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SELECTIVE SEPARATION OF NICKEL AND COBALT VIA CO(III) PATHWAYS: A CRITICAL REVIEW OF REDOX CONTROL, SPECIATION, AND PROCESS INTEGRATION

SEPARAÇÃO SELETIVA DE NÍQUEL E COBALTO POR MEIO DE ROTAS COM CO(III): UMA REVISÃO CRÍTICA DO CONTROLE REDOX, DA ESPECIAÇÃO E DA INTEGRAÇÃO DE PROCESSOS

SEPARACIÓN SELECTIVA DE NÍQUEL Y COBALTO MEDIANTE RUTAS CON CO(III): UNA REVISIÓN CRÍTICA DEL CONTROL REDOX, LA ESPECIACIÓN Y LA INTEGRACIÓN DE PROCESOS

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ABSTRACT

Nickel and cobalt separation remains challenging because Ni(II) and Co(II) exhibit similar aqueous chemistry in many hydrometallurgical media. This structured critical narrative review evaluates the deliberate Co(II) oxidation to Co(III) as a separation strategy. The evidence base comprises 71 peer-reviewed publications from 2020 to 2026 covering thermodynamics, oxidative precipitation, electrochemical routes, solvent extraction, ion exchange, alternative media, laterites and mixed hydroxide precipitates, battery recycling, and mechanistic studies. Direct separation evidence is distinguished from contextual mechanistic evidence and benchmarked against established Ni(II)/Co(II) technologies. The analysis shows that oxidation alone does not separate Ni and Co; selectivity requires a controlled fate of Co(III) via hydrolysis/precipitation, ligand stabilization, altered phase-transfer affinity, or electrochemical transport. Performance depends jointly on redox potential, pH, ligand environment, ionic strength, temperature, residence time, impurity load, and back-reduction kinetics. Oxidative precipitation currently provides the clearest direct precedent, whereas electrochemical and hybrid routes offer greater control but less industrial validation. A staged decision framework is proposed for screening, hybridization, scale-up, or rejection of Co(III)-enabled routes.

KEYWORDS: *Nickel. Cobalt. Co(III). Redox control. Selective separation. Hydrometallurgy.*

RESUMO

A separação de níquel e cobalto permanece desafiadora porque Ni(II) e Co(II) apresentam química aquosa semelhante em muitos meios hidrometalúrgicos. Esta revisão narrativa crítica estruturada avalia a oxidação deliberada de Co(II) para Co(III) como estratégia de separação. A base de evidências reúne 71 publicações revisadas por pares, de 2020 a 2026, abrangendo termodinâmica, precipitação oxidativa, rotas eletroquímicas, extração por solventes, troca iônica, meios alternativos, lateritas e precipitados mistos de hidróxidos, reciclagem de baterias e estudos mecanísticos. As evidências diretas de separação são distinguidas das evidências mecanísticas contextuais e comparadas com tecnologias consolidadas para Ni(II)/Co(II). A análise mostra que a oxidação, isoladamente, não promove a separação: a seletividade exige um destino controlado para Co(III), por meio de hidrólise/precipitação, estabilização por ligantes, alteração da afinidade de transferência de fase ou transporte eletroquímico.

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O desempenho depende conjuntamente do potencial redox, do pH, do ambiente ligante, da força iônica, da temperatura, do tempo de residência, da carga de impurezas e da cinética de retro-redução. A precipitação oxidativa apresenta a evidência direta mais robusta, enquanto rotas eletroquímicas e híbridas oferecem maior controle, porém menor validação industrial. Propõe-se um quadro decisório em etapas para triagem, hibridização, escalonamento ou rejeição de rotas baseadas em Co(III).

PALAVRAS-CHAVE: Hidrometalurgia. Níquel. Cobalto. Co(III). Controle redox. Separação seletiva.

RESUMEN

La separación de níquel y cobalto sigue siendo difícil porque Ni(II) y Co(II) presentan una química acuosa similar en muchos medios hidrometalúrgicos. Esta revisión narrativa crítica estructurada evalúa la oxidación deliberada de Co(II) a Co(III) como estrategia de separación. La base de evidencia reúne 71 publicaciones revisadas por pares, de 2020 a 2026, sobre termodinámica, precipitación oxidativa, rutas electroquímicas, extracción por solventes, intercambio iónico, medios alternativos, lateritas y precipitados mixtos de hidróxidos, reciclaje de baterías y estudios mecanísticos. La evidencia directa de separación se distingue de la evidencia mecanística contextual y se compara con tecnologías consolidadas de Ni(II)/Co(II). El análisis muestra que la oxidación por sí sola no separa Ni y Co; la selectividad requiere un destino controlado para Co(III) mediante hidrólisis/precipitación, estabilización mediante ligandos, modificación de la afinidad de transferencia de fase o transporte electroquímico. El desempeño depende conjuntamente del potencial redox, del pH, del entorno de ligandos, de la fuerza iónica, de la temperatura, del tiempo de residencia, de la carga de impurezas y de la cinética de retroreducción. La precipitación oxidativa presenta el antecedente directo más claro, mientras que las rutas electroquímicas e híbridas ofrecen mayor control, aunque con menor validación industrial. Se propone un marco de decisión por etapas para seleccionar, hibridar, escalar o rechazar rutas basadas en Co(III).

PALABRAS CLAVE: *Hidrometalurgia. Níquel. Cobalto. Co(III). Control redox. Separación selectiva.*

INTRODUCTION

Strategic separation problem

Nickel and cobalt occupy overlapping positions in the supply chains of battery materials, laterite-derived intermediates, metallurgical residues, and recycled lithium-ion batteries. Their co-occurrence is advantageous during bulk recovery but becomes a liability when downstream products require narrow impurity specifications. Contemporary processing therefore increasingly separates two questions that were historically treated together: how to maximize dissolution or recovery of Ni and Co, and how to create a chemical contrast strong enough to split the two elements after they enter the same aqueous phase. Reviews of hydrometallurgical processing and battery recycling consistently identify downstream purification as a decisive stage rather than a minor polishing step (Bahfie *et al.*, 2023; de Castro *et al.*, 2024; Dias *et al.*, 2026; Merah *et al.*, 2026).

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The difficulty is rooted in the predominance of divalent Ni and Co under many acidic and moderately complexing conditions. Similar charge, comparable hydration behavior, and overlapping responses to common acidic extractants cause narrow operating windows, multistage requirements, and sensitivity to pH and impurities. Conventional solvent extraction with phosphinic or carboxylic systems remains industrially credible, but the literature also shows that selectivity can be shifted by changing solvation, complexation, buffering, ionic strength, or contactor architecture rather than by relying on nominal metal identity alone (Abo Atia *et al.*, 2023; Rodrigues *et al.*, 2022; Xu *et al.*, 2022; Yuan *et al.*, 2022, 2025).

The Co(III) hypothesis

Cobalt differs from nickel in one potentially exploitable respect: its accessible redox chemistry permits conversion of Co(II) into more strongly hydrolyzing, differently coordinated, or solid-associated Co(III) species. The central hypothesis examined here is therefore not that Co(III) is intrinsically easy to produce, but that a deliberate Co(II)→Co(III) step can create a transient separation handle that is unavailable when both metals remain divalent. Evidence for this idea comes directly from oxidative precipitation and electrochemical studies and indirectly from mineral-surface and electrocatalytic work that resolves Co(III) formation and persistence (Ichlas *et al.*, 2020; Makarava *et al.*, 2024; Manceau & Steinmann, 2022; Fablet *et al.*, 2026).

The approach must nevertheless be framed conservatively. Co(III) is not a single free aqueous species with fixed behavior; its persistence depends on ligands, hydrolysis, surface binding, and the kinetics of reduction. Mechanistic studies on cobalt oxide and manganese oxide surfaces show that high-valent cobalt can be stabilized or transformed at interfaces, whereas solution-phase studies show that coordination can radically alter extraction or electrochemical response. These observations are valuable for mechanism building but cannot automatically be treated as proof of a viable industrial Ni–Co flowsheet (Bouvier *et al.*, 2023; Gamov *et al.*, 2021; M. Shi *et al.*, 2025; Zhao *et al.*, 2023; Z. Zhang *et al.*, 2025; Pereira, 2026a).

Aim and critical questions

This review asks five questions. First, under what thermodynamic and speciation conditions can oxidation produce a cobalt state that is genuinely distinguishable from Ni(II)? Second, which oxidation routes are sufficiently selective and controllable to create that state? Third, which subsequent separation operation—precipitation, solvent extraction, ion exchange, membrane/electrochemical transport, or deposition—can capture the difference before Co(III) is lost? Fourth, how do realistic impurities and feed chemistry narrow the operating window? Fifth,

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when does the additional redox step improve the overall process relative to conventional Ni–Co separation? The intended outcome is a process design framework rather than an argument that Co(III) chemistry should replace established solvent extraction across all applications.

THEORETICAL FRAMEWORK

Thermodynamic basis of the Co(III) route

Redox contrast between Ni and Co

The attraction of a Co(III) route is thermodynamic contrast. In many hydrometallurgical liquors, Ni remains predominantly divalent across the operating region of interest, whereas cobalt can access higher oxidation states under sufficiently oxidizing conditions. Modern E–pH analysis of metal–water systems illustrates that pH and potential jointly determine the stability of dissolved ions, hydrolyzed species, and solids, and therefore that a nominal oxidation potential cannot be interpreted independently of precipitation equilibria (Cao *et al.*, 2020).

This distinction is important because the desired process outcome is rarely “dissolved free Co^{3+}”. A useful Co(III) state may instead be a stabilized complex, a surface-associated species, or an oxyhydroxide-like solid. Manceau and Steinmann (2022) and Zhao *et al.* (2023), for example, show how manganese-oxide surfaces can drive and retain Co(III), while Fablet *et al.* (2026) demonstrate that iron-oxide surfaces can participate in Co(II) oxidation mechanisms. These systems are not direct Ni–Co hydrometallurgical flowsheets, but they demonstrate why the effective redox boundary in a process slurry can differ from a simple dissolved-ion diagram.

The operational redox window

For process design, the relevant window is bounded by three constraints. The lower bound is the potential at which Co(II) oxidation becomes kinetically and thermodynamically significant. The upper bound is set by undesired reactions, including oxidation of ligands, water, reductants, or—in some media—nickel-bearing species. A third boundary is imposed by cobalt hydrolysis or solid formation. The useful region is therefore a moving window controlled by electrolyte composition and by the residence time between oxidation and separation. Makarava *et al.* (2024) provide direct evidence that chloride chemistry can support electrochemical cobalt oxidation, while Illés and Kékesi (2023) emphasize that chloride complexation changes both redox and precipitation behavior relative to sulfate systems.

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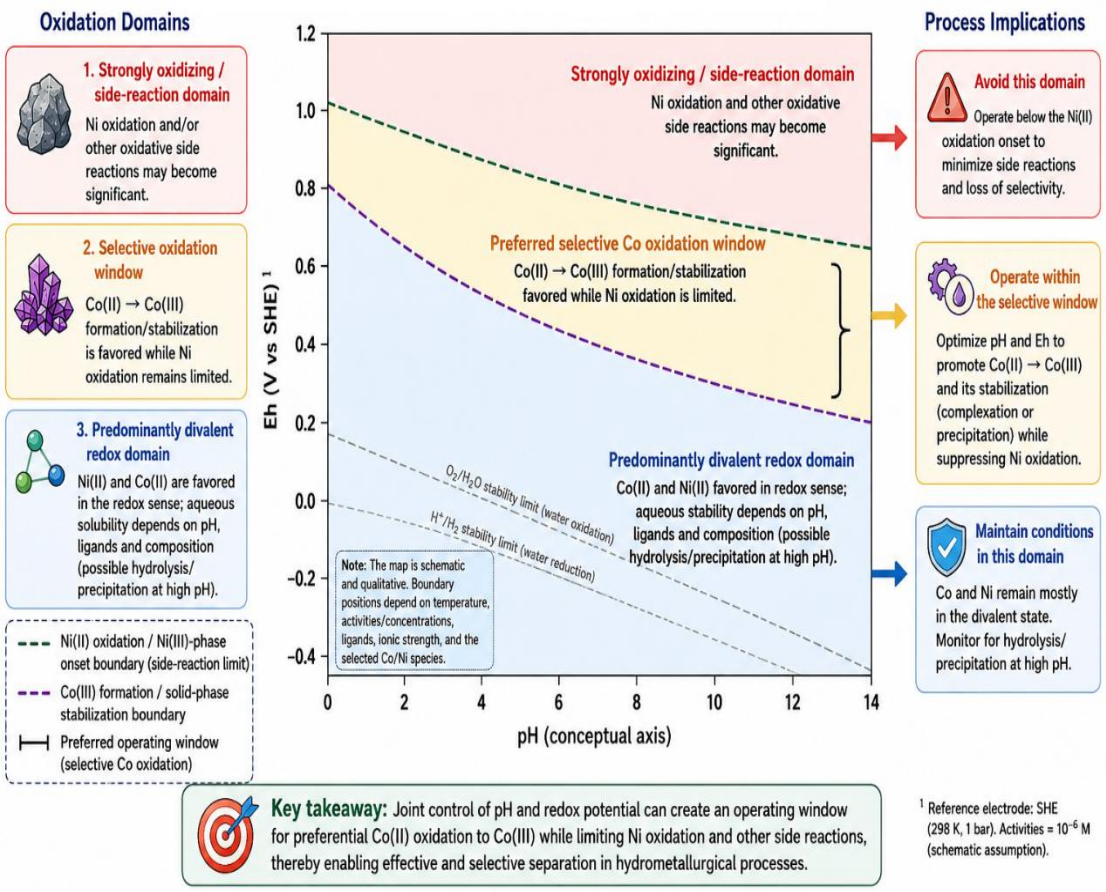
Figure 1 is inserted here to emphasize that the proposed window is conceptual rather than a universal numerical Pourbaix diagram. It should be replaced by feed-specific calculations whenever a target electrolyte and temperature are defined.

Figure 1. Conceptual redox–speciation window for Co(II) oxidation relative to Ni(II) persistence



Note. Author-developed schematic, adapted from the thermodynamic framing of Cao *et al.* (2020) and the redox/speciation evidence of Makarava *et al.* (2024), Illés and Kékesi (2023), Manceau and Steinmann (2022), and Fablet *et al.* (2026). Boundaries are qualitative and must not be interpreted as electrolyte-independent equilibrium lines.

The key implication of Figure 1 is that redox selectivity is inseparable from speciation selectivity. A process can fail even when Co(II) oxidation is thermodynamically favorable if the resulting Co(III) is immediately reduced, if it forms a colloid that retains nickel, or if the oxidant is consumed preferentially by Fe(II), Mn(II), organics, or other species. Conversely, a modest redox

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driving force may be sufficient when the product Co(III) is rapidly removed from solution by a favorable precipitation or complexation sink.

CO(III) SPECIATION, STABILIZATION, AND HYDROLYSIS

Why free Co(III) is the wrong design target

The most important conceptual correction is to treat Co(III) as a family of coordinated and condensed states rather than as a persistent free aquo ion. Ligand identity can shift both the redox potential and the lifetime of high-valent cobalt. Gamov *et al.* (2021) demonstrate differentiated interactions of Co(II), Co(III), Ni(II), and Zn(II) with hydrazone-derived ligands, while Yuan *et al.* (2022) show more broadly that solvation can be deliberately manipulated to change Co/Ni extraction behavior. The same principle underlies deep-eutectic and solvometallurgical systems, where coordination environments depart markedly from dilute-aqueous assumptions (Peeters *et al.*, 2020, 2022; Schiavi *et al.*, 2021; C. Wang *et al.*, 2025; J. Wang *et al.*, 2025; C. Wang *et al.*, 2026).

Hydrolysis as a separation sink

Hydrolysis converts a redox difference into a phase difference. Oxidative precipitation studies repeatedly exploit the lower practical stability of oxidized cobalt-bearing solids relative to Ni(II) in solution. In mixed hydroxide and synthetic Ni–Co liquors, the outcome depends on pH trajectory, oxidant type, anion chemistry, temperature, and aging. Ichlas *et al.* (2020) provide one of the clearest direct examples in which cobalt and manganese are selectively oxidatively precipitated after sulfuric-acid leaching of a mixed Ni–Co hydroxide precipitate. Wen *et al.* (2024) further demonstrate that chloride and sulfate media do not behave identically, which is a reminder that hydrolysis and complexation must be evaluated together rather than as independent modules.

Cobalt hydroxide precipitation without deliberate high-valent stabilization remains relevant as a comparator. Djoudi *et al.* (2021) show that temperature affects cobalt hydroxide precipitation behavior, while Cao *et al.* (2025) demonstrate how upstream precipitation used for impurity management can also entrain valuable Ni and Co. These studies reinforce a practical rule: any Co(III)-based precipitation route must be judged on selectivity of the complete solid–liquid split, not on cobalt removal alone.

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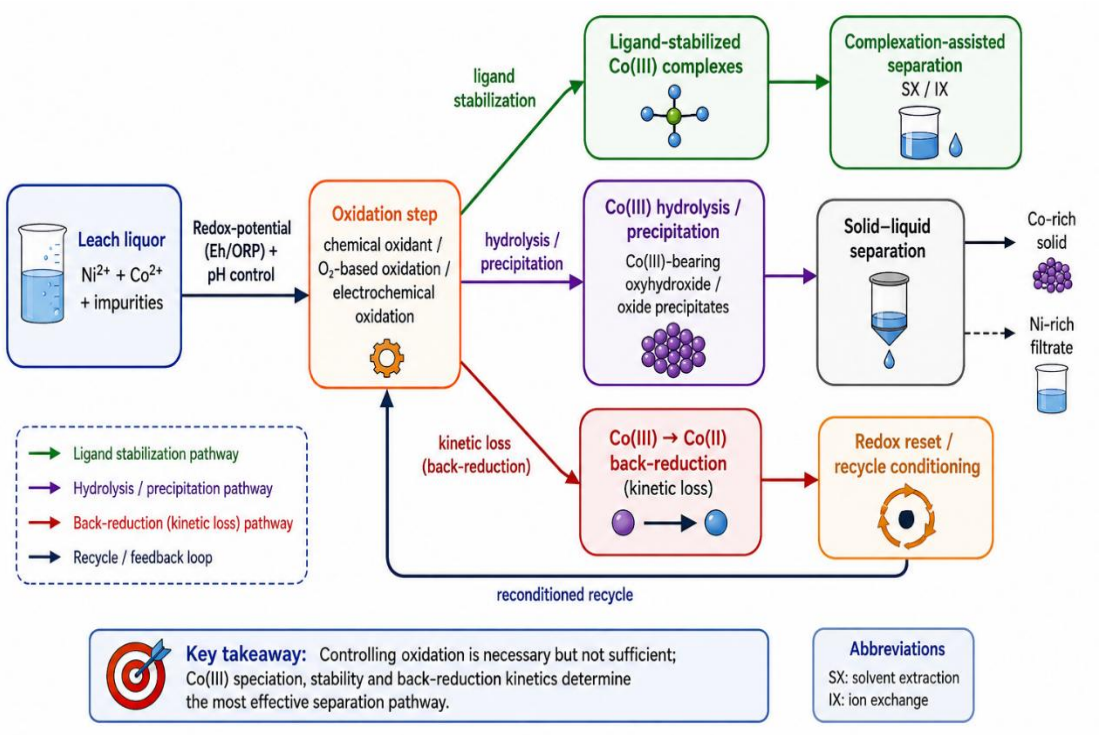
Kinetic persistence and back-reduction

The useful lifetime of Co(III) can be shorter than the hydraulic residence time of a poorly integrated circuit. Operando and surface-sensitive studies provide evidence that cobalt oxidation states can change reversibly as local coordination and surface structure evolve (Bouvier *et al.*, 2023; Z. Zhang *et al.*, 2025). Y. Zhang *et al.* (2022) similarly illustrate rapid Co(II)→Co(III) conversion in an engineered electrochemical environment. These studies are contextual rather than direct Ni–Co separations, but they establish the mechanistic plausibility of fast oxidation coupled to equally consequential subsequent transformations.

Figure 2 is included here because it translates this chemistry into process logic: oxidation yields several possible fates for cobalt, only some of which are useful for separation.

Figure 2. Competing fates of Co(III) after deliberate oxidation of a Ni–Co liquor



Note. Author-developed synthesis, adapted from Makarava *et al.* (2024), Manceau and Steinmann (2022), Bouvier *et al.* (2023), M. Shi *et al.* (2025), Zhao *et al.* (2023), Y. Zhang *et al.* (2022), and Z. Zhang *et al.* (2025).

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Figure 2 highlights that an oxidation reactor should be specified together with the downstream sink. If precipitation is intended, nucleation, particle growth, filtration, and nickel entrainment become design variables. If a ligand-stabilized Co(III) complex is intended, ligand degradation and stripping chemistry become critical. If electrochemical deposition or membrane transport is intended, current efficiency, mass-transfer polarization, and electrolyte management must be included in the same optimization.

METHODOLOGY

Review design and boundaries

The manuscript is a structured critical narrative review, not a systematic review or meta-analysis. The evidence base consists of 71 selected peer-reviewed publications from 2020–2026. The corpus was assembled around redox control, Co(II)/Co(III) speciation, oxidative precipitation, electrochemical separation, solvent extraction, feed-specific hydrometallurgy, impurity management, and emerging separation media. Older foundational electrochemical data were not reconstructed as a separate historical corpus; instead, recent studies that explicitly connect thermodynamics with modern hydrometallurgical conditions were prioritized. The principal unit of appraisal is therefore not publication count but the strength of the link between cobalt oxidation state and an actual Ni–Co separation consequence.

Evidence hierarchy

For interpretation, the studies were grouped into four evidence functions. Direct separation evidence includes experiments where a Ni–Co-bearing solution undergoes oxidative precipitation, electrochemical deposition, solvent extraction, or another operation that produces distinct Ni- and Co-rich products. Mechanistic redox evidence includes studies that directly identify Co(III) formation, surface stabilization, or redox kinetics but do not themselves demonstrate a practical Ni–Co separation. Process-integration evidence covers real feedstocks, impurity removal, upstream leaching, and downstream product recovery. Comparator evidence covers conventional or emerging non-Co(III) separations that define the performance threshold a new redox route must exceed. Table 1 maps the entire corpus to these roles; this mapping also prevents contextual mechanistic studies from being overinterpreted as demonstrations of process.

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Table 1. Evidence map for the 71-publication corpus used in this critical review

Evidence function	Representative studies	Use in this review
Direct Co(III)/oxidative or redox-enabled separation	Ichlas *et al.* (2020); Hussaini *et al.* (2021); Illés and Kékesi (2023); Nguyen and Lee (2023); Wen *et al.* (2024, 2025); Makarava *et al.* (2024); Shekarian *et al.* (2022, 2025, 2026); Nagai *et al.* (2026); Yan *et al.* (2026); Y. Shi *et al.* (2026).	Highest relevance
Electrochemical, membrane, and ion-transport comparators	Kim *et al.* (2021); Alsoliman *et al.* (2024); T. Li *et al.* (2026); Sun *et al.* (2025); Virolainen *et al.* (2021).	Direct/benchmark
Mechanistic Co(II)→Co(III) formation or stabilization	Manceau and Steinmann (2022); Zhao *et al.* (2023); Bouvier *et al.* (2023); Y. Zhang *et al.* (2022); Z. Zhang *et al.* (2025); M. Shi *et al.* (2025); Fablet *et al.* (2026); Xiang *et al.* (2026); Gamov *et al.* (2021); Yasin *et al.* (2024).	Mechanistic/contextual
Conventional SX, complexation, and alternative media	Abo Atia *et al.* (2023); Bahfie *et al.* (2023); Rodrigues *et al.* (2022); Sadehlari and Dubljevic (2025); Schaeffer *et al.* (2020); Mohammed *et al.* (2024); W. Li *et al.* (2026); Xu *et al.* (2022); Yuan *et al.* (2022, 2025); Matiti *et al.* (2026); Ilyas *et al.* (2022, 2023); Peeters *et al.* (2020, 2022); Schiavi *et al.* (2021); C. Wang *et al.* (2025); J. Wang *et al.* (2025); C. Wang *et al.* (2026); Binnemans and Jones (2023); Zeng *et al.* (2026); B. Zhang *et al.* (2025).	Benchmark/context
Feed preparation, leaching, recovery, and process integration	de Castro *et al.* (2024); Dias *et al.* (2026); Faris *et al.* (2023); Hu *et al.* (2022); Lim *et al.* (2023); Lou *et al.* (2023); Lu *et al.* (2021); Meshram *et al.* (2020); Prasetyo *et al.* (2022); Ranganathan *et al.* (2024); Takahashi *et al.* (2020); Tang *et al.* (2026); S. Wang *et al.* (2020); Y. Wang *et al.* (2025); Wen and Lee (2024); Nguyen and Lee (2025).	Integration/context
Thermodynamics, impurity behavior, sustainability, and systems appraisal	Cao *et al.* (2020, 2025); Djoudi *et al.* (2021); Merah *et al.* (2026); Zheng *et al.* (2026).	Cross-cutting

Note. Author-developed synthesis, adapted from the complete reference corpus compiled for this review. Direct evidence refers to studies that link a separation operation to Ni/Co partitioning; contextual evidence is used only for mechanisms or benchmarking.

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The evidence distribution reveals a central asymmetry. A large body of modern literature demonstrates methods for separating Ni(II) and Co(II), yet only a smaller subset directly exploits a controlled change in oxidation state as the decisive separation lever. Consequently, this review places greater weight on mechanistic consistency and process coupling than on citation frequency. A high separation factor measured in a purified synthetic solution is considered less transferable than a moderately selective result that withstands realistic impurity concentrations, solid-phase formation, recycling, and continuous operation.

RESULTS AND DISCUSSION

Oxidation strategies for converting Co(II) to a separable state

Chemical oxidants and oxidative precipitation

Chemical oxidation is the most direct route from a mixed divalent liquor to the selective formation of solids. Permanganate, hypochlorite-type oxidants, ozone, persulfate-derived chemistry, dissolved oxygen under suitable catalytic conditions, and other oxidants can shift cobalt and manganese toward less soluble states. Hussaini *et al.* (2021) combine oxidant-assisted treatment with mixed Ni–Co hydroxide processing, whereas Ichlas *et al.* (2020), Nguyen and Lee (2023), and Wen *et al.* (2024) demonstrate how oxidative precipitation can be integrated into multistep recovery circuits. These studies provide the strongest direct precedent for the Co(III) concept because oxidation is coupled to an observable separation operation.

Ozone is particularly useful as a mechanistic benchmark because it can generate strong oxidation without leaving a metal-bearing counter-ion. Shekarian *et al.* (2022, 2025, 2026) progressively develop ozone oxidative precipitation from process concept to kinetic and mechanistic treatment. The advantage is not reagent-free operation in an absolute sense—ozone generation requires energy and gas–liquid transfer—but avoidance of a persistent added salt. The limitations are equally important: gas–liquid mass transfer, radical or secondary reaction pathways, pH drift, and nonselective oxidation of co-solutes can dominate at scale.

The most recent oxidative approaches also show that the direction of oxidation need not be limited to cobalt. Yan *et al.* (2026) use persulfate-derived chemistry to reconstruct nickel-bearing material in a way that enables cobalt removal, and Nagai *et al.* (2026) combine selective Mn oxidation with preferential Ni reduction. These papers broaden the design space: the industrial question is not necessarily “How can Co alone be oxidized?” but “Which controlled redox asymmetry generates the most separable phase architecture for a specific feed?”

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Electrochemical oxidation and deposition

Electrochemical methods replace a stoichiometric oxidant with an imposed potential or current, thereby providing superior temporal control and facilitating reagent recycling. Makarava *et al.* (2024) directly examine electrochemical cobalt oxidation in chloride media, while Kim *et al.* (2021) demonstrate selective cobalt and nickel electrodeposition by integrating electrolyte and interface control. Y. Shi *et al.* (2026) further couple electrochemical reduction with solubility-product differences to separate Ni and Co from acidic leachate. These approaches are attractive because potential, local pH, mass transfer, and electrode surface can be manipulated independently, but they shift the burden from reagent selectivity to reactor engineering.

Bioacid-mediated electrowinning provides a further example of coupling chemistry with electrochemical driving force. T. Li *et al.* (2026) demonstrate selective cobalt and nickel separation through a mediated electrowinning strategy. Sun *et al.* (2025) similarly integrate electrochemical operations with acid recovery in spent-$LiCoO_2$ processing. Together, these studies suggest that future Co(III) circuits may be better understood as electrochemically conditioned separation systems rather than stand-alone oxidation reactors.

Surface-mediated and bio-derived oxidation

Mineral and biogenic oxide surfaces can oxidize and sequester cobalt. Manceau and Steinmann (2022) provide atomistic insight into Co(II) oxidation by birnessite, Zhao *et al.* (2023) show how aqueous Mn(II) modifies sorption and oxidation at birnessite surfaces, and M. Shi *et al.* (2025) link cobalt enrichment to the average oxidation state of biogenic manganese oxides. Fablet *et al.* (2026) extend the mechanistic picture to $Fe_{3-}\delta O_4$ nanoparticle surfaces. These mechanisms could inspire reusable redox sorbents or catalytic precipitation seeds, but current evidence is stronger for mechanistic feasibility than for hydrometallurgical scale-up.

Table 2. Critical comparison of Co(II) oxidation strategies relevant to Ni–Co separation

Strategy	Main advantage	Scale-up liability	Evidence status
Chemical oxidant + precipitation	Fast response; simple stirred equipment	Oxidant consumption; salt load; Ni co-precipitation	Directly demonstrated
Ozone oxidative precipitation	No metal counter-ion; controllable gas dosing	Mass transfer; ozone generation energy; off-gas handling	Directly demonstrated

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Strategy	Main advantage	Scale-up liability	Evidence status
Electrochemical oxidation/deposition	Potential control; reagent minimization; possible recycle	Electrode area; current efficiency; fouling; conductivity	Direct and emerging
Redox-active oxide surface	Can couple oxidation and sorption/precipitation	Surface capacity; regeneration; competing ions	Mechanistic/contextual
Hybrid ligand–redox system	Can stabilize a targeted Co(III) complex	Ligand cost, degradation, stripping complexity	Emerging

Note. Author-developed synthesis, adapted from Ichlas *et al.* (2020), Hussaini *et al.* (2021), Shekarian *et al.* (2022, 2025, 2026), Makarava *et al.* (2024), Kim *et al.* (2021), T. Li *et al.* (2026), Manceau and Steinmann (2022), Zhao *et al.* (2023), M. Shi *et al.* (2025), and Fablet *et al.* (2026).

Table 2 shows why there is no universally superior oxidant. Chemical oxidation is operationally simple but can create reagent and residue penalties. Electrochemical routes offer fine control but require high-quality reactor design and stable electrodes. Surface-mediated routes could reduce reagent consumption but must demonstrate regeneration and capacity under realistic metal loading. The appropriate choice therefore depends on the downstream separation sink and on whether the plant is reagent-, energy-, or equipment-constrained.

SEPARATION MECHANISMS ENABLED BY REDOX AND SPECIATION CONTROL

Oxidative precipitation

Oxidative precipitation is the most conceptually direct Co(III)-enabled separation. A mixed Ni(II)–Co(II) liquor is oxidized under pH conditions where the oxidized cobalt product hydrolyzes or forms an oxide/oxyhydroxide-like solid while most Ni remains dissolved. Ichlas *et al.* (2020) and Wen *et al.* (2024) show that the practical outcome depends strongly on solution chemistry. Nguyen and Lee (2023) demonstrate how oxidative precipitation can be sequenced with cementation and solvent extraction, illustrating that the redox operation is best viewed as one element of a multi-unit flowsheet rather than a complete recovery process.

The critical selectivity metric is not cobalt precipitation percentage in isolation. A successful route must also report nickel loss, impurity deportment, product filterability, washing behavior, redissolution requirements, and the oxidation state/mineralogy of the recovered solid. Ranganathan *et al.* (2024), although focused on manganese recovery, is instructive because it

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explicitly links oxidative precipitation to an electrochemically useful product. This product-oriented perspective is equally important for cobalt: a poorly filterable or difficult-to-redissolve Co-rich solid can erase the apparent advantage of high solution selectivity.

Solvent extraction after redox or coordination conditioning

Conventional SX remains the benchmark because it has established contactor technology, continuous counter-current design, and predictable scale-up. Rodrigues *et al.* (2022) compare mixer-settlers with an agitated column for Cyanex 272 Co/Ni separation, thereby directly addressing the choice of contactor. Abo Atia *et al.* (2023) show that silica and other impurities can become decisive in real hydroxide-derived feeds, while Xu *et al.* (2022) demonstrate the value of synergistic extractant systems and full elemental mass balances. Matiti *et al.* (2026) examine the effects of amine modification and diluent choice on the behavior of Cyanex 272.

For a Co(III)-enabled SX route to justify itself, oxidation must produce either a cobalt species with much stronger extractability than Ni(II) at a lower pH or a species that is selectively rejected by the organic phase while nickel transfers. The broader extraction literature demonstrates that this type of selectivity engineering is plausible. Yuan *et al.* (2022, 2025) show that solvation and complexing agents can suppress or enhance metal transfer, while Sadehlari and Dubljevic (2025) demonstrate the combined influence of extractant saponification and acetate buffering. The implication is that redox and coordination should be optimized together rather than sequentially.

Fully aqueous, deep-eutectic, and switchable coordination routes

Alternative media demonstrate that the chemical similarity between Ni and Co is not immutable. Schaeffer *et al.* (2020) achieve selective separation of Mn/Co/Ni in a fully aqueous system. Peeters *et al.* (2020, 2022) and Schiavi *et al.* (2021) use nonconventional solvents to recover cobalt from battery cathode materials, while C. Wang *et al.* (2025), J. Wang *et al.* (2025), and C. Wang *et al.* (2026) show how coordination and solvent regeneration can be manipulated in choline-chloride-based deep-eutectic systems. Zeng *et al.* (2026) further introduce switchable coordination chemistry. These studies are mainly comparators to the Co(III) route, but they establish a high bar: if ligand or solvent engineering can achieve equivalent selectivity without a high-potential oxidation step, the redox route must offer a clear advantage in reagent recycle, product quality, or integration.

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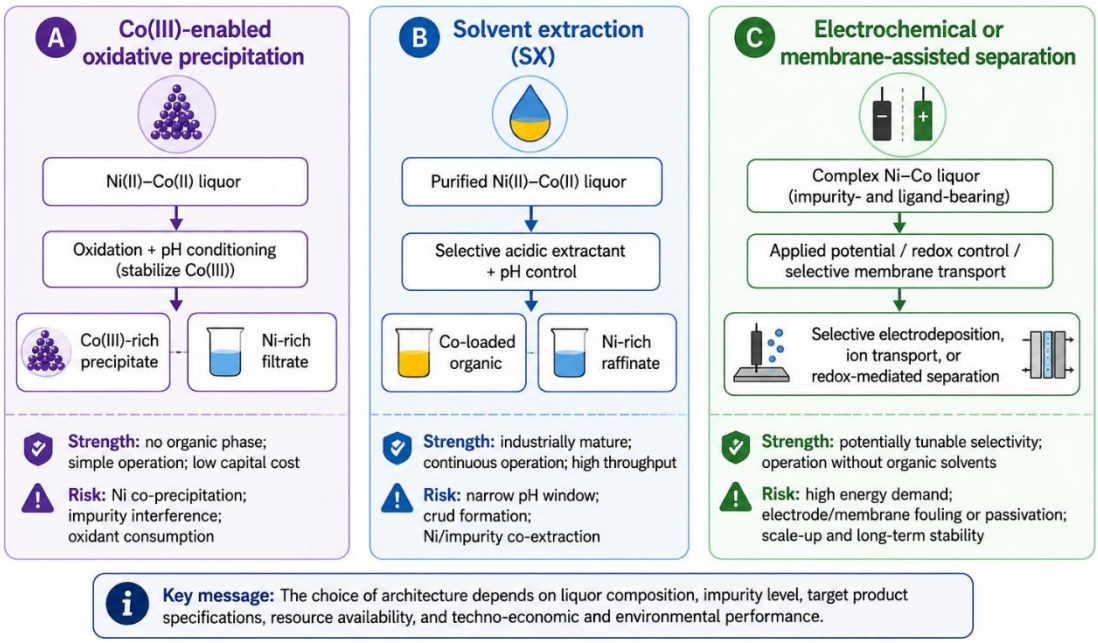
Membrane, ion-exchange, and electrochemical transport

Ion transport can create separation even when bulk thermodynamic selectivity is limited. Alsoliman *et al.* (2024) combine electrodeionization and complexation to separate Ni and Co from a synthetic pregnant leach solution. Virolainen *et al.* (2021) demonstrate the role of ion exchange in removing Fe, Al, Mn, and Cu from battery leachates—an upstream function that can be crucial before redox conditioning. Kim *et al.* (2021) and Y. Shi *et al.* (2026) present electrochemical routes in which electrolyte and interface design, or local chemical conditions, generate separation. These approaches are particularly well-suited to Co(III) chemistry because they can integrate oxidation, transport, and reduction within a closed electrical circuit.

Figure 3 compares these architectures at the flowsheet level.

Figure 3. Comparison of oxidative precipitation, conventional solvent extraction, and electrochemical/hybrid architectures for Ni–Co separation



Note. Author-developed synthesis, adapted from Ichlas *et al.* (2020), Wen *et al.* (2024, 2025), Rodrigues *et al.* (2022), Kim *et al.* (2021), Alsoliman *et al.* (2024), and Y. Shi *et al.* (2026).

The comparison makes clear that the Co(III) route should not be assessed only on the separation factor. Oxidative precipitation may reduce organic-solvent inventory but increases solid handling and oxidant demand. Conventional SX is mature but requires organic-phase

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management and often multistage pH control. Electrochemical/hybrid systems may reduce reagent use and offer rapid control but introduce electrode, conductivity, and power-density constraints. The strongest future designs are therefore likely to combine these mechanisms selectively rather than insist on a single unit operation.

KINETICS, MASS TRANSFER, AND ANALYTICAL CONTROL

Oxidation kinetics versus hydrodynamics

Thermodynamic feasibility is insufficient when oxidation, hydrolysis, nucleation, or phase transfer is slower than mixing and residence-time scales. The ozone studies of Shekarian *et al.* (2025, 2026) explicitly treat chemical kinetics and mechanism, while electrochemical studies inherently couple reaction rates to mass transfer at electrodes. In stirred oxidative precipitation, scale-up changes gas dispersion, local pH, and supersaturation. In electrochemical cells, current density changes boundary-layer gradients. A laboratory optimum based on bulk Eh can therefore become unstable when translated to larger reactors with spatially distributed reaction zones.

The practical control variable should be a state estimate rather than a single ORP reading. ORP integrates multiple redox couples and may not uniquely indicate the Co(II)/Co(III) ratio. The study by Yasin *et al.* (2024) is valuable because it demonstrates simultaneous analytical determination of Co(II) and Co(III) using spectrophotometric data and multivariate models. For industrial development, this kind of oxidation-state-specific analytics should be combined with total Co/Ni assays, pH, temperature, conductivity, and particle-size/solid-phase measurements.

Nucleation, growth, and solid–liquid separation

When Co(III) is intentionally converted to a solid, nucleation and growth determine whether the separation is operable. Very fine oxide or oxyhydroxide particles may provide high chemical selectivity but poor filtration. Co-precipitation can increase with increasing surface area or with simultaneous formation of Fe/Al hydroxides. The precipitation work of Djoudi *et al.* (2021) and the laterite impurity-removal study of Cao *et al.* (2025) show why temperature and precipitant choice affect both target recovery and valuable-metal losses. These observations support staged precipitation and controlled seeding rather than a single aggressive pH jump.

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Back-reduction and redox buffering

A Co(III) species can be lost through reaction with residual reductants, dissolved organics, ferrous iron, sulfite/sulfide species, reduced mineral surfaces, or electroactive ligands. This problem is especially relevant in battery leachates, where reductive leaching is frequently used to dissolve cathode materials. S. Wang *et al.* (2020), Prasetyo *et al.* (2022), Lu *et al.* (2021), and Takahashi *et al.* (2020) describe routes whose upstream objective is efficient cobalt dissolution, often under conditions designed to keep cobalt in a reduced, soluble state. Therefore, a Co(III) separation step placed immediately downstream of such leaching requires removal or exhaustion of the reducing inventory before oxidation.

IMPURITY EFFECTS AND FEED-SPECIFIC CONSTRAINTS

Iron, aluminum, manganese, copper, and magnesium

Real Ni–Co liquors are rarely binary. Laterite and mixed-hydroxide solutions contain Fe, Al, Mn, Mg, Ca, and sometimes Cu/Zn; battery leachates add Li, Mn, Al, Cu, graphite-derived organics, and variable acid or chloride content. Each impurity can alter the Co(III) route through at least one of four mechanisms: oxidant consumption, competitive complexation, co-precipitation, or modification of interfacial/electrochemical kinetics. The study by Cao *et al.* (2025) is particularly instructive because it demonstrates that impurity removal itself can cause meaningful Ni losses, so the upstream purification step must be included in the overall selectivity balance.

Manganese is both a competitor and a possible process ally. Oxidative precipitation often removes Mn together with Co, which can be favorable if a mixed Co–Mn product is acceptable but problematic when battery-grade cobalt purity is required. Wen *et al.* (2024), Ichlas *et al.* (2020), and the ozone studies of Shekarian *et al.* (2022, 2025, 2026) all emphasize coupled Co/Mn behavior. Conversely, Mn-oxide surfaces can oxidize and retain cobalt, as shown by Manceau and Steinmann (2022), Zhao *et al.* (2023), and M. Shi *et al.* (2025). Thus, Mn cannot be treated merely as an impurity concentration; its oxidation state and mineral/colloidal form matter.

Copper can strongly interfere with complexation and extraction, especially in alkaline or glycine media. Mohammed *et al.* (2024) and W. Li *et al.* (2026) show that Cu/Ni/Co separation depends on ligand environment and extraction sequence. Fe and Al can form voluminous precipitates or consume alkalinity and oxidant, while Mg can dominate reagent demand in laterite-derived solutions. Upstream ion exchange, selective precipitation, or SX may therefore be

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economically justified even when it sacrifices some flowsheet simplicity (Abo Atia *et al.*, 2023; Virolainen *et al.*, 2021; Xu *et al.*, 2022).

Table 3. Impurity mechanisms that can narrow the practical Co(III) separation window

Impurity or matrix component	Primary interference	Design response
Fe	Redox demand; hydrolysis; scavenging/co-precipitation	Remove or stabilize before Co oxidation; avoid simultaneous gelatinous precipitation
Al	Hydrolysis and entrainment	Stage pH control; separate before high-pH Co treatment
Mn	Co-oxidation / co-precipitation; redox-active oxide formation	Define whether Co–Mn coproduct is acceptable; control Mn oxidation state
Cu	Competitive complexation / preferential extraction / electrode deposition	Early Cu removal or selective ligand strategy
Mg/Ca	Alkalinity and precipitant demand; organic-phase loading in some systems	Use upstream impurity removal and avoid excessive pH excursion
Residual reductants/organics	Back-reduction of Co(III); oxidant consumption	Destroy/exhaust reductant before redox conditioning

Note. Author-developed synthesis, adapted from Cao *et al.* (2025), Abo Atia *et al.* (2023), Virolainen *et al.* (2021), Wen *et al.* (2024), Shekarian *et al.* (2022, 2025, 2026), Mohammed *et al.* (2024), W. Li *et al.* (2026), and Xu *et al.* (2022).

Table 3 illustrates why a “binary Ni–Co test” should be regarded as a screening experiment rather than a process validation. A credible scale-up program needs synthetic matrices with progressively realistic impurity loading followed by real PLS tests. The transition from purified binary solution to real feed is a formal gate in the decision framework presented below.

FEEDSTOCK CONTEXT: LATERITES, MHP, BATTERY LEACHATES, AND METALLURGICAL RESIDUES

Laterite and mixed hydroxide precipitate

Laterite processing provides a strong test case because Ni is usually the major payable metal while Co is a lower-concentration coproduct embedded in a high-impurity matrix. Cao *et al.*

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(2020) demonstrate the value of thermodynamic E–pH analysis for lateritic systems, while Hu *et al.* (2022) and Y. Wang *et al.* (2025) examine ammonia leaching of polymetallic or mixed hydroxide precipitates. Wen *et al.* (2025) directly address recovery of pure Co(II) and Ni(II) solutions from a synthetic sulfate laterite liquor by precipitation and solvent extraction. These studies collectively suggest that the best location for a Co(III) step is likely after major Fe/Al removal but before final Ni/Co polishing, where cobalt concentration is high enough to justify treatment and the reducing impurity inventory is lower.

The feed history matters. If a mixed hydroxide precipitate has been generated under reducing conditions or contains Mn-rich phases, the dissolution route determines the initial Co oxidation state and the residual oxidant/reductant demand. Hussaini *et al.* (2021) and Ichlas *et al.* (2020) are particularly relevant because they work directly with mixed Ni–Co hydroxide materials and demonstrate how oxidation chemistry can be used during selective leaching or subsequent precipitation.

Lithium-ion-battery recycling

Battery recycling supplies a second major context but with a different redox baseline. Many leaching routes deliberately reduce higher-valent cobalt in cathode oxides to soluble Co(II), so a downstream Co(III) separation step partially reverses the upstream redox strategy. This is not necessarily inefficient if reductive dissolution is essential for high metal recovery, but it creates a redox loop that must be justified by selectivity. The recycling literature documents multiple alternatives—ionic liquids, deep-eutectic solvents, SX, electrochemical deposition, and staged precipitation—that already achieve substantial Ni/Co differentiation (de Castro *et al.*, 2024; Ilyas *et al.*, 2022, 2023; Kim *et al.*, 2021; Peeters *et al.*, 2020, 2022; Schiavi *et al.*, 2021).

Reduction smelting followed by hydrometallurgy creates yet another chemistry. Nguyen and Lee (2023, 2025) integrate ferric sulfate leaching, cementation, SX, oxidative precipitation, and final salt production from reduction-smelted alloys. This type of staged flowsheet is a useful model for Co(III) integration because it explicitly assigns specific impurities to specific unit operations rather than requiring a single “universal” separator.

Slags, sulfides, and heterogeneous secondary feeds

Metallurgical slags and sulfide-derived materials introduce high Fe-, Cu-, silicate-, and sulfur-bearing inventories. Faris *et al.* (2023) emphasize the diversity of direct leaching routes for nickel sulfide concentrates, while Meshram *et al.* (2020), Lim *et al.* (2023), Lou *et al.* (2023), and Tang *et al.* (2026) cover complex slag or sludge feedstocks. These systems are less obvious

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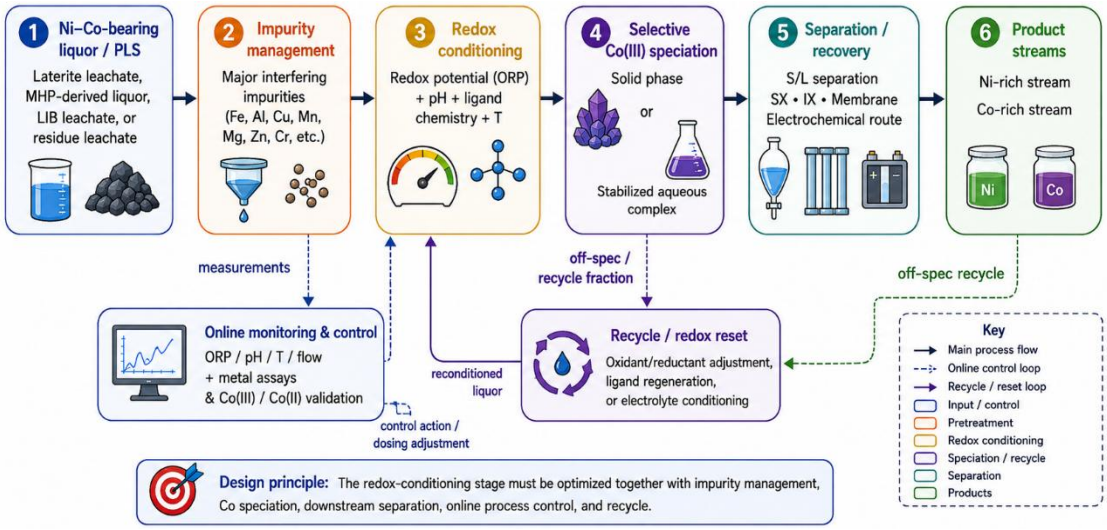
candidates for immediate Co(III) separation due to high oxidant demand and impurity loading. Their likely role is as upstream feed sources whose leachates require aggressive purification before any fine redox-based Ni–Co split.

PROCESS INTEGRATION AND FLOWSHEET DESIGN

Why oxidation cannot be a stand-alone unit

The central process-design conclusion of the literature is that oxidation selectivity must be preserved through the next operation. An oxidant can create Co(III), yet separation fails if the product remains in the same phase as Ni or rapidly reverts to Co(II). Therefore, a Co(III)-enabled circuit should be designed as a coupled sequence: impurity management → redox conditioning → selective cobalt fate → phase separation → product recovery → redox or reagent recycle. The sequencing follows the logic observed in integrated laterite, MHP, and battery-recycling circuits, even when those circuits do not explicitly use Co(III) as their primary separation variable (Abo Atia *et al.*, 2023; Hu *et al.*, 2022; Nguyen & Lee, 2023; Wen *et al.*, 2025; Pereira, 2026b).
Figure 4 is inserted here to show the required integration and feedback loops.

Figure 4. Integrated redox-conditioned flowsheet for Ni–Co separation with impurity management, online control, phase separation, and redox recycle



Note. Author-developed synthesis, adapted from Abo Atia *et al.* (2023), Ichlas *et al.* (2020), Makarava *et al.* (2024), Nguyen and Lee (2023, 2025), Rodrigues *et al.* (2022), Wen *et al.* (2024, 2025), and Kim *et al.* (2021).

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The feedback loops in Figure 4 are not optional refinements. Online pH and ORP control is required because oxidation and hydrolysis consume or release protons and because feed composition changes. A Co(II)/Co(III)-specific analytical signal would be preferable to ORP alone. Product recycle is needed because off-spec cobalt-rich solids or organic/electrochemical phases can otherwise accumulate nickel losses. Finally, the redox-reset loop provides a route for the regeneration of reductants or oxidants rather than one-pass reagent consumption.

Hybridization with solvent extraction or ion exchange

A hybrid flowsheet can use Co(III) chemistry to reduce the burden on a mature downstream separator rather than replace it. For example, oxidative precipitation can remove most Co and Mn while a smaller SX circuit performs final Ni/Co polishing. Alternatively, a mild redox conditioning step can alter complexation sufficiently to reduce the number of SX stages. Alsoliman *et al.* (2024) demonstrate the broader value of hybridizing electrodeionization with chemical complexation, while Rodrigues *et al.* (2022) and Sadehlari and Dubljevic (2025) show how contactor architecture and buffering influence conventional Co/Ni SX performance. The industrially attractive target may therefore be fewer stages, lower organic inventory, or less saponification—not complete elimination of SX.

Product recovery and redox reset

A cobalt-rich Co(III) solid is an intermediate, not necessarily a final product. It may require reductive dissolution before crystallization, electrowinning, or precursor synthesis. Conversely, a ligand-stabilized Co(III) complex may require controlled reduction during stripping. Wen and Lee (2024) demonstrate chemical reduction after SX to recover Ni and Co powders, while Sun *et al.* (2025) emphasize acid recovery within an electrochemical circuit. These examples reinforce the importance of closing chemical loops when comparing flowsheets.

BENCHMARKING AGAINST CONVENTIONAL AND EMERGING NI–CO SEPARATION

Conventional SX as the reference case

A critical review of a new separation concept must compare it with the best available alternative, not with an idealized weak baseline. Cyanex-272-type chemistry and related extractant systems remain the principal benchmark because they are well studied and readily staged. Bahfie *et al.* (2023) summarize conventional versus ionic-liquid extraction, Rodrigues *et al.* (2022) provide continuous-contacting evidence, and Matiti *et al.* (2026) explore extractant modification and diluent effects. Xu *et al.* (2022) demonstrate that synergistic solvent systems

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can integrate leaching, precipitation, extraction, scrubbing, and stripping with elemental mass balance.

Solvation and ligand engineering further raise the benchmark. Yuan *et al.* (2022, 2025) show that deliberate complexation can improve non-saponification separation, while Sadehlari and Dubljevic (2025) demonstrate strong interaction between partial saponification and acetate buffering. In alkaline glycine/glycinate media, Mohammed *et al.* (2024) and W. Li *et al.* (2026) show that sequence and competing Cu extraction influence Ni/Co behavior. A Co(III) route must therefore demonstrate value under the same feed complexity rather than only against a simple sulfate binary solution.

Emerging solvent and coordination systems

Deep-eutectic, solvometallurgical, and switchable-coordination approaches challenge the assumption that high selectivity requires an oxidation-state change. Peeters *et al.* (2020, 2022), Schiavi *et al.* (2021), C. Wang *et al.* (2025), J. Wang *et al.* (2025), C. Wang *et al.* (2026), and Zeng *et al.* (2026) show that coordination chemistry and solvent structure can be engineered to differentiate Co and Ni. Binnemans and Jones (2023), however, caution that academic selectivity must be reconciled with viscosity, solvent recovery, toxicity, cost, and industrial practicality. The same caution applies to Co(III) chemistry: a strong laboratory separation factor does not compensate for poor reagent recycle or unstable continuous operation.

Techno-economic and environmental benchmarking

Few Co(III)-specific studies provide complete techno-economic or life-cycle comparisons. The study by B. Zhang *et al.* (2025) is therefore important because it explicitly validates a sustainable cobalt separation concept with techno-economic analysis and life-cycle assessment. The broader lesson is methodological: redox routes should be assessed at flowsheet level, including oxidant or electricity production, neutralization demand, residue generation, solvent or membrane replacement, and product finishing. A route that reduces organic extractant inventory may still increase global impact if it requires energy-intensive ozone generation or repeated oxidation/reduction cycles.

Table 4. Benchmarking criteria for deciding whether a Co(III)-enabled route improves on conventional Ni–Co separation

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Criterion	Required metrics	Critical interpretation
Selectivity	Ni loss, Co recovery, impurity rejection, product purity	Must outperform or simplify multistage SX
Chemical intensity	Oxidant/reductant, base/acid, ligands, wash water	Include recycle and neutralization—not only fresh reagent
Energy intensity	Ozone/electrolysis, pumping, mixing, heating	Report per mass of separated Co/Ni product
Operability	Eh/pH tolerance, feed variability, phase disengagement/filterability	Demonstrate beyond optimized batch point
Circularity	Reagent/electrolyte recovery, residue reuse, solvent lifetime	Quantify closed-loop fraction
Scale-up evidence	Continuous operation, pilot duration, mass balance closure	Required before industrial superiority can be claimed

Note. Author-developed synthesis, adapted from Rodrigues *et al.* (2022), Bahfie *et al.* (2023), Binnemans and Jones (2023), B. Zhang *et al.* (2025), Alsoliman *et al.* (2024), and the oxidative-precipitation studies cited in the results and discussion.

Table 4 emphasizes the full economic and environmental burden rather than the selectivity number alone, a distinction that is especially important for cobalt. Because the cobalt concentration in laterite feeds may be lower than that of nickel, a technically elegant Co(III) step can be uneconomical if oxidant demand or electrode area scales with total solution flow instead of with cobalt inventory.

RESEARCH GAPS AND A DECISION FRAMEWORK FOR SCALE-UP

Priority knowledge gaps

The first gap is the lack of oxidation-state-resolved data in hydrometallurgical matrices. Many studies quantify total cobalt without directly measuring Co(II) versus Co(III). Combining total metal assays with oxidation-state-specific spectroscopy or chemometrics, as Yasin *et al.* (2024) did, would enable mass-balance closure on the redox pathway. The second gap is kinetic coupling: oxidation rate, hydrolysis, nucleation, filtration, and back-reduction should be measured together in one experiment instead of separately.

The third gap is impurity realism: validation must progress from binary Ni–Co solutions to real process liquors. The fourth gap is continuous operation, which requires stability, online control, solids management, and reagent recycling before industrial viability can be claimed. The fifth gap is comparative systems analysis, in which a Co(III) route is compared with optimized SX,

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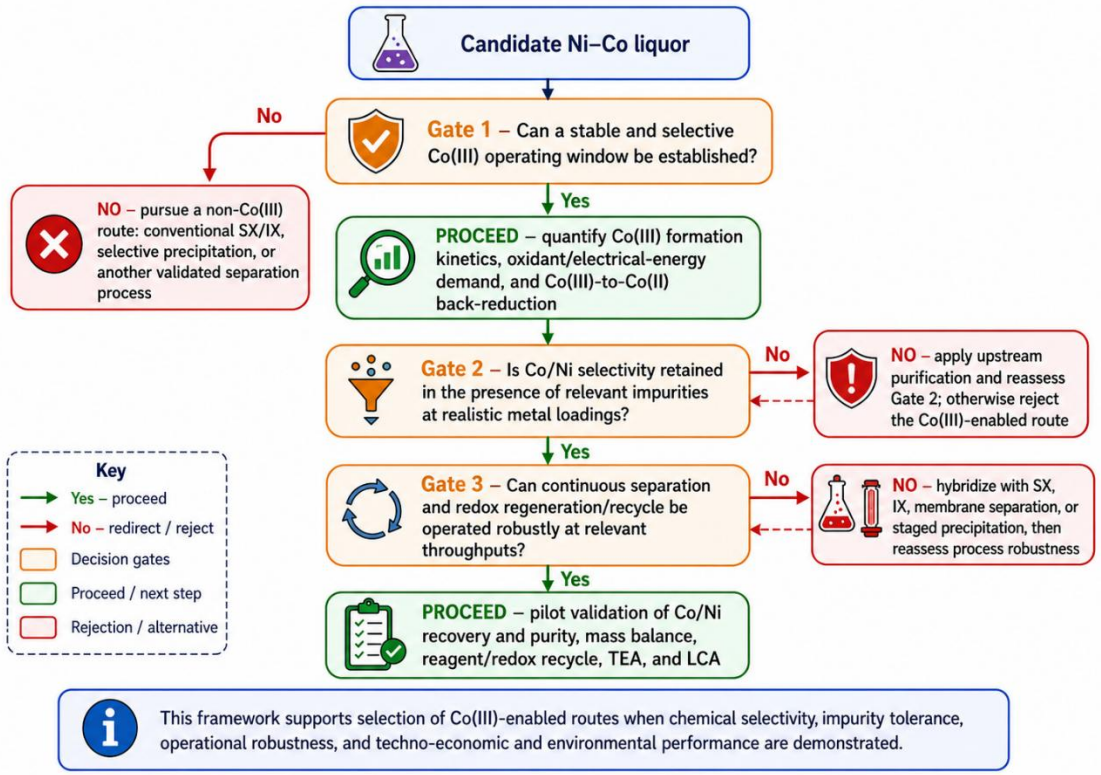
aqueous or membrane alternatives, and electrochemical deposition under identical feed and product specifications.

Three-gate development logic

A development program should use explicit stop/go gates: Gate 1 checks for a reproducible Co(III) window and useful cobalt fate before Ni response; Gate 2 adds impurities and tests for selectivity at target concentrations; Gate 3 requires continuous operation with recycled reagents/electrolyte, stable product quality, and initial techno-economic and environmental assessment. Failure at any gate should revert to conventional SX, staged precipitation, or another mature method instead of forcing Co(III) forward.

Figure 5 formalizes this decision process.

Figure 5. Decision framework for screening, rejecting, hybridizing, or scaling a Co(III)-enabled Ni–Co separation route



Note. Author-developed synthesis, adapted from the direct oxidative/electrochemical evidence of Ichlas *et al.* (2020), Wen *et al.* (2024, 2025), Makarava *et al.* (2024), Shekarian *et al.* (2022,

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2025, 2026), Kim *et al.* (2021), Y. Shi *et al.* (2026), and the scale-up benchmarking of Rodrigues *et al.* (2022) and B. Zhang *et al.* (2025).

The framework deliberately includes a rejection option. The goal of critical review is not to maximize the number of applications assigned to Co(III) chemistry, but to identify the subset in which redox asymmetry provides sufficient process value to justify additional control complexity. In highly impure, reducing, or low-cobalt feeds, the correct engineering decision may be to use established purification and SX. In cleaner feeds with a sharp oxidation/precipitation window, or where organic-solvent inventory is a major constraint, a Co(III)-enabled hybrid circuit may be attractive.

CONCLUSIONS AND RECOMMENDATIONS

Selective Ni–Co separation through Co(III) chemistry is chemically credible but should be viewed as a coupled redox–speciation–separation strategy rather than as an oxidation step in isolation. The useful process window opens when cobalt can be converted from Co(II) to a state sufficiently persistent to undergo a distinct phase transition, coordination reaction, transport response, or electrochemical reaction relative to Ni(II). In practice, this window is controlled by pH, redox potential, ligand environment, ionic medium, temperature, residence time, and impurity loading.

Oxidative precipitation currently provides the clearest direct demonstration of the concept because it immediately converts redox contrast into a solid–liquid separation. Electrochemical routes offer finer control and greater opportunities for reagent recycling, but they require further validation of current efficiency, electrode durability, hydrodynamics, and continuous operation. Ligand-assisted and solvent-based systems show that redox control must also compete with increasingly sophisticated non-redox alternatives.

The largest barrier to industrial implementation is not the existence of Co(III), but the robustness of the complete operating envelope. Back-reduction, oxidant consumption by impurities, Ni co-precipitation, colloid formation, and the need for continuous oxidation-state control can erase laboratory selectivity. Accordingly, the most credible near-term applications are hybrid circuits in which a controlled redox step reduces the burden on a downstream mature separator rather than attempts to replace the entire purification train.

Future work should prioritize oxidation-state-resolved analytics, real-feed impurity matrices, continuous reactor tests, reagent and electrolyte recycle, and flowsheet-level techno-economic and life-cycle comparison. A Co(III) route should advance only when it passes explicit

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thermodynamic, impurity-tolerance, operability, and sustainability gates under the same product specifications used to judge conventional Ni–Co separation.

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Conflicts of interest

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Data availability

No new experimental data were generated. The evidence base consists of the published sources listed in the References section.

Author contributions

Conceptualization, literature curation, critical analysis, synthesis, visualization, and manuscript preparation were performed by the author.

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