dominated by serpentine and chlorite, in which nickel is structurally bound within Mg-silicate frameworks. These minerals resist both reduction and ammoniacal dissolution, making the Caron process ineffective for such feedstocks (Kaczan et al., 2021; Tian et al., 2021).

Figure 4 schematically illustrates the dominant nickel-hosting mineral phases in limonitic and saprolitic laterites and their implications for Caron processing.

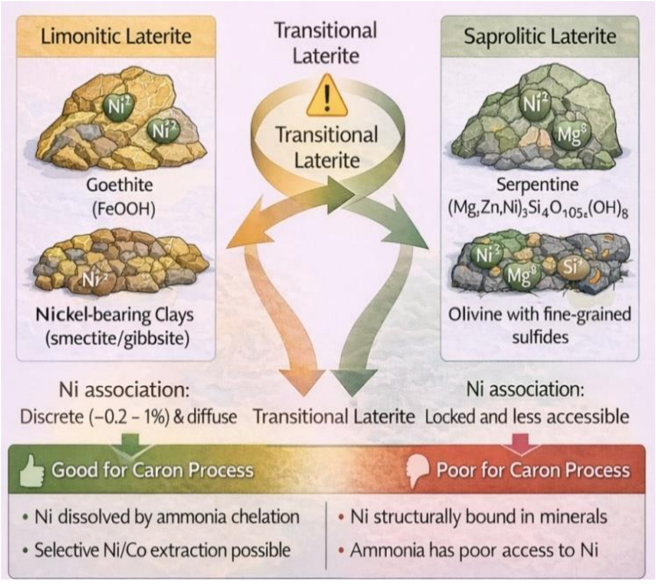


Figure 4. Schematic representation of nickel association in lateritic mineral phases and its impact on Caron process suitability. Adapted from Chen et al. (2021), Pandey et al. (2023), and Kaczan et al. (2021).

As shown in Figure 4, the liberation of nickel during the goethite-to-hematite transformation is a prerequisite for successful selective reduction, thereby explaining the strong mineralogical constraint on Caron feedstock selection.

4.4. Constraints imposed by low-grade and high-iron ores

Processing low-grade (<1.0 wt.% Ni) and very high-Fe laterites poses a fundamental limitation for the Caron process. Lower nickel grades increase energy intensity per unit of recovered metal, while high iron contents increase the risk of Fe metallization and ammonia losses (Stanković et al., 2020; Valencia et al., 2025).

Recent studies emphasize that although process modifications and additives can partially mitigate these effects, feedstock mineralogy remains the dominant constraint, often outweighing gains from reactor design or reagent optimization (Caetano et al., 2025; Zappala et al., 2024).

5. Reduction stage: thermochemistry and process control

5.1. Typical operating conditions (temperature, atmosphere, residence time)

The Caron reduction stage converts NiO/CoO to metallic Ni/Co while suppressing Fe metallization through controlled solid–gas reduction at ~650–850 °C, with residence times from tens of minutes to hours, depending on reactor type and ore reactivity (Pandey et al., 2023; Zevgolis & Daskalakis, 2022). The “optimal window” is narrower than older descriptions due to mineralogy-driven sintering, gas diffusion limits, and temperature excursions, which can quickly lead to excess Fe reduction and refractory phase formation (Palma et al., 2025; Coelho et al., 2025).

To consolidate the scattered operational evidence, Table 3 consolidates typical reduction windows and their reported effects on Ni/Co recovery and Fe carryover.

Table 3. Typical operating conditions for Caron-type selective reduction (temperature, atmosphere, residence time) and major reported outcomes. Adapted from Pandey et al. (2023), Sun et al. (2021), Chen et al. (2021), and Palma et al. (2025).

Parameter	Typical range / condition	Observed outcome	Implication for Caron process
Reduction temperature (°C)	650 – 700	Partial NiO/CoO reduction	Limited Ni metallization; low leachability
Reduction temperature (°C)	700 – 800	Selective Ni/Co metallization	Optimal window for ammoniacal leaching
Reduction temperature (°C)	> 800	Fe metallization onset	Increased NH_3 consumption and losses
Residence time (min)	20 – 40	Incomplete reduction	Insufficient Ni/Co recovery
Residence time (min)	40 – 90	Dispersed Ni/Co metal formation	Favorable microstructure for leaching
Residence time (min)	> 120	Sintering and encapsulation	Reduced porosity and leach kinetics
Reducing atmosphere	CO–CO_2 (5–20% CO)	Controlled reduction potential	Balance between selectivity and kinetics
Reducing atmosphere	H_2–H_2O (5–15% H_2)	Fast Ni reduction	Requires strict temperature control
Reducing atmosphere	Excess CO or H_2	High metallization of Fe	Loss of selectivity
Oxygen partial pressure (pO_2)	10^{-16} – 10^{-18} atm	Ni/Co reduced, Fe stable	Target selectivity window
Additives (optional)	Na_2SO_4, sulfur-bearing compounds	Enhanced Ni particle growth	Improved leachability; added complexity
Ni metallization (%)	70 – 90	High Ni dissolution	Efficient ammoniacal leaching
Fe metallization (%)	< 5 – 10	Limited Fe dissolution	Lower reagent consumption
Calcine microstructure	Porous, fine Ni metal	Fast leach kinetics	Desired Caron calcine
Calcine microstructure	Dense, spinel-rich	Poor accessibility	Ni losses to residue

A recurring conclusion across studies is that “good selectivity” is not simply a function of temperature; it emerges from the coupled control of **pO_2/pCO**, residence time, and heat-release patterns that regulate the reduction front and prevent iron runaway.

5.2. Selectivity of Ni/Co reduction versus Fe

Selectivity depends on conditions where NiO and CoO reduce preferentially, while Fe oxides largely stay unreduced. Iron exists in multiple forms (e.g., hematite, magnetite, wüstite, Fe). Once wüstite forms, the system becomes sensitive to small changes in gas composition and temperature (Chen et al., 2021; Khasanov et al., 2022). Increasing CO, temperature, or time improves Ni reduction but also pushes Fe toward metallization, thereby reducing the selectivity of ammoniacal leaching (Sun et al., 2021; Ilyas et al., 2020).

A critical limitation in the recent literature is that “selective reduction” is sometimes claimed based on bulk assays that do not resolve where Ni resides (metallic particles vs. silicate-bound Ni) or explicitly quantify iron metallization—two metrics that strongly predict Caron leachability (Chen et al., 2021; Hou, 2022).

Figure 5 presents a conceptual thermodynamic selectivity map that links reduction potential to the stability of NiO/CoO and iron oxides under Caron-relevant conditions.

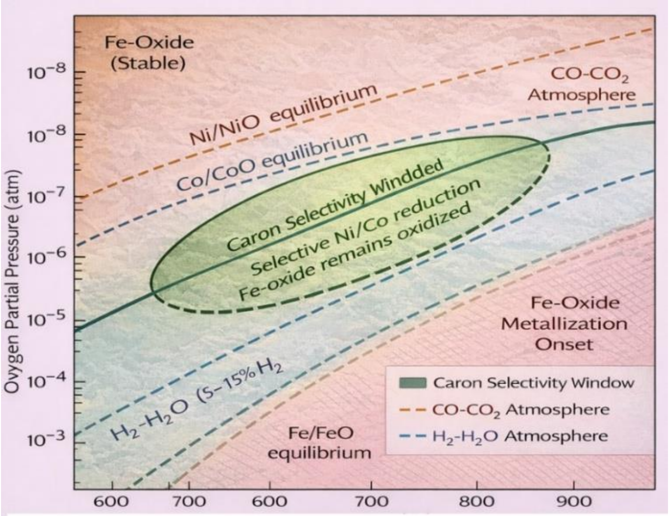


Figure 5. Conceptual thermodynamic selectivity diagram for NiO/CoO reduction relative to iron oxide reduction under controlled reducing atmospheres. Adapted from Chen et al. (2021), Khasanov et al. (2022), and Pandey et al. (2023).

The literature trend is clear: thermodynamics can indicate feasibility, but process control determines whether the system remains within a selectivity corridor long enough to produce a leachable calcine.

5.3. Formation of metallic phases and refractory spinels

Two competing microstructural outcomes dominate Caron reduction performance:

1. Dispersed Ni/Co metallic particles accessible to ammoniacal leaching
2. Encapsulated metal and/or refractory spinel formation (e.g., ferrites/spinels) that decreases leachability and can “lock” Ni/Co in stable matrices

Refractory spinels and ferrite-like structures may form or stabilize during roasting/reduction, especially with local overheating, strong reducing conditions, or unfavorable gangue chemistry, promoting solid-state reactions and densification (Chen et al., 2021; Tian et al., 2021). Recent studies also show that post-combustion events can reshape the calcine microstructure, increasing sintering and reducing porosity—effects often missed when only final metal recoveries are reported (Palma et al., 2025).

Because many studies report trends rather than standardized metrics, Figure 6 should present selectivity indicators (e.g., Ni metallization vs. Fe metallization, or Ni recovery vs. Fe dissolution) as functions of temperature and CO fraction.

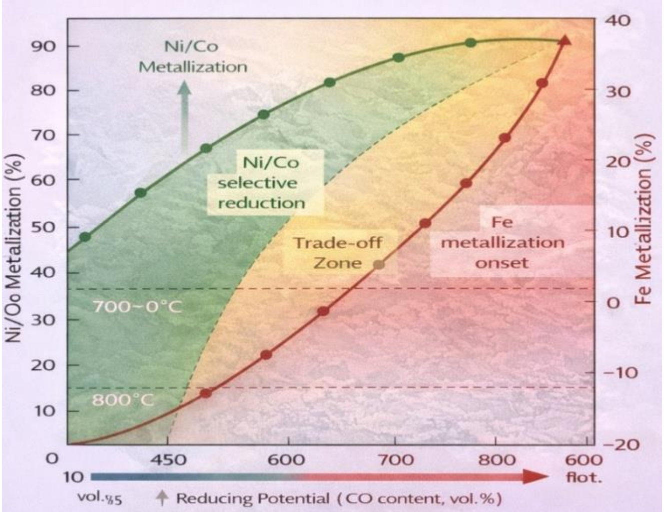


Figure 6. Reported trends of selective reduction performance versus temperature and reducing potential. Adapted from Sun et al. (2021), Chen et al. (2021), and Ilyas et al. (2020).

This trade-off highlights that many reported improvements are trajectory-dependent—they boost Ni reduction but can worsen Fe behavior without proper atmosphere and heat management.

5.4. Recent advances (2020–2025) in thermodynamic and kinetic modeling

From 2020 to 2025, advances cluster into four themes:

i. Thermodynamic framing of selectivity using equilibrium analysis and phase stability interpretations to explain why certain conditions favor Fe metallization or refractory phase stabilization (Chen et al., 2021; Khasanov et al., 2022).
ii. Kinetic studies that treat reduction as diffusion- and reaction-front-controlled, emphasizing ore texture, particle size, and gas–solid contact limits (Sun et al., 2021; Hou, 2022).

iii. Additive-assisted reduction (e.g., salts, sulfur-bearing additives, mixed reductants) aims to alter reaction pathways and metal particle growth while moderating Fe reduction—yet often with incomplete discussion of downstream implications (e.g., impurity transport, solution purification penalties, and corrosion risks) (Suharno et al., 2021; Pintowantoro et al., 2021; Oliveira, 2021).
iv. Process-control-aware studies linking thermal excursions (including post-combustion) and operational instability to microstructural outcomes and selectivity loss (Palma et al., 2025; Angulo-Palma et al., 2024; Angulo-Palma et al., 2025).

A key gap is the limited use of standardized selectivity indices in published papers. Modeling is often incomplete, failing to link predicted phase evolution to measured Fe metallization and leaching response—an essential integration for process improvement (Pandey et al., 2023; Tian et al., 2021).

To emphasize the process-control dimension, Figure 7 should depict practical control logic that links the temperature profile, off-gas composition, and residence-time adjustments to selectivity outcomes.

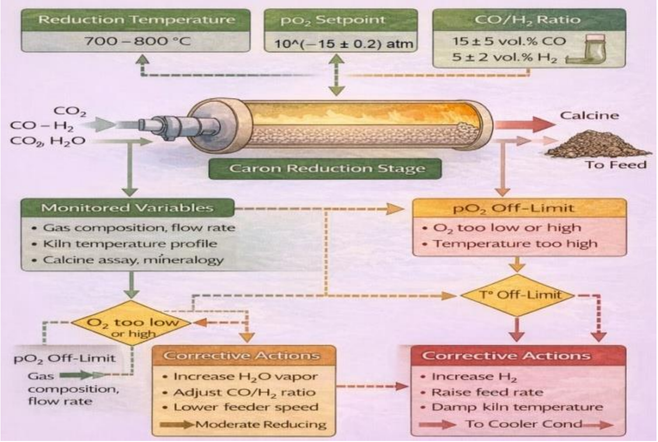


Figure 7. Control-oriented schematic for the Caron reduction stage (setpoints, monitored variables, and corrective actions) to maintain Ni/Co selectivity while suppressing Fe metallization. Adapted from Palma et al. (2025), Angulo-Palma et al. (2024), and Pandey et al. (2023).

Viewing reduction as a controllable, feedback-driven stage helps explain why similar nominal "temperatures" can yield contradictory outcomes across studies: the effective reduction potential is governed by transient and spatial gradients, not solely by a single furnace setpoint.

6. Ammoniacal leaching and metal recovery

6.1. Fundamentals of selective ammoniacal leaching

The defining feature of the Caron process is the use of ammoniacal carbonate solutions (NH_3–$(NH_4)_2CO_3$) to selectively dissolve metallic Ni and Co generated during reduction roasting, while iron and most gangue elements remain in the solid phase. Selectivity arises from the strong tendency of Ni^{2+} and Co^{2+} to form stable ammine complexes, whereas Fe^{3+} and Fe^{2+} are thermodynamically unfavorable in ammoniacal media under controlled redox conditions (Ilyas et al., 2020; Hu et al., 2022).

Unlike acidic leaching routes, ammoniacal systems operate at near-neutral pH and atmospheric pressure, reducing corrosion and allowing ammonia recycling, but at the cost of slower kinetics and sensitivity to calcine quality (Stanković et al., 2020; Borda & Torres, 2023).

Figure 8 schematically illustrates the selective dissolution of metallic Ni and Co in ammoniacal carbonate solutions, while retaining iron-bearing phases.

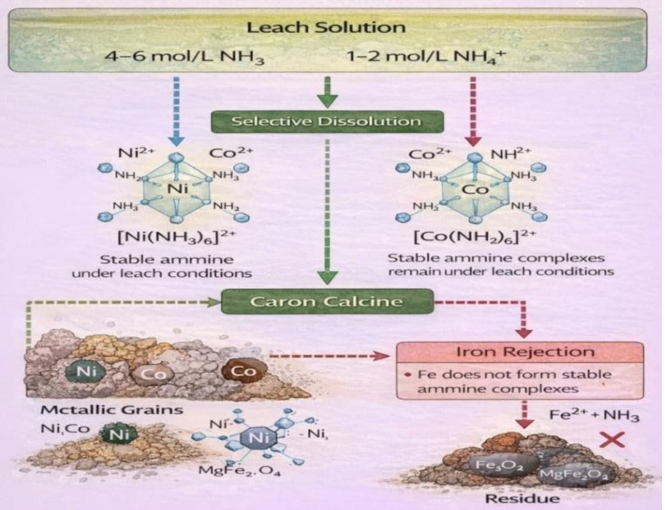


Figure 8. Conceptual mechanism of selective ammoniacal leaching of Ni and Co from Caron calcine, highlighting ammine complex formation and iron rejection. Adapted from Ilyas et al. (2020), Hu et al. (2022), and Stanković et al. *(2020).*

As shown in Figure 8, the efficiency of ammoniacal leaching depends critically on the extent of metallic Ni/Co formation and on the accessibility of these phases to the leachant solution.

6.2. Dissolution kinetics of metallic Ni and Co

The kinetics of Ni and Co dissolution in ammoniacal media are typically governed by surface reaction control at early stages, followed by diffusion limitations as porous product layers and carbonate precipitates form (Ilyas et al., 2020; Hosseini Nasab et al., 2020). Temperature (often 25–60 °C), ammonia concentration, and agitation intensity strongly influence dissolution rates.

Experimental studies consistently report faster dissolution of Ni than of Co, reflecting differences in surface oxidation and complexation kinetics. Poorly reduced calcines or those with encapsulated metal particles exhibit sluggish kinetics, reinforcing the strong coupling between the reduction and leaching stages (Chen et al., 2021; Hou, 2022).

Figure 9 presents representative dissolution curves for Ni and Co in ammoniacal carbonate solutions reported in recent Caron-related studies.

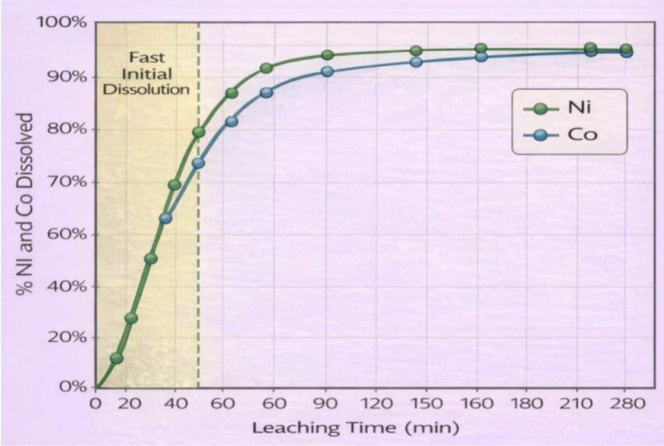


Figure 9. Typical dissolution kinetics of Ni and Co during ammoniacal leaching of Caron calcines. Adapted from Ilyas et al. (2020), Hosseini Nasab et al. (2020), and Hou (2022).

The divergence between Ni and Co dissolution rates underscores the need to optimize leaching time to balance recovery with reagent consumption and ammonia losses.

6.3. Metal losses and reagent consumption

Ammoniacal leaching causes notable metal losses due to incomplete reduction, metal encapsulation, and mechanical separation losses (Stanković et al., 2020; Borda & Torres, 2023). Excessive Fe metallization or calcine sintering raise nickel losses to tailings.

Ammonia consumption is limited by volatilization, side reactions catalyzed by metallic iron, and purge streams for impurity control. Carbonate use is affected by gas–liquid equilibria and solution practices (Hu et al., 2022; Valencia et al., 2025).

Table 4 summarizes reported ranges of Ni/Co losses and ammonia/carbonate consumption in ammoniacal leaching systems.

Table 4. Reported metal losses and reagent consumption in ammoniacal leaching of Caron calcines. *Adapted from* Stanković et al. (2020), Borda and Torres (2023), and Valencia et al. (2025).

Parameter	Typical range/value	Primary cause	Process implication
Ni loss to residue (%)	5 – 15	Incomplete Ni metallization; encapsulation in spinels	Direct loss of recovery; linked to reduction quality
Co loss to residue (%)	10 – 25	Partial oxidation; weaker ammine complex stability	Co more sensitive than Ni to process deviations
Fe dissolution to PLS (g/L)	< 0.5	Partial Fe^{2+} solubilization	Increases downstream purification load
NH_3 consumption (kg/t calcine)	5 – 20	NH_3 volatilization; side reactions	Strongly affected by Fe metallization
$(NH_4)_2CO_3$ consumption (kg/t calcine)	3 – 15	Carbonate buffering; losses in bleed streams	Impacts reagent recycle efficiency
NH_3 losses to gas phase (%)	5 – 12	Stripping, temperature excursions	Requires efficient gas recovery
NH_3 degradation due to Fe^0 (%)	up to 20	Catalytic NH_3 cracking on metallic Fe	Critical penalty of poor selectivity
Leach residue mass yield (%)	70 – 85	High gangue and Fe oxide content	Drives residue handling and disposal costs
Typical Ni recovery in leach (%)	80 – 95	Function of reduction selectivity	Upper bound constrained by calcine quality
Typical Co recovery in leach (%)	65 – 90	Redox control and NH_3 stability	Higher variability than Ni

The data show that improvements in leaching efficiency are often offset by higher reagent demand, underscoring the importance of integrated optimization across roasting, leaching, and solution management.

6.4. Downstream recovery: precipitation, solvent extraction, stripping, and refining

Pregnant ammoniacal leach solution (PLS) usually undergoes processing to recover nickel and cobalt as intermediates or final products. Common methods include selective precipitation (e.g., carbonates, hydroxides), solvent extraction with oxime-based extractants, followed by stripping and refining to produce high-purity Ni and Co compounds (Ilyas et al., 2023; Astuti et al., 2023).

Recent work links downstream recovery to battery-grade materials, emphasizing controlled production of mixed hydroxide precipitates (MHP) or purified solutions for sulfate crystallization. However, ammoniacal systems impose constraints on impurity control and solvent stability, which are often underreported in studies (Faubert, 2023; Wen et al., 2025).

Figure 10 outlines the primary downstream recovery options used for ammoniacal leach solutions in Caron-type flowsheets.

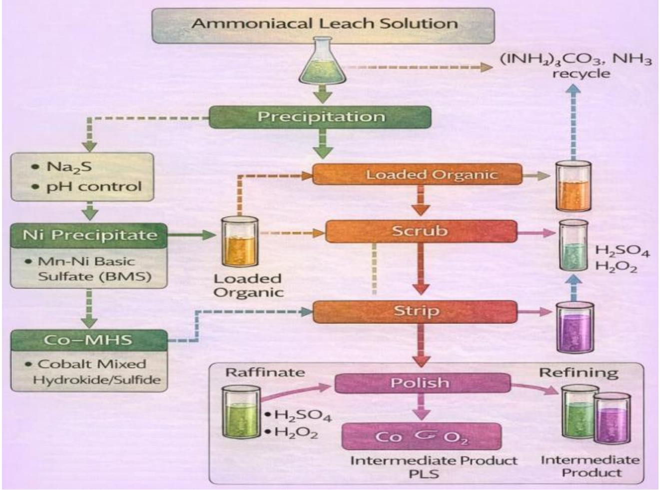


Figure 10. Simplified downstream processing routes for Ni and Co recovery from ammoniacal leach solutions, including precipitation, solvent extraction, stripping, and refining.

Adapted from Ilyas et al. (2023), Astuti et al. (2023), and Faubert (2023).

Figure 10 shows that downstream complexity can rival that of the upstream process, reinforcing the view that the viability of the Caron process must be assessed at the flowsheet level rather than solely by leaching performance.

7. Process performance and comparative assessment

7.1. Metallurgical efficiency (Ni and Co)

The Caron process usually recovers 70–85% Ni and less Co, sensitive to mineralogy and reduction quality (Stanković et al., 2020; Ilyas et al., 2020). Compared to acid routes, recoveries are limited by incomplete reduction and metal encapsulation in refractory phases during roasting (Chen et al., 2021).

HPAL reports >90% Ni and Co recoveries from limonitic ores due to high-temperature, high-pressure dissolution (Çoban & Baş, 2024; Zablotskaya et al., 2024). Atmospheric leaching yields intermediate recoveries, limited by iron control and acid use. Hybrid methods combining reduction with leaching seek to improve selectivity and recovery (Hariyanto et al., 2023; Garavito-Huertas et al., 2025).

Table 5 consolidates reported ranges of Ni and Co recovery for the Caron process and competing routes under representative operating conditions.

Table 5. Comparative metallurgical performance of nickel laterite processing routes (Ni and Co recoveries). Adapted from Stanković et al. (2020), Çoban and Baş (2024), Hariyanto et al. (2023), and Zablotskaya et al. (2024).

Processing route	Typical feed type	Ni recovery (%)	Co recovery (%)	Key metallurgical features
Caron process	Limonitic / transitional laterites	80 – 95	65 – 90	Selective Ni/Co recovery; sensitive to reduction control and mineralogy
HPAL	Limonitic laterites	90 – 98	85 – 98	High recoveries; high acid consumption and residue management challenges
Atmospheric leaching (AL)	Limonitic / mixed laterites	70 – 90	60 – 85	Lower CAPEX than HPAL; slower kinetics and larger reactors
RKEF	Saprolitic laterites	85 – 95 (Ni to FeNi)	< 50	Co largely reports to slag; optimized for ferronickel production
Selective reduction–leaching (hybrid)	Transitional laterites	85 – 95	75 – 90	Combines thermal selectivity with hydrometallurgy; narrow operating window
Bioleaching (emerging)	Low-grade laterites	50 – 80	40 – 70	Low energy intensity; long residence times and scale-up risk

The comparison in Table 5 shows that the higher recoveries achieved by HPAL and some hybrid routes come at the cost of increased process severity and downstream complexity, whereas Caron-type flowsheets trade recovery for selectivity.

7.2. Global energy consumption

Energy demand represents one of the principal drawbacks of the Caron process. The combined requirements for ore drying, calcination, and reduction roasting translate into high specific energy consumption per tonne of recovered nickel, particularly for low-grade, high-Fe ores (Moats & Davenport, 2024; Vahed et al., 2021). When normalized to Ni output, Caron energy intensity is often comparable to or higher than that of HPAL, despite HPAL's high-pressure operation (Valencia et al., 2025).

RKEF remains the most energy-intensive route overall but benefits from economies of scale and direct ferronickel production. Atmospheric leaching is less energy-intensive thermally, but it shifts the burden to the chemical energy embedded in acid consumption (Pandey et al., 2023).

Figure 11 compares indicative energy intensities for major laterite processing routes, normalized to the ton of nickel produced.

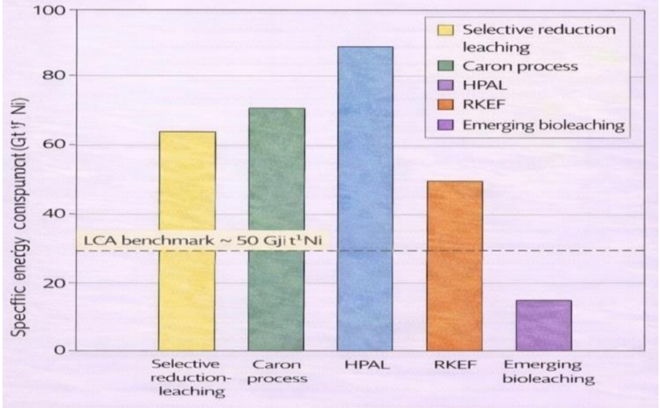


Figure 11. Indicative specific energy consumption of nickel laterite processing routes (per t Ni). Adapted from Moats and Davenport (2024), Vahed et al. (2021), and Valencia et al. (2025).

Figure 11 underscores that the Caron process has an unfavorable energy intensity compared with metallurgical recovery, a key driver of its declining industrial adoption.

7.3. Reagent and water consumption

Reagent consumption patterns differentiate laterite processing routes. In the Caron process, ammonia and carbonate are the main costs, with losses caused by volatilization, iron-catalyzed decomposition, and purge. Water demand is moderate but increases with extensive washing and recycling.

HPAL consumes very high sulfuric acid, especially for high-Mg or high-Al ores, while atmospheric leaching faces similar but less capital-intensive challenges. Hybrid methods reduce reagent use by pre-conditioning ore (e.g., reduction or calcination), but thermal steps may offset gains (Zappala et al., 2024; Wang et al., 2024).

Table 6 summarizes the reported ranges of reagent and water consumption for the principal laterite processing routes.

Table 6. Comparative reagent and water consumption for nickel laterite processing routes. *Adapted from* Hu et al. (2022), Borda and Torres (2023), Çoban and Baş (2024), and Zappala et al. (2024).

Processing route	Main reagents	Typical reagent consumption	Water consumption	Key implications
Caron process	NH_3, $(NH_4)_2CO_3$, reductant (coal/CO/H_2)	NH_3: 5–20 kg/t calcine; $(NH_4)_2CO_3$: 3–15 kg/t	2–5 m³/t ore	High recycle potential; sensitive to Fe metallization
HPAL	H_2SO_4, limestone/lime	H_2SO_4: 250–450 kg/t ore	4–10 m³/t ore	Very high acid demand; large neutralization residues
Atmospheric leaching (AL)	H_2SO_4, oxidants	H_2SO_4: 100–250 kg/t ore	5–8 m³/t ore	Lower pressure but high solution volumes
RKEF	Coal/coke, fluxes	Reductant: 200–350 kg/t ore	1–3 m³/t ore	Low water use; high fossil energy dependence
Selective reduction–leaching (hybrid)	Reductant + acid or NH_3	Acid: 50–150 kg/t ore or NH_3: 5–15 kg/t	2–4 m³/t ore	Balanced reagent profile; narrow operating window
Emerging bioleaching	Acid generated in situ, nutrients	External acid: < 50 kg/t ore	6–12 m³/t ore	Low reagent intensity; long residence times

The data in Table 6 indicate that no single route minimizes both energy and reagent consumption simultaneously, reinforcing the need for route selection to be site- and ore-specific.

7.4. Critical comparison with HPAL, atmospheric leaching, and hybrid routes

A critical comparison shows the Caron process is constrained by energy intensity and moderate recoveries but benefits from selective iron rejection, lower corrosion, and operational familiarity (Stanković et al., 2020; Pandey et al., 2023). HPAL offers better recoveries and flexibility for limonitic ores but has high capital costs, complex materials, and residue management issues (Çoban & Baş, 2024; Zablotskaya et al., 2024).

Atmospheric leaching is a lower-CAPEX alternative but struggles with iron control and scalability, while hybrid methods combine thermal pre-treatment and chemical leaching, though many are still at lab or pilot scale with limited long-term testing.

Figure 12 presents a qualitative decision matrix comparing major laterite processing routes across metallurgical, energetic, and operational criteria.

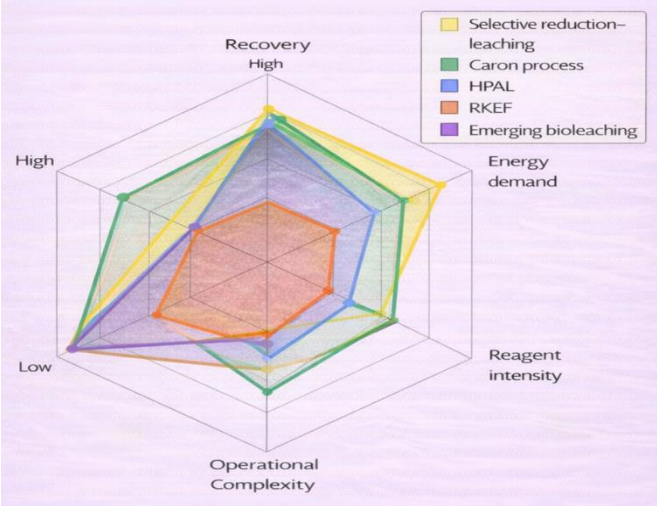


Figure 12. Qualitative comparison of nickel laterite processing routes across recovery, energy demand, reagent intensity, and operational complexity. Adapted from Pandey et al. (2023), Moats and Davenport (2024), and Caetano et al. (2025).

The matrix shows that the Caron process is no longer universally competitive, yet it remains relevant in niche scenarios where feed mineralogy, infrastructure, or regulatory constraints favor selective alkaline processing.

8. Environmental and sustainability aspects

8.1. CO_2 emissions associated with the reduction stage

The Caron process, among laterite routes, faces environmental penalties due to its thermal front-end—drying, calcination, and selective reduction—where fuel combustion dominates CO_2 emissions. This is especially critical for low-grade, high-Fe feeds, which require more ore heating per tonne of Ni, thereby increasing CO_2 intensity (Kirimli, 2023; Iyer & Kelly, 2022). The battery-material supply chain has also heightened scrutiny of nickel's CO_2 footprint, including intermediate and downstream products (Kalungi et al., 2024).

Figure 13 provides an indicative comparison of CO_2 intensity across major laterite processing routes, highlighting the disproportionate role of thermal energy in Caron-type flowsheets.

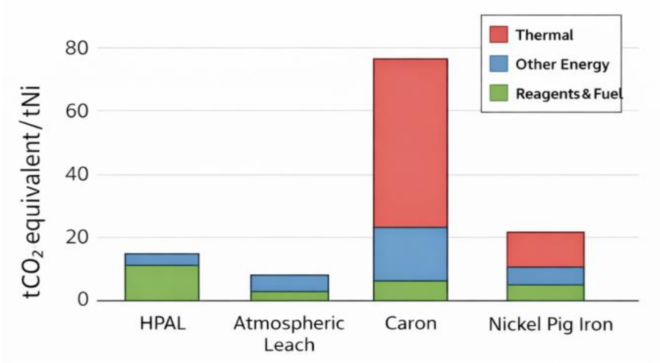


Figure 13. Indicative CO_2 intensity of nickel laterite processing routes (per t Ni), emphasizing the reduction-stage contribution in Caron-type flowsheets. Adapted from Iyer and Kelly (2022), Kirimli (2023), and Kalungi et al. (2024).

While route-specific values remain site-dependent (fuel mix, electricity grid, heat integration), the overall trend is robust: thermal pre-treatment and reduction remain structural drivers of Caron's carbon footprint.

8.2. Solid residues: generation, composition, and stability

Residue generation and stability are key sustainability issues. Caron produces a calcine residue ("cinder") after ammoniacal leaching, rich in Fe oxides and gangue minerals, and possibly containing Ni/Co depending on reduction and phases. Concerns include mass yield, long-term stability, and metal mobility under disposal conditions (Bartzas et al., 2021). Meanwhile, laterite waste is increasingly considered for reuse, but geochemical variability and regulatory constraints limit its practical applications (Balbin et al., 2023).

For resistant oxidized nickel ores and difficult feeds, residue management is complex because mineralogical constraints shift metals into less reactive phases, increasing poorly. Table 7 illustrates the principal solid residue streams associated with Caron-type processing, along with key stability considerations and typical environmental risk drivers.

Table 7. Main solid residue streams in Caron-type processing and their environmental/stability considerations (conceptual summary). *Adapted from* Bartzas et al. (2021), Balbin et al. (2023), and Tauakelov et al. (2025)

Residue stream	Process origin	Dominant mineralogical phases	Key stability considerations	Main environmental risk drivers
Reduced laterite residue (calcine / reduction residue)	Thermal reduction stage (kiln/roaster)	Magnetite (Fe_3O_4), wüstite (FeO), residual silicates, partially reduced goethite/hematite	Mineralogical reactivity depends on the reduction degree and potential oxidation of Fe^{2+} phases.	Dust generation, oxidation-driven volume changes, and potential trace metal release
Leach residue (ammoniacal leaching tailings)	Ammonia–ammonium carbonate leaching	Silicates (serpentine, olivine), quartz, iron oxides, minor unreacted Ni–Fe phases	Generally low acid potential; stability depends on particle size and residual alkalinity.	Fine particle dispersion, tailings storage stability, and seepage management
Iron-rich residue/precipitates	Iron removal and purification stages	Ferrihydrite, goethite, hematite, mixed Fe–Al hydroxides	The transformation from an amorphous to a crystalline phase influences permeability and strength.	Potential entrainment of Ni, Co, Mn; long-term consolidation behavior
Gypsum or carbonate-rich residues (if neutralization applied)	Effluent neutralization/residue conditioning	Gypsum ($CaSO_4 \cdot 2H_2O$), carbonates ($CaCO_3$, $MgCO_3$)	Generally stable under neutral pH; solubility is sensitive to water chemistry	Sulfate release, scaling, and leachate salinity
Off-gas dusts and fines	Kiln, roaster, and material handling (baghouse/cyclones)	Fine iron oxides, silicates, Ni-bearing particulates	High surface area increases reactivity; requires controlled handling	Airborne dispersion, metal-rich fine fractions
Spent refractory and kiln lining debris	Maintenance and relining operations	Alumina-based refractories, spinel, MgO-rich phases	Chemically stable but mechanically heterogeneous	Disposal volume and potential trace metal contamination

The evidence suggests that residue sustainability in Caron is less a single "waste issue" and more a coupled problem spanning ore type → reduction mineralogy → residual phases → disposal behavior, requiring site-specific characterization and risk-based management.

8.3. Recycling of ammonia and carbonate: benefits and limitations

Caron's main advantage is the potential for closed-loop ammonia and carbonate recycling, which can lower reagent demand and aqueous discharge. However, practical constraints such as impurity buildup, purge requirements, volatilization, and operational controls limit the recycle loop. These factors impact sustainability and costs (Iyer & Kelly, 2022). Environmentally, the benefits of recycling must be weighed against the thermal CO_2 burden to ensure balanced sustainability claims.

Figure 14 outlines the core NH_3–$(NH_4)_2CO_3$ recycle loop and the key points where losses, purge, and impurity control affect both the environmental footprint and process stability.

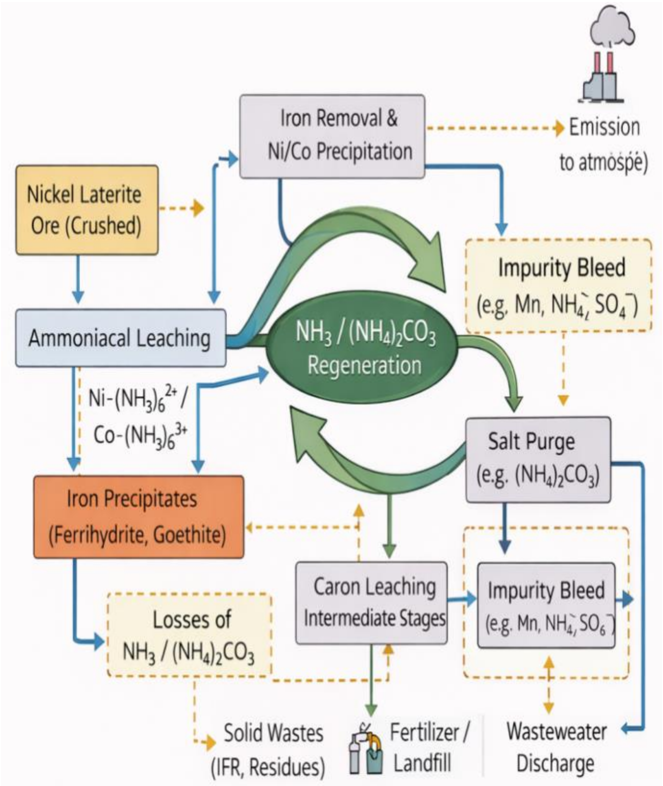


Figure 14. Conceptual ammonia–carbonate recycle loop in Caron-type flowsheets, including key loss and purge points. Adapted from Iyer and Kelly (2022).

This framing clarifies that Caron's sustainability cannot be inferred from "recycle potential" alone; performance depends on achievable recycling efficiency given realistic impurity and operational constraints.

8.4. Published LCA evidence (2020–2025): what is available and what remains weak

Between 2020 and 2025, LCA-related evidence has expanded primarily through (i) life-cycle inventories for critical materials, (ii) thesis-based full supply-chain assessments, and (iii) route-screening comparisons that emphasize nickel's strategic role in battery systems (Iyer & Kelly, 2022; Kirimli, 2023; Kalungi et al., 2024). However, the literature still exhibits recurring limitations for robust route-level conclusions: inconsistent system boundaries, variable co-product allocation, and sparse primary industrial datasets for Caron-specific loops.

Industry-facing sustainability reports frequently connect route competitiveness to greenhouse gas limits and resource efficiency, but these sources vary methodologically and should be seen as contextual, not definitive, LCA evidence (Schodde & Guj, 2025).

Figure 15 presents a boundary-and-hotspot map suitable for harmonizing future LCAs comparing Caron with acid and pyrometallurgical alternatives.

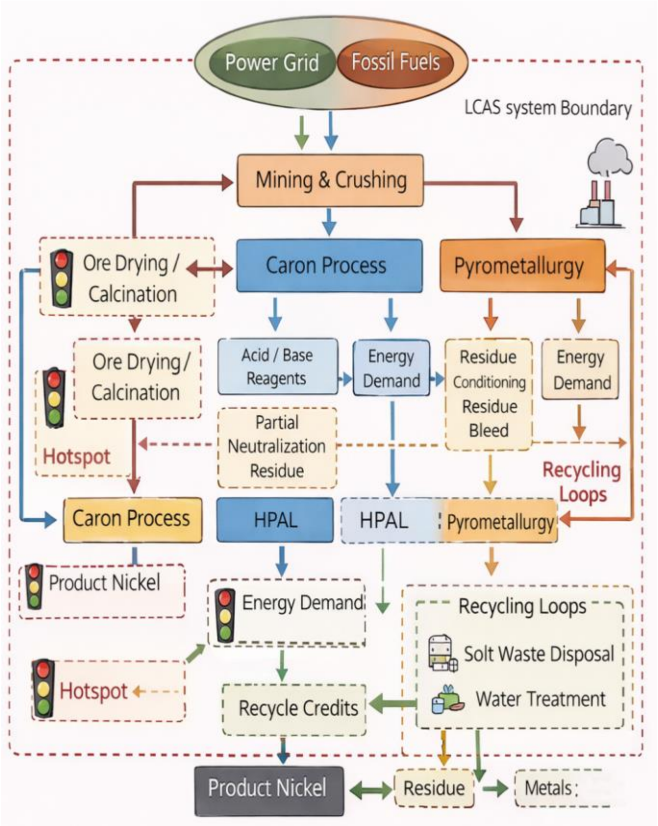


Figure 15. Proposed LCA boundary and hotspot map for nickel laterite processing routes (energy, reagents, residues, and recycling loops). Adapted from Iyer and Kelly (2022), Kirimli (2023), and Schodde and Guj (2025).

A key implication is that meaningful decarbonization comparisons require consistent treatment of energy sources, ore-grade normalization, residue fate, and recycling credits—otherwise, apparent "winners" reflect modeling choices rather than technological reality.

8.5. Alignment with decarbonization targets

Decarbonization for Caron-type processing depends on two main strategies: (i) decreasing thermal emissions via electrification, low-carbon fuels, and heat recovery; and (ii) boosting nickel recovery or feed upgrading to lessen heated mass per Ni unit. Additionally, residue management and valorization must be environmentally evaluated rather than automatically assumed beneficial (Bartzas et al., 2021; Balbin et al., 2023). As nickel is vital for energy-transition materials, decarbonization pressures will likely influence which laterite routes are investable and socially acceptable (Kalungi et al., 2024; Schodde & Guj, 2025).

9. Technological improvements and hybrid concepts (2020–2025)

9.1. Recent modifications to the Caron process

Between 2020 and 2025, the dominant “Caron improvement” narrative shifted from altering the core logic (selective reduction → ammoniacal leaching) to engineering selectivity, intensifying kinetics, and reducing energy and reagent penalties. Common modifications include: (i) additive-assisted selective reduction, (ii) improved roasting/reduction control and modeling, and (iii) rethinking downstream recovery to upgrade Caron liquors or intermediates into modern products (Angulo-Palma et al., 2024, 2025; Chen, Jak, & Hayes, 2021a-d; Astuti et al., 2023; Asadrokht & Zakeri, 2023).

Several advanced extraction strategies and modeling approaches have been explored at the thesis level, providing valuable mechanistic insights that are not always captured in journal articles (Djouani, 2022).

9.2. Integration with thermal or mechanical pre-treatments

Efforts target decoupling liberation and reactivity from bulk heating. Mechanical methods, such as mechanochemical processing and ultrasound, aim to enhance leaching or reduce residence time but mostly have limited lab data and limited mass and energy analysis (Çetintaş & Bingöl, 2020). Chemo-physical beneficiation and pre-concentration strategies aim to lower gangue carryover and thermal mass, which depend on laterite mineralogy and variability (Asadrokht & Zakeri, 2022; Mweene et al., 2024; Zappala, Balucan, Vaughan, & Steel, 2020; Zappala & McDonald et al., 2024). Segregation-based thermal strategies are also being reconsidered as upgrading or transitional options for nickel laterites (Iwasaki et al., 2024).

Figure 16 maps the principal pre-treatment options reported between 2020 and 2025 and indicates where each approach targets the Caron bottlenecks (selectivity, kinetics, energy, residue).

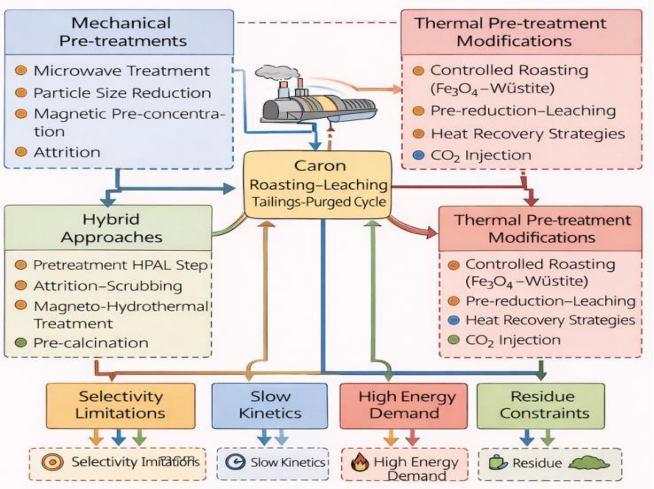


Figure 16. Pre-treatment integration map for Caron-type flowsheets (mechanical, thermal, and hybrid concepts) and their targeted bottlenecks. Adapted from Çetintaş and Bingöl (2020), Asadrokht and Zakeri (2022), Mweene et al. (2024), and Zappala and McDonald et al. (2024).

The critical limitation is that many studies report improved extraction but do not demonstrate net sustainability gains once additional unit operations, consumables, and energy inputs are accounted for.

9.3. Alternative reductants: hydrogen and process-gas strategies

A clear 2020–2025 intensification theme is the shift from conventional CO/solid carbon dominance toward hydrogen-enabled reduction (or hydrogen-containing atmospheres) to increase selectivity and potentially reduce direct CO_2 emissions. Experimental work on hydrogen reduction of laterites and related modeling indicates that process control (temperature–time–gas composition) is decisive for suppressing Fe reduction while enabling Ni/Co metallization (Wijenayake et al., 2021; Hou, 2022; Alsabak & Dilmaç, 2025). Complementary studies reinforce the role of gas composition and reduction time in defining selective reduction windows (Sun et al., 2021).

In practice, hydrogen concepts face two recurring constraints: (i) the risk of forming refractory phases (including complex spinels) that “lock” Ni/Co, and (ii) the need for robust gas-handling and heat management at scale—issues that are often under-addressed in bench-scale demonstrations (Liu et al., 2025; Palma et al., 2025).

Table 8 compares the reported reduction conditions for selective reduction under conventional atmospheres versus hydrogen-containing systems, and identifies the control variables that govern Ni/Co selectivity relative to Fe.

Table 8. Reported reduction windows and control variables for selective reduction of Ni/Co from laterites using conventional atmospheres vs hydrogen-containing systems (2020–2025). *Adapted from* Sun et al. (2021), Wijenayake et al. (2021), Hou (2022), Liu et al. (2025), Palma et al. (2025), and Alsabak and Dilmaç (2025).

Reduction atmosphere	Typical temperature range (°C)	pO_2 / gas composition	Target reduced phases (Ni/Co vs Fe)	Key control variables	Reported selectivity trends	Main technical limitations
$CO–CO_2$ (gas mixtures)	650–850	Controlled CO/CO_2 ratio (buffered pO_2)	Ni^0, Co^0; partial $Fe_3O_4 \rightarrow FeO$	Gas ratio, temperature ramp, residence time	Moderate Ni/Fe selectivity achievable	Narrow operating window; risk of Fe metallization
$H_2–N_2$ (diluted hydrogen)	550–750	Low pO_2, controlled H_2 partial pressure	Preferential Ni^0, Co^0; Fe mostly as Fe_3O_4	H_2 concentration, heating rate, ore mineralogy	High intrinsic selectivity in lab scale	Hydrogen consumption, safety, scale-up uncertainty
Pure H_2	500–700	Very low pO_2	Rapid Ni^0 and Co^0 formation; Fe reduction risk	Temperature control, residence time	High kinetics, poor Fe control if overheated	Loss of selectivity at higher T; high gas demand
Solid carbon (char / coal)	700–900	Local reducing micro-environments	Ni^0, Co^0; extensive FeO/Fe^0 formation	Carbon ratio, particle contact	Low selectivity	Strong Fe reduction; high CO_2 footprint
$CO–H_2$ blends	600–800	Tunable redox via gas blending	Ni^0, Co^0 favored over Fe	Gas composition, residence time	Improved flexibility vs single-gas systems	Process complexity
H_2 with controlled pre-oxidation	550–700	Stepwise pO_2 control	Ni^0 formation after Fe stabilization	Oxidation state, heating profile	Improved Ni/Fe selectivity	Added unit operations
H_2 + catalytic/mineral modifiers	500–700	Low pO_2, enhanced kinetics	Accelerated Ni^0, Co^0 nucleation	Additives, surface chemistry	Promising lab-scale results	Reagent cost, residue impacts
H_2 under microwave-assisted heating	450–650	Localized low pO_2	Fast Ni^0 reduction	Heating mode, particle size	High apparent selectivity	Limited scalability

Critically, the current evidence supports hydrogen as a technically promising reductant, but not yet a proven solution for industrial selectivity, economics, and system-level decarbonization without integrated energy and gas-supply analysis.sis.

9.4. Additive-assisted selective reduction: salts, sulfur, and mixed reductants

Additive-assisted reduction uses salts and sulfur additives like sodium sulfate, sodium chloride, sodium carbonate, and thiosulfate, along with mixed reductants (coal + oil), to promote Ni/Co metallization and limit Fe reduction, affecting microstructure, phase changes, sulfur effects, and kinetics (Suharno et al., 2021; Pintowantoro et al., 2021; Angulo-Palma et al., 2024, 2025; Chen et al., 2025). Chen–Jak–Hayes studies explain how these factors determine 'metallization vs trapping' (Chen et al., 2021a-d).

Figure 17 compares the reported directional effects of major additive families on selective reduction outcomes, highlighting where evidence is consistent and where results are more specific.

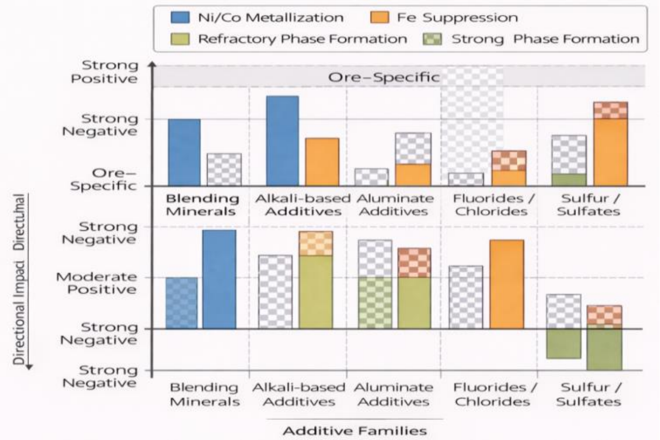


Figure 17. Directional effects of additive families on selective reduction outcomes for Caron-type processing (Ni/Co metallization, Fe suppression, refractory phase formation). Adapted from Suharno et al. (2021), Pintowantoro et al. (2021), Angulo-Palma et al. (2024, 2025), Chen, Jak, and Hayes (2021a, 2021b, 2021c, 2021d), and Chen et al. (2025).

A critical review indicates that additives can “move the needle,” but outcomes remain strongly ore-mineralogydependent, and several studies still lack pilot-scale validation with complete mass/energy balances.

9.5. Electrification, low-carbon integration, and MOE coupling concepts

The literature on electrification in 2020–2025 mainly views it as a systems concept rather than a proven change: replacing fossil thermal duties with electric heating, adding renewable electricity, and improving heat recovery. It can reduce scope-1 emissions but doesn't address Caron's core constraints: selective reduction chemistry, residue, and impurities (Sun et al., 2024; Valencia et al., 2025).

A hybrid concept links laterite upgrading with electrometallurgical platforms, including MOE thinking, to shift decarbonization from chemical reductants to electricity. In Caron-focused literature, this is mostly an integration opportunity rather than an established "Caron–MOE" template. Credible proposals require clearer interface definitions (feed conditioning, phase control, impurity management, product specs) (Sun et al., 2024; Moats & Davenport, 2024).

Figure 18 presents a conceptual schematic hybrid architecture that retains Caron-style selective reduction and ammoniacal selectivity while shifting major heat duties and/or final upgrading toward electrified platforms.

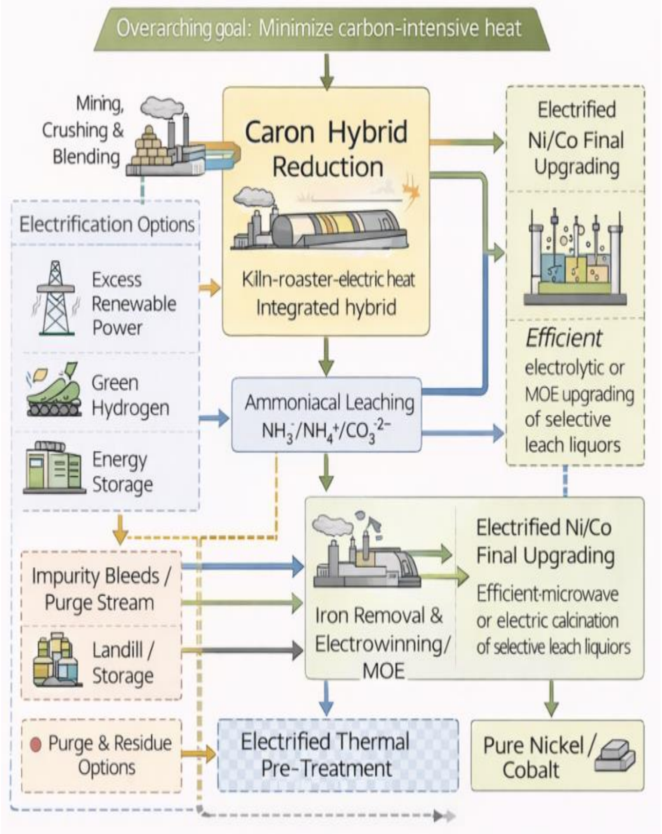


Figure 18. Conceptual schematic hybrid architecture linking Caron-type selective reduction/leaching with electrification and electro-metallurgical upgrading concepts (including MOE-type pathways). Adapted from Moats and Davenport (2024), Sun et al. (2024), and Valencia et al. (2025).

From a critical review standpoint, the hybrid opportunity is real, but the evidence remains largely conceptual: the literature rarely provides an integrated demonstration of operability, impurity control, and full sustainability accounting across the combined system.

10. Future perspectives and research gaps

10.1. Scientific gaps identified in the recent literature (2020–2025)

Recent literature agrees that the main "bottleneck" of the Caron process is no longer proving Ni and Co can be selectively recovered, but demonstrating robust inter-deposit performance under mineralogical variability. This involves maintaining selectivity against iron and controlling refractory phases. Studies show that small changes in temperature, atmosphere, and residence time can cause Ni and Co to be either effectively metallized or trapped in spinels and refractory phases, impairing ammoniacal leaching (Chen, Jak, & Hayes, 2021a-d; Sun et al., 2021; Liu et al., 2025).

Many studies show localized improvements—such as in extraction, kinetics, or reagent use—without assessing overall mass, energy, and water balances or flowsheet impacts, like the energy cost of thermal stages versus gains from better selectivity. Fragmentation exists between the process and sustainability literature: life cycle assessments and supply chain studies examine macro-level impacts, while metallurgical research rarely reports operational data suitable for inventory purposes the process and sustainability literature: life cycle assessments and supply chain studies examine macro-level impacts, while metallurgical research rarely reports operational data suitable for inventories.022).

10.2. R & D needs to make the process competitive

(i) Selectivity window with demonstrated operational control at pilot scale

R & D must move from "bench-scale optimal conditions" to realistic operational ranges with defined tolerances for feed variability, such as composition, moisture, particle size, and mineralogy. Pilot-scale validation of control strategies (temperature, atmosphere, residence time) and calcine quality metrics is essential, linked to operational metrics (Chen, Jak, & Hayes, 2021a–d; Palma et al., 2025; Chen et al., 2025).

(ii) Effective integration of pre-treatments and beneficiation

The competitiveness of the Caron process for low-grade, high-iron ores hinges on reducing the processed thermal mass per Ni/Co recovered. R & D should compare pre-concentration methods—chemo-physical beneficiation, magnetic separation, hybrid reduction–separation—using criteria like energy use, CAPEX, and losses (Asadrokht & Zakeri, 2022; Tian et al., 2021; Garavito-Huertas et al., 2025; Lv et al., 2025).

(iii) Downstream alignment with modern products (purified solutions, MHP/MHS, intermediates)

Even when ammoniacal leaching is selective, overall competitiveness depends on the downstream circuit, including impurity removal, precipitation routes, and integration with SX/stripping/refining in reagent-recycle setups. While the literature notes potential pathways, it lacks integrated demonstrations that combine product quality, circuit closure, and operational stability (Astuti et al., 2023; Hu et al., 2022; Wen et al., 2025).

(iv) Sustainability data: complete inventories and comparability with HPAL/AL/RKEF

Caron-based flowsheets require transparent inventory management and benchmarking to remain competitive. R & D opportunities include heat-recovery networks, alternative reductants like hydrogen, electrification, and LCA-ready design (Page et al., 2021; Sun et al., 2024; Valencia et al., 2025).025).

10.3. Potential role of the Caron process in circular nickel value chains

The Caron process could become relevant again in circular nickel chains if repositioned as a selective platform for oxidized feeds, where ammoniacal leaching and reagent recycling offer advantages over routes that produce large sulfate solutions or high iron in PLS. This involves (i) integrating pretreatments that improve selectivity and reduce slag, and (ii) coupling with purification methods to produce intermediates for batteries or alloys (Moats & Davenport, 2024; Sun, Zhou, & Huang, 2024). However, 2020–2025 studies lack complete case studies with verifiable data, especially under closed ammonia/carbonate loops and specific final products (Valencia et al., 2025; Iyer & Kelly, 2022).

Table 9 summarizes the identified research gaps and indicates the level of evidence required (laboratory → pilot → demonstration) for incremental advances to achieve technological competitiveness.

Table 9. Research gaps and required evidence level to advance Caron-type flowsheets from laboratory optimization to competitive deployment (2020–2025). *Adapted from* Mweene et al. (2024), Zappala and McDonald et al. (2024), Page et al. (2021), Valencia et al. (2025), and Iyer and Kelly (2022).

Research gap/challenge	**Typical claims in literature**	**Missing evidence**	**Required evidence level**	**Key metrics to be demonstrated**
Selective reduction robustness across ore types	Improved Ni/Co metallization and Fe suppression in single-ore studies	Lack of validation across variable laterite mineralogies	Pilot → Demonstration	Ni/Fe selectivity stability, sensitivity to ore chemistry
Hydrogen-based reduction selectivity	Faster kinetics and lower apparent reduction temperature	No integrated assessment of H_2 supply, recycling, and losses	Pilot	H_2 consumption (kg/t Ni), selectivity window width, safety
Additive-assisted selectivity control	Additives enhance Ni reduction or Fe suppression	Ore-specific responses, incomplete mass balances	Pilot	Additive dosage, residue chemistry, net selectivity gain
Energy intensity reduction	Local energy savings reported for modified roasting	No full accounting of added unit operations	Pilot → Demonstration	Net energy (GJ/t Ni), heat recovery efficiency
Ammonia–carbonate recycle efficiency	High recycle potential claimed (>90%)	Limited data on impurity buildup and purge losses	Pilot	Recycle efficiency, purge rate, NH_3 losses
Residue stability and disposal behavior	Residues described as “benign” or “stable”	Lack of long-term geochemical and physical stability data	Pilot → Demonstration	Leachability, oxidation behavior, dust generation
Integrated circuit operability	Unit operations are optimized individually	No continuous, closed-circuit demonstrations	Demonstration	Availability, uptime, control stability
System-level decarbonization potential	CO_2 reductions inferred from partial substitution	Inconsistent LCA boundaries and assumptions	Pilot → Demonstration	t CO_2-e/t Ni, boundary-consistent LCA
Economic competitiveness	CAPEX/OPEX discussed qualitatively	Absence of validated techno-economic models	Demonstration	Cash cost ($/t Ni), CAPEX intensity
Electrified / hybrid architectures	Conceptual integration with MOE or electrified units	No integrated flowsheet demonstrations	Demonstration	Energy source mix, operability, product quality

Many reported “improvements” are only meaningful with full circuit closure, inventory-quality data, and validated operational stability.

11. Conclusions

This review analyzed the Caron process in modern nickel laterite processing from 2020 to 2025. Despite its long history, it faces structural issues, including high energy use in thermal pre-treatment and reduction, moderate recoveries, and sensitivity to feed mineralogy. These limitations hinder its competitiveness against HPAL for limonitic ores and RKEF for saprolitic feeds.

Research shows the Caron process is dynamic, with advances in thermodynamics, process control, and additive strategies enhancing Ni/Co selectivity while suppressing iron. Progress in ammoniacal leaching and recovery reinforces this, aligning with modern battery-grade nickel products. However, many improvements remain at the lab scale and lack comprehensive assessments of mass, energy, and sustainability.

The review emphasizes that the Caron process's viability depends on integrated performance across the entire flowsheet, not just on metallurgical recovery or selectivity. Its relevance depends on factors such as ore mineralogy, infrastructure, and strategic advantages, including iron rejection and corrosion control. In favorable conditions, Caron concepts can have niche importance or serve as platforms for hybrid methods.

Looking beyond 2025, the Caron process is best viewed as a selective, adaptable framework rather than a universal solution. Its role depends on advances in electrification, energy integration, hydrogen reduction, and the circular economy. If research successfully couples selective reduction with process control, feed upgrading, and life-cycle performance, Caron-inspired flowsheets could support diversified nickel supply chains. Without such validation, it will likely remain in academic or limited industrial use.

In this sense, the Caron process stands as both a technological legacy and a test case: a reminder that metallurgical selectivity, energy efficiency, and sustainability must evolve in tandem for mature processes to remain relevant in an increasingly decarbonized and resource-constrained metallurgical landscape.

12. References

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Author Contributions (CRediT taxonomy)

Antonio Clareti Pereira: Conceptualization; Methodology; Literature review; Data curation; Formal analysis; Visualization; Writing – original draft; Writing – review & editing.

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