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Conventional Ion-Exchange and Chelating Resins for Metal Recovery: A Critical Comparison of Selectivity, Dynamic Performance, Regeneration, and Process Integration

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ABSTRACT: Conventional ion-exchange and chelating resins are widely used for metal recovery, purification, and polishing, yet they are still frequently compared using equilibrium capacity rather than process function. This structured critical review examines how charge-driven exchange and ligand-controlled coordination translate into selectivity, kinetics, breakthrough behavior, regeneration, fouling, resin lifetime, and flowsheet integration. Topic-structured searches covering 2018–31 August 2026 yielded 313 candidate records, of which 110 peer-reviewed publications were retained for critical synthesis. Evidence was weighted from batch equilibrium and kinetic studies through fixed-bed or reactor operation, regeneration, real-matrix validation, pilot or multicolumn demonstrations, and selected industrial-scale applications. Across rare-earth elements, Cu–Ni–Co systems, battery-recycling liquors, Sc/V/Ga separations, Zr/Hf and radionuclide systems, precious metals, and industrial wastewaters, the evidence shows that equilibrium qmax and single-solute distribution coefficients are poor stand-alone indicators of process readiness. Representative dynamic studies report outcomes ranging from a Cu breakthrough capacity of 16.51 mg g−1 to an REE eluate concentration factor of 236×, while selected continuous and industrial-scale studies demonstrate high product purity, sustained metal recovery, and concentrated regenerates when feed chemistry and cycle design are controlled. Conventional and chelating resins are therefore best viewed as complementary rather than substitutive technologies. The review proposes a minimum reporting framework for scale-up-relevant studies based on representative feed chemistry, working capacity, breakthrough criteria, regenerant demand, product purity, multicycle durability, and flowsheet integration. Hybrid flowsheets emerge as a particularly defensible strategy for converting resin selectivity into process value.

KEYWORDS: chelating resins; ion exchange; metal recovery; selectivity; regeneration; process integration.

Highlights

- Conventional ion exchange favors robust bulk duties; chelation adds ligand-controlled selectivity.
- Speciation, breakthrough, and working capacity are more informative than batch qmax alone.
- Regeneration, fouling, and resin lifetime determine whether selectivity creates process value.
- A scale-up reporting framework links real feeds, multicycle operation, TEA, and hybrid flowsheets.

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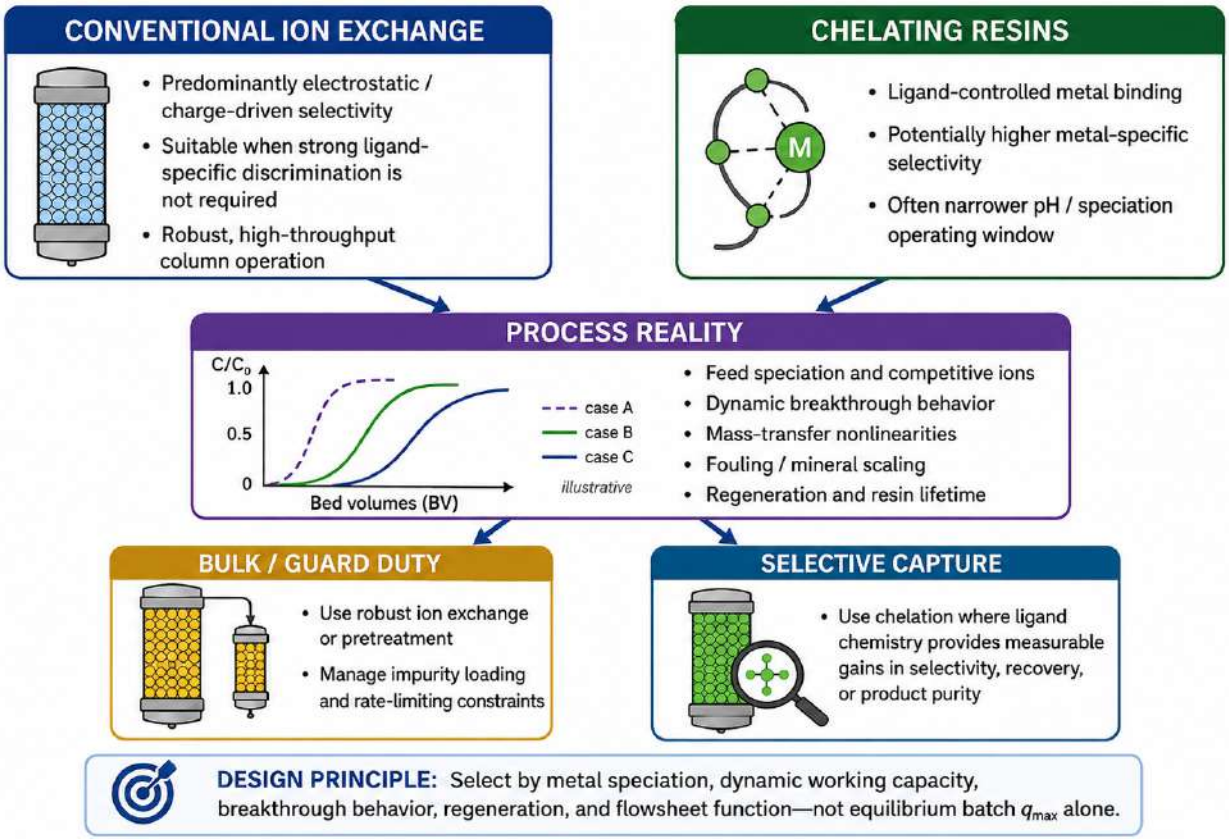
Graphical Abstract



1. INTRODUCTION

Selective recovery of dissolved metals increasingly sits at the intersection of primary-resource hydrometallurgy, treatment of metallurgical effluents, recycling of batteries and electronic waste, and recovery of critical elements from secondary residues. In these systems, the process challenge is rarely the simple capture of a metal from water. The difficult task is to recover a target ion from a chemically crowded solution while preserving product purity, reagent economy, hydraulic operability, and the possibility of regenerating the separation medium. Ion exchange remains one of the most established solid-phase tools for this purpose, while chelating and ligand-functionalized resins have expanded the accessible selectivity window by embedding coordination chemistry directly into the polymer phase. (Botelho Junior, Dreisinger, & Espinosa, 2019; El Ouardi et al., 2023; Moreira et al., 2021; Sener et al., 2021; Sharifian & Wang, 2024; Silva et al., 2018; Srivastava et al., 2026; Taglieri et al., 2026)

The central conceptual problem is that “ion-exchange resin” and “chelating resin” are often used interchangeably, even though their dominant binding mechanisms, operating envelopes, and scale-up risks can differ substantially. Strong-acid cation exchangers and strong-base anion exchangers are governed mainly by charge compensation and electrostatic exchange, whereas chelating resins rely on ligand–metal coordination superimposed on electrostatic, solvation, and transport effects. This distinction matters because a material that appears highly selective in a low-ionic-strength batch test can lose its advantage when metal speciation, competing ions, acidity, or intraparticle transport changes. Conversely, a conventional exchanger with only moderate intrinsic selectivity can be the more economical choice when a bulk impurity-removal duty is operated at high throughput. (Alexandratos & Zhu, 2018; Callura et al., 2019; Cheremisina et al., 2025; Nesbitt, 2020; Page et al., 2019; Silva et al., 2022; Yan et al., 2024)

The literature has expanded rapidly from conventional sulfonic and quaternary-ammonium matrices to iminodiacetate, aminophosphonic, phosphonic, bis-picolylamine, amidoxime, macrocyclic, phosphorylated, ionic-liquid-functionalized, solvent-impregnated, and hybrid porous materials. These developments have improved selectivity for rare-earth elements, scandium, copper, nickel, cobalt, uranium, thorium, zirconium, hafnium, gallium, vanadium, and precious metals. At the same time, the diversity of

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materials has made performance comparison more difficult because reported metrics range from maximum batch capacity and distribution coefficients to dynamic breakthrough capacity, resin-in-leach recovery, multicolumn fractionation, and pilot or industrial throughput. (Ang et al., 2018; Archer et al., 2022; Cui et al., 2020; Dai et al., 2026; Du et al., 2026; Gao et al., 2025; Liang et al., 2024; Liu et al., 2021; Liu et al., 2024; Qin et al., 2026; Yi et al., 2026; Zhou et al., 2025)

A critical review must therefore ask a different question from "which resin has the highest capacity?" The more consequential question is which combination of binding mechanism, feed chemistry, particle-scale transport, dynamic operation, regeneration route, and flowsheet role creates a measurable process-level advantage. Techno-economic and environmental outcomes depend not only on the resin purchase price but also on pretreatment, reagent circulation, product concentration, rinse-water demand, cycle life, waste generation, and the separation stages that are displaced or simplified elsewhere in the plant. Studies of critical-metal recovery, acid and metal reclamation, and circular treatment schemes increasingly support this broader system boundary. (Duclos et al., 2020; Larochelle et al., 2021; Smerigan et al., 2025; Wołowicz et al., 2024; Zhao et al., 2026)

Recent reviews have made important contributions by cataloguing functional groups, examining Cu–Ni–Co recovery, summarizing rare-earth ion exchange, or comparing technologies for dilute REE streams. However, these reviews do not jointly use dynamic working capacity, regeneration, resin lifetime, real-feed validation, and flowsheet role as a common basis for comparing conventional and chelating resins. The present review is focused specifically on this process-level gap. Table 1 positions the contribution relative to representative recent reviews.

Table 1. Positioning of the present review relative to representative resin and metal-recovery reviews

Review	Primary scope	Dynamic/column evidence	Regeneration/ lifetime	Scale/process integration	Gap relative to present review
Silva et al. (2018)	Functional-group families for metal-ion separation	Partial	Partial	Limited	Broad resin-selection reference; not organized around scale-up evidence
Botelho Junior, Dreisinger, & Espinosa (2019)	Chelating resins for Cu/Ni/Co in mining streams	Partial	Partial	Partial	Metal-family focus; limited cross-class comparison
El Ouardi et al. (2023)	REE ion exchange from secondary resources	Partial	Partial	Partial	REE-specific rather than cross-metal/process-function comparison
Sharifian & Wang (2024)	Modified resin approaches for REE recovery	Partial	Yes	Limited	Material modification and REE focus dominate
Dai et al. (2026)	Cross-technology REE recovery from aqueous streams	Partial	Partial	Yes	Cross-technology, but not a conventional-IX versus chelating-resin framework
Taglieri et al. (2026)	Systematic mapping of REE recovery from WEEE	Coded as maturity evidence	Partial	Yes	Feedstock-specific systematic map rather than resin-mechanism comparison
Present review	Conventional IX vs. chelating resins across metal systems	Central criterion	Central criterion	Central criterion	Links speciation → breakthrough → regeneration → lifetime → flowsheet value

Note. The comparison is based on the stated scope and emphasis of the cited reviews. "Partial" indicates that the topic is present but is not used as the principal cross-study evaluation axis.

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This positioning deliberately narrows the novelty claim. The contribution is not the cataloging of another resin family, but a process-selection framework that asks whether chemical selectivity survives realistic competition, flow, regeneration, repeated use, and integration with surrounding unit operations.

This review critically compares conventional ion-exchange and chelating resins across five linked levels of evidence: molecular binding mechanisms; equilibrium and kinetic behavior; multicomponent and real-matrix selectivity; dynamic column or reactor performance; and industrial process integration. Particular emphasis is placed on acidic hydrometallurgical liquors and secondary-resource feeds, where ionic strength and speciation are especially consequential. Regeneration and resin lifetime are treated as primary performance variables rather than postscript considerations. The objective is not to rank all resins on a single universal scale, but to identify where each class is mechanistically and operationally advantaged and to define the minimum evidence required for a laboratory result to be reasonably interpreted as scale-up relevant.

2. REVIEW SCOPE, SEARCH STRATEGY, AND EVIDENCE ASSESSMENT

2.1 Review design and search window

This study was designed as a structured critical review rather than a systematic review or meta-analysis. Literature discovery centered on Google Scholar and was complemented by publisher and DOI pages for verification of peer-review status, bibliographic metadata, and process details where required. The principal search window was 2018–31 August 2026, selected to capture recent advances in functionalized resins, continuous and multicolumn operation, regeneration, real-matrix validation, and emerging process concepts. This broad discovery strategy supports cross-disciplinary coverage but does not provide the exhaustive database reproducibility that a formal systematic review offers. To mitigate that limitation, searches were topic-structured, citation chaining was applied, and bibliographic details were checked against publisher or DOI records. Older foundational studies were included selectively when needed to interpret established mechanisms or resin behavior.

2.2 Search logic, inclusion, and exclusion

Topic-structured Boolean searches were iteratively combined around a core comparison query: ("ion exchange resin" OR "ion-exchange resin" OR "conventional ion exchange") AND ("chelating resin" OR "chelating ion-exchange resin") AND (metal OR metals) AND (selectivity OR mechanism OR speciation OR regeneration OR "process integration") AND (hydrometallurgy OR "metal recovery" OR separation). Additional search blocks targeted fixed-bed breakthrough and mass transfer; real versus synthetic matrices; multicomponent leachates; regeneration and adsorption–desorption cycles; resin lifetime and degradation; scale-up and industrial operation; and CAPEX/OPEX or techno-economic assessment. Citation chaining and close keyword variants were used to capture studies that employed different resin nomenclature.

The iterative search generated 313 candidate records. After duplicate removal and relevance screening, 110 peer-reviewed publications were retained. Inclusion required direct evidence relevant to ion-exchange or chelating-resin mechanisms, selectivity, metal separation, dynamic operation, regeneration, real feeds, scale-up, or process integration. Review papers were retained when they materially positioned the field. Adjacent non-resin operations such as precipitation, solvent extraction, membranes, or deep-eutectic/ionic-liquid systems were included only when they affected solution speciation, regenerant management, or flowsheet integration. Preprints, duplicate records, tangential adsorption studies, and records without usable comparative evidence were excluded. Because reason-specific exclusion counts were not prospectively logged, a retrospective PRISMA-style flow diagram was not reconstructed.

2.3 Evidence hierarchy and synthesis rules

Each retained study was interpreted according to the strongest evidence it provided: (i) equilibrium or batch selectivity; (ii) particle-scale kinetics or transport; (iii) fixed-bed, resin-in-leach, or reactor performance; (iv) regeneration and elution; (v) representative or real-matrix validation; (vi) pilot, multicolumn, prototype, or industrial operation; and (vii) techno-economic or environmental evidence. Evidence levels were used to limit the strength of process-readiness claims rather than to assign a formal TRL. No pooled meta-analysis was attempted because feed composition, resin architecture, units, breakthrough criteria, and product specifications were too heterogeneous for defensible statistical aggregation. When a process variable was not reported, it was treated as not reported rather than inferred.

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2.4 Quantitative process benchmark

To complement the qualitative framework, Table 2 extracts process-level results from representative studies spanning conventional exchange, chelating resins, resin-in-leach, pilot wastewater treatment, continuous multicolumn operation, and industrial regeneration. Studies were selected for this benchmark to span resin classes, feed complexity, operating modes, and evidence maturity while requiring explicitly reported process-level numerical metrics. The table is therefore selective rather than exhaustive: its purpose is to show which design-relevant metrics become visible when evidence is compared on a process basis rather than by qmax alone.

Table 2. Representative quantitative evidence for dynamic performance, regeneration, and process maturity

Reference	Resin/system	Feed & mode	Quantitative process evidence	Regeneration/cycling	Evidence / main limitation
Callura et al. (2021)	BPG-functionalized polymer	Competitive saline feed; fixed bed	Up to 137× higher REE selectivity; 10% and 50% breakthrough delayed 270× and 128× vs aminated resin; eluate up to 236× feed concentration	Dilute HNO_3 recovery; long-term cycling NR	Strong dynamic proof; durability not established
José & Ladeira (2021)	Lewatit MDS 200H strong-acid resin	AMD-like sulfate feed; columns	REE loading 85% (0.94 mmol g−1); overall recovery 83%; final liquor 39.0 mmol L−1 REE from 3.13 mmol L−1 feed	0.02 M NH_4EDTA gave best fractionation; cycling NR	Representative multicomponent column evidence
Wang et al. (2019)	2-aminomethyl pyridine chelating resin	Simulated Co electrolyte; fixed bed	Cu breakthrough capacity 16.51 mg g−1; saturation 61.72 mg g−1; Cu/Co mass ratio in saturated resin 37.67	Regeneration not central in reported benchmark	Good transport evidence; simulated feed
Kurkinen et al. (2021)	Purolite S940	Industrial phosphogypsum; resin-in-leach	REE loading up to 0.92 equiv kg−1; purity over Ca 70% after repeated RIL; eluate REE purity up to 99.01%	Loading increased through 7 RIL cycles; GLDA/MGDA elution	Strong real-feed cycling; full resin lifetime not established
Czupryński et al. (2022)	Purolite S930 + S920	FGD wastewater; pilot columns	Ni reduced from 89.3 ± 35 to <0.1 µg L−1; Cr/Hg also reduced to <0.1 µg L−1	Elution separated Ni/Fe-rich and Cr/Hg-rich streams; lifetime NR	Pilot real-stream validation
Ulloa et al. (2020)	Bispicolylamine chelating resin	Spent sulfuric-acid metal stream; split regeneration	43% Ni eluted at 98% purity; 47% Cu eluted at 97% purity	10 adsorption–regeneration cycles; Ni adsorption decreased ~10%, Cu removal remained stable	Rare explicit multicycle evidence
Li et al. (2024)	Two cation exchangers + chelating resin	Electroplating wastewater; industrial scale	Effluent Ni <0.1 mg L−1; regenerant >60 g L−1 Ni	2 BV of 6% HCl; >99% acid utilization; cost ¥5.5–9.5 m−3	Industrial evidence with cost data

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Reference	Resin/system	Feed & mode	Quantitative process evidence	Regeneration/cycling	Evidence / main limitation
Wesselborg et al. (2024)	Aminomethyl phosphonic resin	LIB leachate; multicolumn design	99.9% purity Li+Ni+Co product; recoveries 98.9%, 96.6%, 93.7% for Li, Ni, Co	Continuous-cycle design; long-term resin aging NR	Strong process-intensification evidence
Wesselborg et al. (2025)	Aminomethyl phosphonic resin	Spent-LIB leachate; continuous multicolumn	100% purity Li+Ni+Co product; recoveries up to 100%, 99.15%, 96.97% for Li, Ni, Co	Effective continuous desorption; no sorbed-metal accumulation reported	Continuous demonstration; lifetime still shorter than industrial duty
Roa et al. (2024b)	TP272 impregnated + S930 chelating	Real acidic mine water; integrated flowsheet	Fe removal >99.9%, Al removal ~90%, transition metals >99%; REE oxalates >90% purity	H_2SO_4 regeneration integrated with downstream recovery	Strong hybrid flowsheet; reagent burden remains important

Note. NR = not reported in the information extracted for this benchmark. Values are reproduced only where explicitly reported by the cited studies; unlike feed chemistry and units are not normalized across studies. The table is therefore a process-evidence benchmark, not a meta-analysis.

The benchmark makes two points clear. First, dynamic and integrated metrics can invert a ranking based solely on batch capacity: delayed breakthrough, concentrated eluates, product purity, and sustained recovery directly affect column inventory and downstream processing. Second, explicit evidence of resin life remains sparse, even among process-oriented studies. Short multicycle demonstrations are valuable, but they should not be equated with the hundreds or thousands of cycles that may define industrial replacement intervals.

3. FUNDAMENTAL PRINCIPLES AND MECHANISTIC DISTINCTION

3.1 Conventional ion exchange

Conventional ion exchange is based on reversible replacement of counter-ions associated with fixed charges in a polymeric or inorganic matrix. Strong-acid cation exchangers commonly employ sulfonate groups, while strong-base anion exchangers employ quaternary ammonium sites. Selectivity emerges from electrostatic interactions, ion activity, hydration, valence, resin cross-linking, and the composition of the external solution. Because the chemical interaction is not designed around a unique coordination geometry, these resins can be fast and robust but are often vulnerable to competition when multiple ions of comparable charge and activity are present. Their practical strength is therefore more often process simplicity than exceptional molecular discrimination. (José et al., 2021; Page et al., 2019; Roa et al., 2024b; Silva et al., 2022; Souza et al., 2025; Ultarakova et al., 2026)

3.2 Chelating resins

Chelating resins contain immobilized donor groups that form coordinate bonds with dissolved metal species. Iminodiacetate, aminophosphonic and phosphonic groups, amines and picolylamines, amidoxime, sulfur-containing ligands, macrocycles, and other multidentate motifs can discriminate among metals according to Lewis acidity, ligand donor character, coordination geometry, protonation state, and complex stability. The advantage is not absolute: stronger binding can slow desorption, and high selectivity can disappear when the target metal exists predominantly as a complex that is not recognized by the immobilized ligand. Thus, chelation converts chemical specificity into both an opportunity and an additional control variable. (Abbasi et al., 2018; Bao et al., 2018; Fila et al., 2019; Gao et al., 2025; Kołodyńska et al., 2020; Liu et al., 2021; Qin et al., 2026; Wang et al., 2019; Watanabe et al., 2024; Watanabe et al., 2026; Wołowicz et al., 2020; Wołowicz et al., 2024)

3.3 A mechanistic continuum rather than a binary taxonomy

The distinction between the two classes is analytically useful but should not be interpreted as a perfect binary classification. A sulfonated resin can exhibit specific affinity through local hydration and ion pairing, while a chelating resin also contains charged

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sites and experiences electrostatic partitioning. Solvent-impregnated resins, supported ionic-liquid phases, and ligand-grafted porous polymers further blur the boundary by combining extraction, ion exchange, and coordination within a confined solid phase. This continuum explains why the same nominal functional group can perform differently when ligand density, cross-linking, pore size, hydrophobicity, or the surrounding solvent environment changes. (Avdibegović et al., 2018; Avdibegović & Binnemans, 2020; Avdibegović & Binnemans, 2021; Cui et al., 2020; Dewulf et al., 2025; Du et al., 2026; Lanaridi et al., 2021; Mikeli et al., 2024)

Table 3 summarizes the mechanistic differences that should be established before comparing resin performance. The table deliberately separates the dominant interaction from the practical consequence, because similar capacities can arise from very different combinations of affinity and site density.

Table 3. Mechanistic comparison of conventional ion-exchange and chelating resins

Aspect	Conventional ion exchange	Chelating resin	Process implication
Dominant interaction	Electrostatic counter-ion exchange	Coordinate ligand–metal binding	Selectivity responds to different chemical variables
Typical sites	Sulfonate; quaternary ammonium	Iminodiacetate; phosphonic/aminophosphonic; amine/picolylamine; amidoxime; soft donors	Functional group must match target speciation
Main selectivity drivers	Charge, activity, hydration, ionic strength	Ligand affinity, protonation, HSAB character, geometry, speciation	Chelating systems can be more discriminating but less forgiving
Kinetics	Often rapid	Often moderate and chemistry dependent	Dynamic capacity may diverge from equilibrium capacity
Sensitivity to pH	Moderate to high	Often very high	Small pH shifts can reorder selectivity
Competition	Strong when major ions share charge class	Can be reduced when ligand recognition is specific	High background electrolyte remains relevant
Regeneration	Often comparatively simple	May require stronger acid, base, or complexant	Elution chemistry can dominate OPEX and waste
Best process role	Bulk exchange, impurity removal, polishing	Selective capture, fractionation, high-value recovery	Complementary rather than universally substitutive roles

Note. Conceptual synthesis based on the mechanistic distinctions discussed in Silva et al. (2018), Alexandratos and Zhu (2018), Callura et al. (2019), and Watanabe et al. (2024).

Figure 1 illustrates this distinction as a mechanistic continuum from electrostatic exchange to ligand-controlled coordination. The figure is intended as a process-design map rather than a molecular-scale depiction of a specific commercial resin.

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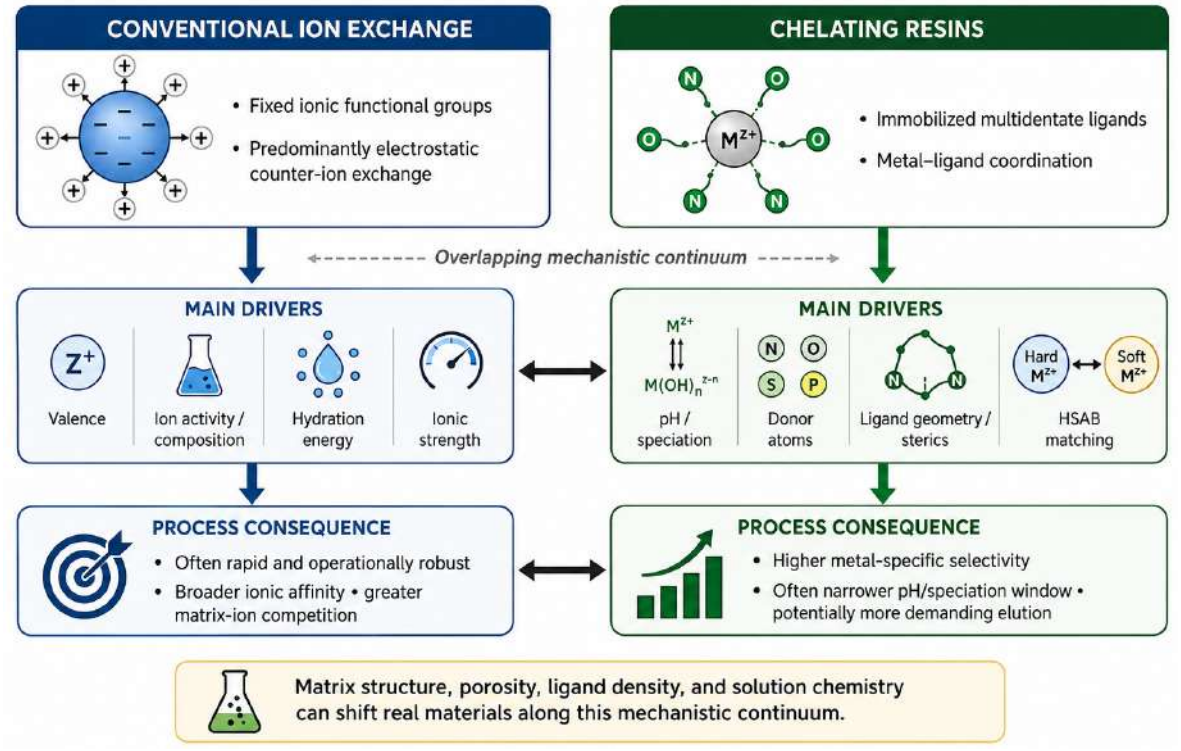

Figure 1. Mechanistic basis of resin selectivity

Note. Author-generated conceptual synthesis based on Silva et al. (2018), Alexandratos and Zhu (2018), Callura et al. (2019), and Watanabe et al. (2024).

The practical consequence of Figure 1 is that resin selection should begin with the dominant aqueous species and the intended separation duty, not with a catalog label. If a target exists as an anionic chloro complex, an anion exchanger may outperform a cation-chelating resin, even when the latter has a higher affinity for the free metal ion. If the target and contaminants are all cationic but differ in ligand affinity, chelation may create a separation that conventional exchange cannot. This mechanism-first approach is particularly important for Zr/Hf, REE, and transition-metal separations in chloride and sulfate media. (Felipe & Ladeira, 2018; Ismail et al., 2025; Ma et al., 2019; Poernomo et al., 2026; Watanabe et al., 2022)

4. EQUILIBRIUM, KINETIC INTERPRETATION, AND MASS-TRANSFER CONSTRAINTS

Equilibrium data are indispensable for identifying whether a resin has sufficient affinity and capacity, but they are frequently overinterpreted. Langmuir and Freundlich fits describe empirical relationships between dissolved concentration and equilibrium loading; they do not independently establish the binding mechanism, nor do high coefficients of determination prove monolayer adsorption, energetic homogeneity, or industrial suitability. Thermodynamic parameter estimation can help distinguish favorable uptake and temperature effects, but such parameters are sensitive to standard-state assumptions, activity corrections, and the chemical form of the sorbing species. Spectroscopic evidence and mechanistic modeling are therefore most informative when combined with solution speciation rather than used as stand-alone proof of chelation. (Alexandratos & Zhu, 2018; Callura et al., 2019; Cheremisina et al., 2025; Vinco et al., 2022; Watanabe et al., 2026)

Kinetic interpretation is similarly vulnerable to oversimplification. Pseudo-first-order and pseudo-second-order models can reproduce many uptake curves even when the rate-controlling process is external film transfer, pore diffusion, chemical reaction, or a combination. Resin particle size, cross-linking, swelling, solution viscosity, and the presence of complexing ligands can all modify the apparent rate. Mechanistic studies on nickel, scandium, vanadium, and multicomponent systems show why intraparticle mass transfer should be treated explicitly when residence time is relevant to design. A resin that reaches a high equilibrium loading after several hours may have poor usable capacity in a column operated with minutes of contact time. (Abbasi et al., 2018; Laatikainen & Sainio, 2019; Nesbitt, 2020; Vinco et al., 2022; Watanabe et al., 2024)

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The distinction between equilibrium capacity and dynamic capacity is particularly important for highly selective ligands. Strong binding can increase equilibrium uptake while simultaneously sharpening concentration gradients inside the particle, slowing desorption, or creating a moving adsorption front that is not fully utilized before breakthrough. Conversely, a lower-affinity exchanger with faster diffusion can deliver higher throughput and a more easily regenerated bed. These tradeoffs explain why material ranking can invert when the basis changes from milligrams per gram at equilibrium to recovered metal per unit bed volume and time over repeated cycles.

Table 4 organizes the major resin functionalities by dominant chemical behavior and practical vulnerability. The categories are intentionally broad because commercial formulations differ in matrix chemistry, cross-link density, porosity, and ligand loading even when they carry the same functional-group name.

Table 4. Functional-group families and their process-relevant behavior

Resin/ligand family	Dominant chemical behavior	Typical strengths	Frequent vulnerabilities	Representative evidence
Strong-acid sulfonic cation exchanger	Charge-based cation exchange	Fast exchange; robust; useful for preconcentration and bulk removal	Limited discrimination among competing cations; strong dependence on sulfate and major-ion composition	José et al. (2021); Page et al. (2019); Silva et al. (2022)
Strong-base anion exchanger	Exchange of anionic metal complexes	Effective for chloro-/sulfato-complex separations and Zr/Hf chemistry	Speciation must favor anionic complexes; competing anions reduce capacity	Ma et al. (2019); Ismail et al. (2025); Poernomo et al. (2026)
Iminodiacetate	Multidentate N/O coordination	Cu/Ni/Co selectivity; established chelating platform	Protonation at low pH; Fe competition; kinetic limitations	Abbasi et al. (2018); Botelho Junior et al. (2019); Vinco et al. (2026)
Phosphonic / aminophosphonic	Hard-donor coordination	Strong affinity for REE, Sc, actinides and hard metal ions	Difficult elution; pH-sensitive loading; possible slow kinetics	Archer et al. (2022); Qin et al. (2026); Zhou et al. (2025)
Picolylamine / amine-rich	N-donor coordination and protonation control	Selective transition-metal removal in acidic media	Protonation, organic fouling, and matrix effects	Liu et al. (2021); Ibebunjo et al. (2024); Wei et al. (2026)
Amidoxime / specialized ligands	Strong specific complexation	Useful for V/Ga/U and tailored separations	Deactivation and regeneration complexity	Cui et al. (2026); Xu et al. (2025)
Solvent-impregnated / ionic-liquid-functionalized	Extraction-like complexation immobilized in a porous support	High selectivity and tunable chemistry	Extractant loss, solvent effects, regeneration, long-term stability	Bao et al. (2018); Du et al. (2026); Mikeli et al. (2024)

Note. Representative rather than exhaustive classification. Functional-group behavior must be interpreted together with solution speciation, resin architecture, and dynamic operating conditions.

Table 4 also highlights why "chelating resin" is too broad a category for direct performance ranking. For example, iminodiacetate resins can favor transition metals but lose effective capacity in strongly acidic media because ligand protonation competes with metal binding; phosphonic systems can retain hard trivalent or tetravalent species more strongly but may demand more aggressive stripping; and solvent-impregnated materials can inherit the selectivity of liquid extractants while adding concerns about extractant retention and pore accessibility. (Bao et al., 2018; Mikeli et al., 2024; Mostajeran et al., 2024; Wang et al., 2022; Xu et al., 2025; Zhou et al., 2025)

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5. SELECTIVITY, METAL SPECIATION, AND CHEMICAL MEDIUM

5.1 pH, protonation, and aqueous speciation

Selectivity is a property of the complete chemical system, not of the resin alone. The same metal can exist as a hydrated cation, hydrolyzed species, sulfate complex, chloride complex, or complex with an intentionally added ligand. These species differ in charge, size, hydration, and ligand-exchange kinetics. At the same time, chelating groups change protonation state with pH, modifying both electrostatic partitioning and donor availability. This coupled speciation problem explains why selectivity sequences measured in one acid medium frequently fail to transfer to another without re-optimization. (Cheremisina et al., 2025; Hu et al., 2024; Page et al., 2019; Silva et al., 2022; Watanabe et al., 2022; Yan et al., 2024; Zhao et al., 2026)

Sulfate media illustrate the issue particularly well. Sulfate can reduce the fraction of free trivalent cations, form anionic or neutral complexes, and compete for anion-exchange sites. For rare-earth systems, sulfate concentration changes exchange behavior and can alter fractionation performance. In transition-metal leachates, sulfate also raises ionic strength and can modify activity coefficients and resin swelling. Chloride systems create a different landscape because some metals form strongly anionic chloro-complexes at high chloride concentration, enabling separations on strong-base anion exchangers that would not be predicted from the free-ion chemistry. (Ang et al., 2018; Dewulf et al., 2025; Felipe & Ladeira, 2018; Ma et al., 2019; Page et al., 2019; Silva et al., 2022)

5.2 HSAB, ligand architecture, and competitive binding

Hard–soft acid–base reasoning provides a useful first-pass framework for chelating-resin design: hard oxygen-donor ligands often favor hard trivalent or tetravalent ions, whereas nitrogen- and sulfur-rich ligands can enhance affinity for softer transition or precious-metal species. However, HSAB is not a complete predictive model. Steric accessibility, coordination number, ligand spacing, hydration energy, proton competition, and pre-existing aqueous complexes can dominate the observed order. Macrocyclic and spatially organized ligands demonstrate that geometry can be engineered to add selectivity beyond simple donor-atom identity. (Gao et al., 2025; Qin et al., 2026; Yi et al., 2026; Zhou et al., 2025)

Figure 2 shows the causal chain that should be followed when interpreting selectivity data. The number of controlling variables increases as a system moves from a synthetic single-solute batch test toward a dynamic industrial feed.

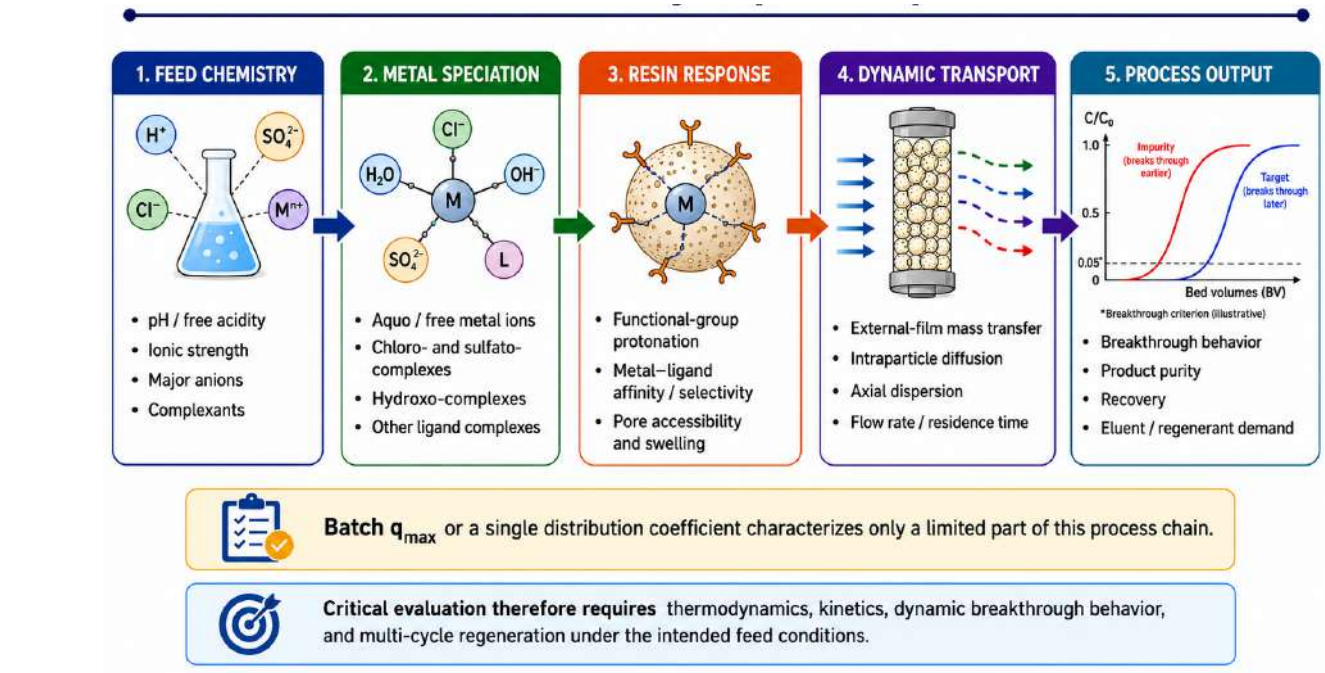

Figure 2. From feed chemistry to process performance

Note. Author-generated conceptual synthesis based on Page et al. (2019), Nesbitt (2020), Laatikainen and Sainio (2019), and Yan et al. (2024).

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Figure 2 makes clear why capacity and selectivity should not be reported without a description of feed chemistry. A meaningful comparison should state total and free metal concentrations where possible, acid concentration, major anions, competing cations, redox state, temperature, and any added complexant. For high-ionic-strength feeds, activities rather than concentrations would be preferable for rigorous thermodynamic treatment, although this is rarely done. Dynamic tests should additionally report superficial velocity, bed height, particle size, residence time, pressure drop, and a consistent breakthrough criterion.

Table 5 translates common performance metrics into the engineering questions they can and cannot answer. The purpose is to prevent the frequent inference that a favorable equilibrium metric automatically implies a viable separation process.

Table 5. Interpretive value and limitations of common resin-performance metrics

Metric	What it can establish	What it does not establish	Recommended companion evidence
Maximum/equilibrium capacity	Potential site utilization under stated conditions	Usable column capacity, selectivity in real feeds, cycle life	Competitive isotherms + breakthrough
Distribution coefficient (Kd)	Affinity at a specified composition	Scale-independent selectivity or throughput	Speciation + separation factor + matrix composition
Separation/selectivity factor	Relative preference between species	Absolute capacity, kinetics, product purity at breakthrough	Dynamic co-loading profiles
Pseudo-order kinetic constant	Empirical rate description	Unique rate-controlling mechanism	Film/intraparticle transport analysis
Breakthrough capacity	Usable capacity at a chosen endpoint	Long-term stability or regenerability	Multiple cycles + mass balance
Bed volumes to breakthrough	Hydraulic productivity for a defined test	Transferability across bed geometry without dimensionless analysis	Residence time, bed height, particle size, Peclet/MTZ information
Elution recovery	Fraction of loaded metal recovered	Eluent consumption, concentration factor, ligand damage	Eluent-to-metal ratio + eluate purity + reuse
Capacity retention over cycles	Short-term resin durability	Multi-month fouling and mechanical attrition	Extended cycling + physical/chemical diagnostics
Real-matrix validation	Robustness to actual impurity spectrum	Full industrial continuity	Pilot control, solids management, TEA/LCA

Note. Critical interpretation framework developed from the recurring limitations identified across batch, column, regeneration, and scale-up studies.

6. PERFORMANCE IN COMPLEX AND REAL MATRICES

6.1 Acidic leachates and high ionic strength

Hydrometallurgical leachates are among the most demanding environments for resin separations because target metals are often minor components relative to acid, alkali and alkaline-earth ions, iron, aluminum, and major anions. Strong acidity suppresses deprotonation of many chelating ligands, while high ionic strength compresses electrostatic selectivity and changes activity. In this regime, laboratory results obtained from dilute synthetic solutions can materially overstate the working capacity and selectivity available in real liquors. Acid-resistant ligand design and deliberate control of protonation have therefore become major directions in resin development. (Canner et al., 2018; Hu et al., 2024; Liu et al., 2021; Ultarakova et al., 2026; Wei et al., 2026)

Iron and aluminum deserve special attention because they combine high concentration with strong affinity for many oxygen-donor ligands. They can consume capacity, block access to sites, precipitate during pH adjustment, and contaminate eluates. In some flowsheets, it is more rational to remove Fe and Al upstream by precipitation or conventional ion exchange than to ask a

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highly selective and expensive chelating resin to tolerate them indefinitely. Multistage removal studies and battery-recycling work reinforce the value of assigning specific impurities to specific unit operations rather than seeking a single universal resin. (Silva et al., 2021; Virolainen et al., 2021; Vinco et al., 2026; Yan et al., 2024)

6.2 Organic ligands, redox chemistry, and non-ideal feeds

Complexing agents can either enable or frustrate selectivity. Ammoniacal, glycine–cyanide, citrate, and deep-eutectic-solvent environments redistribute metals among complexes with different charges and ligand-exchange kinetics. In some cases, speciation can be deliberately used to favor one metal over another; in others, strong aqueous complexation prevents the metal from interacting with the resin. This creates a design space in which solution chemistry and resin chemistry must be co-optimized rather than treated sequentially. (Aberdeen et al., 2025; Aberdeen et al., 2026; Deng et al., 2020; Hedjazi et al., 2018; Laatikainen & Sainio, 2019; Wang et al., 2026)

The same principle applies to secondary resources. E-waste, spent batteries, phosphogypsum, acid mine drainage, bauxite residue, spent catalysts, and tailings waters contain mixtures that vary by source, pretreatment, and leaching chemistry. Results from a "synthetic leachate" become transferable only when the synthetic matrix reproduces the concentrations and speciation of the dominant competitors. Studies using real or near-real liquors provide more credible evidence because they expose the resin to trace contaminants, suspended solids, organic residues, and composition drift that are usually absent from model solutions. (Abeywickrama et al., 2023; Ajiboye et al., 2023; Hermassi et al., 2021; Hermassi et al., 2022; Ibebunjo et al., 2024; Kirillov et al., 2026; Padh et al., 2019; Perez et al., 2020; Romal & DeBraske, 2025; Vecino et al., 2021; Virolainen et al., 2019)

Fouling can be chemical, physical, or hydraulic. Irreversibly bound metals and hydrolysis products cause chemical deactivation; suspended solids and precipitates block pores and bed voids; organics change surface wetting or occupy hydrophobic domains. A resin can therefore retain nominal ligand density while losing effective diffusivity or accessible capacity. Deactivation diagnosis and long-term stability studies are especially valuable because they move beyond the common assumption that capacity loss is explained only by ligand destruction. (Lazar et al., 2025; Xu et al., 2025)

7. APPLICATION LANDSCAPE ACROSS CRITICAL AND STRATEGIC METALS

7.1 Rare-earth elements and scandium

Rare-earth separations are a natural test case for the distinction between ion exchange and chelation because adjacent lanthanides have similar charge and ionic radii. Strong-acid resins remain useful for preconcentration and fractionation when combined with controlled eluents, while ligand-functionalized polymers and phosphonic materials seek greater intrinsic differentiation. Column studies, phosphogypsum resin-in-leach processes, acidic mine-water treatment, and supported ionic-liquid phases show that practical separation often depends as much on elution and process staging as on loading selectivity. (Callura et al., 2021; Cui et al., 2020; El Ouardi et al., 2023; Hermassi et al., 2021; Hermassi et al., 2022; Huan et al., 2026; José et al., 2021; José et al., 2024; Kurkinen et al., 2021; Kurkinen et al., 2026; Liang et al., 2024; Liu et al., 2024; Souza et al., 2025; Virolainen et al., 2019; Zhou et al., 2025)

Scandium illustrates the advantage and the penalty of strong complexation. Chelating and solvent-impregnated resins can load scandium selectively from sulfate or chloride media, but efficient stripping may require carefully selected acids or complexants. The strongest sorbent is not necessarily the best process material if elution is incomplete or produces an excessively dilute product. Recent thermodynamic and kinetic work on scandium underscores the need to connect binding strength with desorption energy, residence time, and fractionation strategy. (Bao et al., 2018; Mikeli et al., 2024; Mostajeran et al., 2024; Qin et al., 2026; Smyshlyaev et al., 2022; Watanabe et al., 2022; Watanabe et al., 2024; Watanabe et al., 2026)

7.2 Copper, nickel, cobalt, vanadium, gallium, and battery metals

For Cu–Ni–Co systems, iminodiacetate and amine-rich resins have been studied for impurity removal, selective recovery, and treatment of mining residues, electroplating streams, and battery-recycling liquors. The strongest process evidence comes from studies that move beyond batch equilibrium to continuous columns, multistage impurity removal, or real leachates. Copper often binds strongly to nitrogen-donor ligands, which can be advantageous for removing Cu from Ni/Co circuits but can also make regeneration demanding. Split regeneration and staged elution provide a way to recover metals selectively after co-loading. (Abbasi et al., 2018; Botelho Junior et al., 2018; Botelho Junior, Dreisinger, & Espinosa, 2019; Botelho Junior, Jiménez Correa, et al., 2019;

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Ibebunjo et al., 2024; Padh et al., 2019; Perez et al., 2020; Silva et al., 2021; Strauss et al., 2021; Ulloa, Martínez-Minchero, et al., 2020; Ulloa, Bringas, & San-Román, 2020; Wang et al., 2019; Wei et al., 2026; Wołowicz et al., 2020)

Vanadium and gallium further demonstrate how oxidation state and ligand functionality control performance. Phosphorylated, amidoxime, and multifunctional chelating materials can differentiate metal species in acidic or alkaline media, but the relevant mechanism can involve not only adsorption but also decomplexation, protonation shifts, or cascade desorption. These examples are important because they show that a resin process can be designed around a sequence of chemical states rather than a single equilibrium step. (Cui et al., 2026; Liu et al., 2024; Vinco et al., 2022; Vinco et al., 2026; Wang et al., 2022; Wang et al., 2026)

7.3 Zr/Hf, radionuclides, precious metals, and specialized separations

Zirconium–hafnium separation is a stringent selectivity problem because the two tetravalent metals have closely similar chemical behavior. Both anion-exchange and chelating approaches have been explored, particularly in sulfate or chloride media, where speciation can yield separable anionic complexes or differential affinities. Recent work ranges from batch and column studies to prototype continuous adsorption columns and explicit stripping studies, illustrating the need to evaluate loading and regeneration as a coupled separation cycle rather than as independent experiments. (Felipe & Ladeira, 2018; Ismail et al., 2025; Jakóbik-Kolon & Bok-Badura, 2022; Ma et al., 2019; Poernomo et al., 2026)

Radionuclide and actinide separations similarly benefit from strong ligand interactions but impose stringent requirements for chemical stability and product purity. Chelating resins have been examined in acidic decontamination streams and in U/Th/REE systems, while spatially engineered ligands and phosphonic composite resins seek stronger discrimination among hard multivalent ions. These systems also demonstrate that radiation resistance, secondary-waste generation, and containment can become as important as equilibrium selectivity. (Ang et al., 2018; Canner et al., 2018; Qin et al., 2026; Yi et al., 2026)

Precious-metal recovery occupies a different chemical regime. Gold can be recovered as anionic chloride complexes on anion exchangers, while platinum-group metals are often targeted with supported ionic liquids or ligand-functionalized phases. Because these metals are valuable at low concentration, high distribution coefficients can be economically relevant even when total loading is modest; however, selectivity against base metals and the concentration factor achieved during elution determine whether the process creates a saleable or refinable product. (Lanaridi et al., 2021; Niu et al., 2024; Wołowicz et al., 2024)

Table 6 condenses the application evidence into the process function most commonly assigned to each resin class. It also highlights where evidence has progressed from equilibrium studies to dynamic or pilot demonstrations.

Table 6. Application and evidence map for resin-based metal separations

Application domain	Dominant challenge	Resin/process strategy	Evidence maturity represented in the literature
REE from mine waters / phosphogypsum	Low concentration; closely related ions; sulfate competition	Strong-acid IX, chelating resin, resin-in-leach, staged elution	Batch, fixed-bed, resin-in-leach, pilot and fractionation studies
Sc recovery	Strong selectivity needed against Fe/Al/REE; difficult stripping	Chelating and solvent-impregnated resins with controlled elution	Batch, fixed-bed, laboratory/pilot campaigns
Cu/Ni/Co hydrometallurgy	High Fe and acid; transition-metal competition	Iminodiacetate, amine/picolylamine, split regeneration	Batch, continuous columns, industrial wastewater application
Battery-recycling liquors	Mixed Li/Ni/Co/Mn/Cu/Fe/Al; continuity	Selective impurity removal and multicolumn IX	Single column to continuous multicolumn processes
Zr/Hf and radionuclides	Extremely similar chemistry; high-purity products	Anion exchange, chelation, controlled stripping	Batch/column, prototype continuous adsorption, specialized stripping

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Application domain	Dominant challenge	Resin/process strategy	Evidence maturity represented in the literature
Au/PGM streams	Very low target concentration; complex anionic species	Anion exchange and supported ionic-liquid phases	Batch/column and targeted recovery studies
Industrial wastewater / FGD / electroplating	Variable composition; regulatory discharge + metal value	Robust IX, chelating polishing, regeneration loops	Pilot and industrial-scale demonstrations

Note. Representative synthesis of the application studies reviewed; "maturity" refers to the experimental scale reported, not a formal technology-readiness-level assignment.

The pattern in Table 6 is more informative than a simple list of adsorption capacities. Conventional exchangers remain prominent where the process objective is bulk preconcentration, guard-bed service, or impurity removal, while chelating and impregnated materials are concentrated in duties where the value of incremental selectivity justifies greater chemical and operational complexity. The emergence of continuous multicolumn operation further reduces the usefulness of comparing materials only under batch conditions. (Czupryński et al., 2022; Li et al., 2024; Nouri-Khangah et al., 2023; Pranudta et al., 2021; Wesselborg et al., 2024; Wesselborg et al., 2025)

8. Dynamic Operation, Scale-Up, and Process Integration

8.1 From batch screening to fixed-bed design

A batch test establishes whether interaction is possible under a selected composition; a column test establishes whether that interaction can be exploited under flow. Fixed-bed behavior introduces axial dispersion, external-film mass transfer, intraparticle diffusion, bed utilization, pressure drop, and a moving mass-transfer zone. The resulting breakthrough curve therefore links feed chemistry to usable working capacity. Because selectivity can deteriorate as the bed approaches saturation, product purity should be evaluated across the loading front rather than inferred from an equilibrium separation factor. (Ajiboye et al., 2023; Callura et al., 2021; Emam et al., 2024; Wang et al., 2019; Xiao et al., 2026)

Figure 3 provides a conceptual illustration of why dynamic tests can reverse the ranking suggested by batch data. The curves are schematic and are not fitted to any specific experimental dataset.

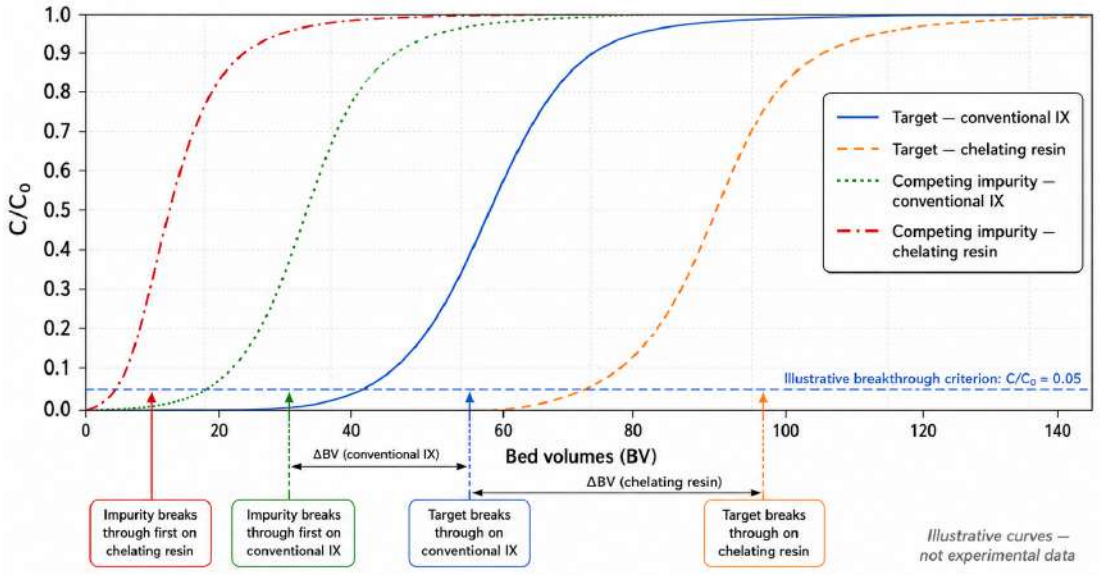

Figure 3. Conceptual breakthrough behavior in a competitive feed

Note. Author-generated schematic based on the dynamic-evaluation principles used in Callura et al. (2021), Ajiboye et al. (2023), Wang et al. (2019), and Xiao et al. (2026). Curves are conceptual and are not experimental data.

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In Figure 3, every solute ultimately tends toward $C/C_0 = 1$ as the bed approaches saturation; the useful separation is created by differences in breakthrough position and mass-transfer-zone development, not by an artificial sub-unity terminal plateau. The engineering benefit of the more selective resin is therefore expressed as delayed target breakthrough and earlier passage or lower co-loading of competitors. This framing is closer to plant economics because it determines treated solution volume, regeneration frequency, eluate purity, and resin inventory. A credible scale-up dataset should report the breakthrough criterion, mass balance, operating velocity, bed dimensions, particle-size range, feed variability, and the state of the resin after regeneration.

8.2 Resin-in-leach, multicolumn, and pilot operation

Not all resin processes use a conventional packed bed. Resin-in-leach can integrate dissolution and sorption to maintain a low dissolved-metal concentration and improve overall recovery, but it introduces particle separation, resin attrition, and contactor-design questions. Mini-pilot Pachuca work and phosphogypsum resin-in-leach studies show how hydrodynamics and solid–resin handling become part of the separation problem. Pilot-scale wastewater studies add another dimension by exposing the bed to sustained feed variability and realistic impurity loading. (Kirillov et al., 2026; Kurkinen et al., 2021; Kurkinen et al., 2026; Nouri-Khangah et al., 2023; Virolainen et al., 2019)

Continuous multicolumn systems represent a further step toward process intensification. Battery-recycling studies have moved from single-column experiments toward simulated-moving-bed-like configurations and continuous recovery of Li + Ni + Co mixtures. Such architectures can increase resin productivity and enable fractionation, but they require reliable cycle timing, valve logic, regenerant management, and a process model that links equilibrium with mass transfer. They also make resin stability more important because a small loss of capacity per cycle accumulates rapidly under continuous operation. (Wesselborg et al., 2024; Wesselborg et al., 2025)

Published dynamic results illustrate the difference between material screening and process performance. Callura et al. (2021) reported REE selectivity gains of up to 137-fold and eluate concentration factors of up to 236-fold in functionalized-resin columns. In battery recycling, Wesselborg et al. (2024) reported a Li + Ni + Co product purity of 99.9% with recoveries of 98.9%, 96.6%, and 93.7%, respectively; the subsequent continuous multicolumn demonstration reported recoveries of up to 100%, 99.15%, and 96.97% while producing a combined Li + Ni + Co fraction reported at 100% purity (Wesselborg et al., 2025). These outcomes are not directly comparable because the feeds and process objectives differ, but they demonstrate why purity, recovery, throughput, and regeneration must accompany equilibrium capacity in scale-up claims.

Table 7 places representative studies on an evidence ladder from batch to industrial implementation. The table is not a formal TRL assessment; it is a way to distinguish chemical proof-of-concept from process evidence.

Table 7. Representative progression from laboratory screening to process-scale evidence

Evidence level	What is demonstrated	Representative examples	Remaining scale-up question
Batch equilibrium/kinetics	Affinity, capacity, preliminary selectivity, rate	Abbasi et al. (2018); Callura et al. (2019); Watanabe et al. (2024)	Will selectivity survive flow and competition?
Fixed-bed column	Breakthrough, dynamic capacity, co-loading, elution profile	Callura et al. (2021); Ajiboye et al. (2023); Wang et al. (2019)	Will cycles remain stable in the real matrix?
Resin-in-leach / reactor pilot	Hydrodynamics and integrated leach–sorption behavior	Nouri-Khangah et al. (2023); Kirillov et al. (2026)	Can resin/solids separation and attrition be controlled?
Pilot wastewater / real-stream validation	Sustained operation under realistic variability	Czupryński et al. (2022); Pranudta et al. (2021)	What are resin life and full operating costs?
Prototype / multicolumn continuous	Cycle sequencing and process continuity	Poernomo et al. (2026); Wesselborg et al. (2024, 2025)	Can control, regeneration, and product quality remain stable?
Industrial-scale application	Full-scale throughput and regeneration logistics	Li et al. (2024)	Can performance be generalized to other feed chemistries?

Note. The literature spans substantially different feed chemistries and resin classes; the table compares evidence type rather than absolute technical performance.

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8.3 Integration with precipitation, solvent extraction, membranes, and polishing

Industrial flowsheets rarely benefit from forcing one separation technology to perform every duty. Precipitation can remove high-load impurities cheaply; solvent extraction can handle large metal inventories and produce concentrated organic phases; membranes can recover water or acid; ion exchange can polish dilute streams; and chelating resins can selectively capture a valuable or problematic metal. The most credible applications therefore use resin selectivity where it has the highest marginal value rather than treating resin as a stand-alone replacement for all conventional operations. (Avdibegović et al., 2018; Hermassi et al., 2021; Lebron et al., 2024; Roa et al., 2024a; Roa et al., 2024b; Vecino et al., 2021)

In this review, precipitation, solvent extraction, membranes, ionic-liquid phases, and related non-resin operations are not evaluated as co-equal primary technologies. They are included only where they alter feed speciation, remove high-load impurities, recover acid or water, concentrate eluates, or otherwise determine whether the resin step creates a net flowsheet advantage.

Figure 4 presents a generic hybrid flowsheet in which conventional ion exchange handles bulk impurity removal, a chelating bed performs selective capture, and downstream precipitation, solvent extraction, or electrowinning produces the final product. The regenerant loop is shown explicitly because it is a major determinant of both economics and environmental burden.

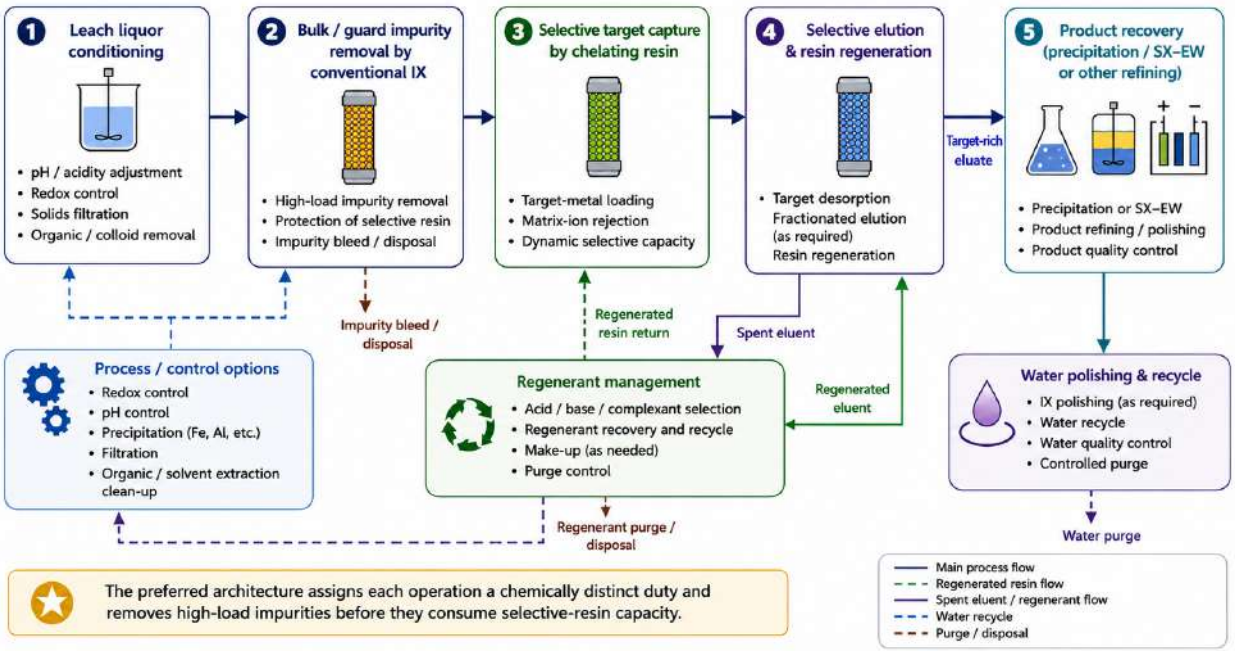

Figure 4. Hybrid resin flowsheet for complex hydrometallurgical liquors

Note. Author-generated conceptual synthesis based on Hermassi et al. (2021), Roa et al. (2024a, 2024b), Lebron et al. (2024), and Vecino et al. (2021).

The flowsheet in Figure 4 also clarifies why upstream conditioning can be more valuable than further resin functionalization. Redox adjustment, partial Fe/Al precipitation, filtration, or organic removal can protect the selective bed and lengthen the cycle. Downstream, the eluate can be treated by precipitation or solvent extraction at a much smaller volumetric flow than the original leachate. This concentration-and-polishing logic is one of the strongest arguments for integrating resin operations into rather than outside of established hydrometallurgical flowsheets.

9. REGENERATION, ELUTION, FOULING, AND RESIN LIFETIME

Regeneration is often the point at which an attractive batch sorbent becomes an unattractive process material. Stronger metal–ligand binding can improve loading selectivity while increasing the chemical driving force required for stripping. Acids, bases, salts, complexants, and redox-active eluents can all be effective, but their performance should be judged by metal recovery, concentration factor, product purity, resin reconditioning, reagent consumption, rinse demand, and the fate of the spent eluent. A

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reported desorption percentage without an eluent-to-resin or eluent-to-metal ratio is therefore insufficient for process comparison. (Deng et al., 2020; Jakóbik-Kolon & Bok-Badura, 2022; Kurkinen et al., 2021; Mikeli et al., 2024; Mostajeran et al., 2024; Wang et al., 2022)

Split and cascade regeneration can convert differential binding strength into product separation. In Cu/Ni systems, staged eluents can selectively strip one metal before the other; in Sc, V, and Ga systems, complexants or sequential acidity can create concentrated fractions. However, repeated chemical swings can change resin swelling, ligand protonation, and mechanical integrity. The regeneration route should therefore be developed simultaneously with loading conditions, rather than after the adsorption chemistry has been optimized in isolation. (Cui et al., 2026; Ulloa, Martínez-Minchero, et al., 2020; Wang et al., 2022)

The limited multicycle datasets available are especially informative. Ulloa, Martínez-Minchero, et al. (2020) achieved 98% Ni purity after acid elution and 97% Cu purity after ammoniacal elution; after 10 adsorption–regeneration cycles, Cu removal remained essentially stable whereas Ni adsorption decreased by about 10%. In the phosphogypsum RIL system of Kurkinen et al. (2021), REE loading and purity improved through seven loading cycles and two-step elution produced a REE fraction with purity up to 99.01%. These studies show that cycling should be reported together with selective recovery and capacity retention rather than as an isolated "reusability" percentage.

Long-term capacity loss can result from ligand degradation, irreversible binding, pore blockage, osmotic stress, or extractant loss from impregnated resins. Studies specifically addressing deactivation and physical/chemical stability are still far less common than single-cycle uptake studies, despite their direct relevance to resin replacement cost and waste generation. In situ regeneration and diagnostic approaches are valuable because they distinguish reversible fouling from irreversible material decay. (Lazar et al., 2025; Xu et al., 2025)

Table 8 compares regeneration strategies and the process tradeoffs they introduce. The "best" eluent is the one that closes the complete mass and reagent balance, not necessarily the one that gives the highest desorption in a single test.

Table 8. Regeneration and elution strategies for resin processes

Strategy	Primary mechanism	Advantages	Main risks / costs	Useful reporting variables
Strong acid	Proton competition and complex dissolution	Simple, widely available, compatible with many cation-chelating resins	Corrosion, acid consumption, dilute eluate, ligand damage	Acid mol per mol metal; concentration factor; capacity retention
Strong base/alkaline salt	Deprotonation or speciation shift	Useful for selected anion/ligand systems	Precipitation risk; caustic handling; osmotic stress	Base use; solids formation; resin swelling
Complexing agent (oxalate, citrate, EDTA-type)	Forms soluble metal complex and displaces resin ligand	Can selectively strip strongly bound metals	Reagent recovery; downstream complex destruction; COD/salt load	Complexant/metal ratio; reuse; product compatibility
Split/cascade elution	Sequential exploitation of binding differences	Produces separate metal fractions from co-loaded resin	More tanks, valves, control and wash water	Fraction purity; cut points; recycle volumes
Electrochemical regeneration	Potential-driven ion release / resin-state control	May reduce chemical regenerant demand	Electrical complexity; electrode integration; scale-up maturity	Energy per mol metal; Faradaic efficiency; cycle stability
In situ reactivation/ cleaning	Removes foulants or restores accessible sites	Extends resin life without replacement	Incomplete recovery; potential ligand damage	Restored capacity; fouling diagnostics; lifetime extension

Note. Regeneration strategy should be optimized jointly with loading and downstream product recovery. Examples include Jakóbik-Kolon and Bok-Badura (2022), Ulloa, Martínez-Minchero, et al. (2020), Wang et al. (2022), Vapnik et al. (2021), and Xu et al. (2025).

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Electrochemically regenerated ion-exchange concepts are especially interesting because they aim to replace repeated chemical addition with controlled redox or potential changes. Their appeal is strongest where regenerant handling dominates the process burden, but electrochemical hardware, energy use, and compatibility with real feeds must be included in the comparison. The same caution applies to ionic-liquid and deep-eutectic systems: solvent reuse can be limited by hydration, proton depletion, and chemical drift even when first-cycle selectivity is excellent. (Aberdeen et al., 2026; Vapnik et al., 2021)

10. TECHNO-ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

A resin process cannot be assessed economically from resin price and equilibrium capacity alone. Capital requirements include columns or contactors, pumps, tanks, filters, instrumentation, regenerant and wash systems, solids handling, and potentially multiple columns for continuous service. Operating costs include resin make-up, acid or base, complexants, water, energy, waste neutralization, labor, and product finishing. A higher-priced chelating resin may be justified when it eliminates downstream purification stages, reduces total reagent demand, or recovers a high-value metal from a dilute stream; it is more difficult to justify when the same duty can be performed by a robust conventional exchanger. (Larochelle et al., 2021; Smerigan et al., 2025)

Environmental assessment must use the same system boundary. Resin synthesis, chemical regenerants, eluate treatment, water use, and disposal or recycling of spent resin can offset gains attributed to high selectivity. Conversely, selective recovery can avoid bulk precipitation sludge, lower metal losses, or enable water recycle. Life-cycle studies in metal-recovery systems illustrate that process optimization can shift impacts among chemicals, energy, and waste rather than simply reduce all categories simultaneously. (Duclos et al., 2020; Romal et al., 2025; Smerigan et al., 2025)

Economic and environmental performance are also strongly feed-specific. Acid mine drainage and phosphogypsum contain low-value bulk matrices with comparatively low target concentrations, making logistics and reagent intensity decisive. Battery leachates and industrial electroplating streams can contain higher-value metals at concentrations that support smaller equipment and more concentrated eluates. Network sourcing and centralized treatment concepts may be required where individual streams are too small or variable to support dedicated recovery facilities. (Larochelle et al., 2021; Romal & DeBraske, 2025; Smerigan et al., 2025)

An industrial-scale application illustrates the value of closing this balance. In the nickel-recovery system reported by Li et al. (2024), two cation-exchange beds followed by a chelating bed reduced effluent Ni to below 0.1 mg L−1, while aeration-assisted regeneration with 2 bed volumes of 6% HCl achieved an acid utilization ratio above 99% and produced a regenerant containing more than 60 g L−1 Ni. The reported adsorption-and-regeneration cost of ¥5.5–9.5 m−3 for wastewater containing 200–800 mg L−1 Ni is more informative for process selection than resin price or batch capacity in isolation. Comparable full-process cost data remain uncommon; accordingly, this section is framed as techno-economic and environmental considerations rather than as a universal cost ranking.

Table 9 provides a decision framework for selecting among conventional ion exchange, chelating resins, solvent-impregnated or ionic-liquid phases, and hybrid flowsheets. The table is qualitative by design because feed composition and product value dominate universal cost rankings.

Table 9. Qualitative process-selection matrix for resin-based metal recovery

Criterion	Conventional IX	Chelating resin	Impregnated / IL-functionalized resin	Hybrid flowsheet
Intrinsic selectivity	Low–moderate	Moderate–high	Potentially high and tunable	Uses each technology where selectivity is needed
Kinetic simplicity	Generally favorable	Variable; often slower	Variable; pore/extractant transport relevant	Can isolate slow selective step to smaller stream
Tolerance to high ionic strength	Often good but competition increases	Ligand-specific; protonation may limit	Solvent environment may help or destabilize phase	Pretreatment can protect selective stage

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Criterion	Conventional IX	Chelating resin	Impregnated / IL-functionalized resin	Hybrid flowsheet
Regeneration complexity	Low–moderate	Moderate–high	Moderate–high; extractant retention important	Can optimize separate regenerant loops
Dynamic/process maturity	High for conventional duties	Moderate, with growing pilot evidence	Lower and chemistry-specific	Highest when built from mature unit operations
Best economic niche	High-throughput bulk exchange/polishing	High-value selective capture	Difficult separations where extractant chemistry is advantageous	Complex feeds requiring staged impurity removal and recovery
Primary scale-up risk	Breakthrough under competition	Mass transfer + elution + lifetime	Phase stability/leaching + regeneration	Flowsheet complexity and recycle accumulation

Note. Qualitative synthesis; project-specific TEA and environmental assessment are required before technology selection.

A minimum techno-economic comparison should report resin inventory, assumed resin lifetime, working rather than equilibrium capacity, cycle time, regenerant consumption, water balance, product concentration, number of columns, recovery and purity, waste treatment, and the unit operations displaced by the resin step. Without these variables, claims of "low cost" or "green separation" are weak. Environmental claims should likewise state whether acid manufacture, neutralization chemicals, resin production, energy, and spent-resin treatment are included in the boundary.

11. EMERGING MATERIALS AND NEXT-GENERATION PROCESS CONCEPTS

The most important trend is not simply the synthesis of more functional groups, but the deliberate coupling of ligand chemistry with pore architecture and process mode. Hypercrosslinked polymers, phosphorylated porous resins, macrocycle-appended supports, and spatially organized polycarboxyl materials seek to increase accessible site density while preserving diffusion. This is a shift from "adding stronger ligands" toward controlling the microenvironment around the binding site. (Gao et al., 2025; Liang et al., 2024; Liu et al., 2024; Yi et al., 2026)

Ionic-liquid-functionalized and supported ionic-liquid phases extend this idea by immobilizing extraction-like chemistry inside a solid support. They can reproduce the tunability of solvent extraction while avoiding a dispersed organic phase, but their industrial value depends on extractant retention, solvent compatibility, and regeneration. Polar organic solvents can also change metal-chloride speciation, thereby altering the relative performance of ion exchange, extraction chromatography, and solvent extraction. These results reinforce the broader theme that the phase environment is part of the selectivity mechanism. (Avdibegović et al., 2018; Avdibegović & Binnemans, 2020; Avdibegović & Binnemans, 2021; Dewulf et al., 2025; Du et al., 2026; Lanaridi et al., 2021)

Deep eutectic solvents introduce another route for manipulating speciation, including Ni/Co separation. Yet reuse studies show that hydration and proton depletion can cause chemical drift, reminding designers that a solvent or ligand system must remain chemically invariant over cycles to support a stable separation process. The same lesson applies to all "green solvent" claims: solvent composition, make-up demand, product compatibility, and recovery must be quantified over repeated use. (Aberdeen et al., 2025; Aberdeen et al., 2026)

Advanced resin design is also moving toward multifunctional behavior, including simultaneous decomplexation and capture, redox-controlled uptake, and cascade desorption. These functions can reduce the number of unit operations, but they increase the number of coupled chemical variables that must be controlled. The best next-generation materials will therefore be those whose selectivity can be translated into simple and stable operating windows, not merely those with the most complex ligand architecture. (Cui et al., 2026; Vapnik et al., 2021; Wang et al., 2026; Zhao et al., 2026)

Bio-based or lower-impact matrices are attractive from a circularity perspective, but they should be compared using durability and whole-life performance rather than polymer origin alone. A resin that is partially bio-derived but requires frequent

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replacement or aggressive regeneration can have a larger footprint than a durable synthetic resin. Environmental impact assessments of modified biopolymer-based sorbents provide useful direction by beginning to connect material design with process-scale consequences. (Romal et al., 2025)

12. CRITICAL KNOWLEDGE GAPS AND A RESEARCH AGENDA FOR SCALE-UP

The literature is now rich in material discovery but remains uneven in process evidence. The most persistent gap is the reliance on synthetic single-solute or low-complexity matrices followed by short-duration batch testing. This creates an evidence bottleneck: many materials are described as highly selective or reusable without demonstrating breakthrough under realistic competition, multi-cycle elution, pressure-drop stability, or resistance to the impurity spectrum of the intended feed. The gap becomes particularly important when laboratory studies are described as industrially relevant or scale-up ready.

Figure 5 summarizes a minimum evidence ladder for industrial translation. Each step addresses a distinct failure mode that cannot be inferred reliably from the preceding step.

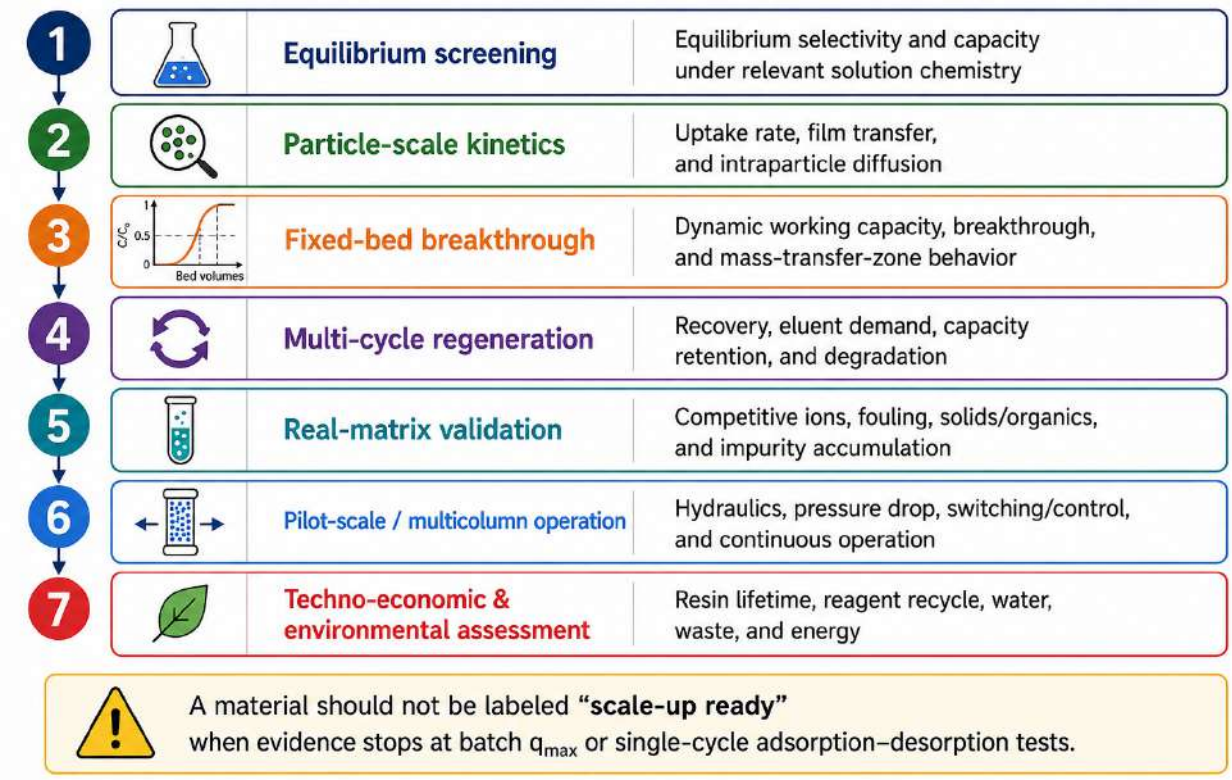

Figure 5. Minimum evidence ladder for industrial translation

Note. Author-generated critical framework informed by the evidence progression represented by Czupryński et al. (2022), Nouri-Khangah et al. (2023), Li et al. (2024), Wesselborg et al. (2024, 2025), and Kirillov et al. (2026).

As Figure 5 indicates, evidence for industrial translation should progress from equilibrium screening through particle-scale kinetics, fixed-bed breakthrough, regeneration cycles, real-matrix validation, pilot or multicolumn operation, and ultimately integrated economic and environmental assessment. Skipping a stage does not automatically invalidate a material, but it constrains the claim that can reasonably be made. A resin supported only by batch data may be a promising sorbent; it should not be described as a commercially ready separation process.

Figure 6 provides an evidence-field map for the representative studies summarized quantitatively in Table 2. The matrix is not a count of the entire 110-paper corpus; it is a visual demonstration of which process evidence blocks are commonly reported together and which remain missing even in mature-looking studies.

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Figure 6. Evidence fields reported by representative process-oriented studies

Study	Real or representative complex feed	Fixed-bed / dynamic-column testing	Elution / regeneration demonstrated	Multi-cycle performance retention	Pilot-scale / industrial validation	Techno-economic / cost assessment
Callura *et al.* 2021	✓	✓	✓	—	—	—
José *et al.* 2021	✓	✓	✓	—	—	—
Wang *et al.* 2019	—	✓	—	—	—	—
Kurkinen *et al.* 2021	✓	—	✓	✓	—	—
Czupryński *et al.* 2022	✓	✓	✓	—	✓	—
Ulloa *et al.* 2020	✓	—	✓	✓	—	—
Li *et al.* 2024	✓	✓	✓	—	✓	✓
Wesselborg *et al.* 2024	✓	✓	✓	—	—	—
Wesselborg *et al.* 2025	✓	✓	✓	—	—	—
Roa *et al.* 2024b	✓	✓	✓	—	—	—

✓ Evidence field demonstrated / reported — Evidence not demonstrated in the reported study

Note. A check mark indicates that the evidence field was reported or demonstrated; it does not imply equivalent experimental scale, rigor, duration, or technology-readiness level across studies.

Note. Author-generated evidence map based on the representative studies summarized in Table 2. A check mark indicates that the corresponding evidence field was explicitly represented in the study; a dash does not imply poor performance, only absence from the selected benchmark evidence.

Figure 6 reinforces the central evidence gap: fixed-bed and real-feed studies are increasingly available, whereas multicycle durability and explicit cost or environmental accounting are still reported much less consistently. This imbalance limits confidence in assumptions about resin replacement intervals and overall process performance, even when short-term separation results are excellent.

A second gap is inconsistent reporting. Studies frequently omit resin preconditioning, wet/dry mass basis, ligand density, particle-size distribution, exact feed speciation, bed voidage, breakthrough criterion, or regenerant volume. These omissions prevent meaningful comparisons even among studies that use the same commercial resin. Standardized reporting would create greater process-design value than another generation of isolated isotherm fits because it would enable more reliable cross-study synthesis and transfer of parameters into process models.

A third gap is long-term stability. Tens of cycles are more informative than one or two, but the life of industrial resin may involve hundreds or thousands of cycles. Mechanical attrition, fouling, ligand oxidation or hydrolysis, extractant leaching, and irreversible impurity uptake should be monitored using mass, capacity, spectroscopic, particle-size, and hydraulic diagnostics, where relevant. Long-term brine treatment and deactivation studies provide useful models for this type of evidence, even when the target application differs. (Lazar et al., 2025; Xu et al., 2025)

A fourth gap is the connection between selectivity and product specification. Many studies report percentage removal, yet a process is often constrained by maximum impurity concentration in the raffinate or product. Reporting product purity, impurity breakthrough, concentration factor, and recovery together would align laboratory work with downstream refining requirements. This is particularly important for nuclear-grade Zr systems, REE fractionation, and high-purity battery-metal products. (Ismail et al., 2025; Ma et al., 2019; Mohammed et al., 2026; Poernomo et al., 2026; Souza et al., 2025)

A fifth gap is process control under variable feeds. Real leachates drift in acidity, metal concentration, oxidation state, and impurity composition. A practical resin process needs a control strategy for cycle termination, switching between columns, regenerant strength, rinse completion, and detection of resin degradation. Multicolumn battery-recycling studies and industrial-scale

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nickel recovery demonstrate the type of operational evidence that should become standard for mature applications. (Li et al., 2024; Wesselborg et al., 2024; Wesselborg et al., 2025)

Table 10 proposes a minimum reporting checklist for resin-separation studies intended to support scale-up claims. Together with the evidence hierarchy in Figure 5 and the process benchmark in Table 2, the checklist is a principal methodological contribution of this review because it converts recurring literature deficiencies into explicit reporting requirements.

Table 10. Minimum reporting checklist for scale-up-relevant resin studies

Evidence block	Minimum information	Why it matters
Feed chemistry	Target + major impurities; acid/base; anions; complexants; pH; temperature; real vs synthetic feed	Defines metal speciation and competitive environment
Resin characterization	Functional group; matrix; wet/dry basis; particle size; capacity/ligand density; conditioning	Enables comparison and mass-transfer interpretation
Equilibrium	Isotherm range; competing ions; mass balance; separation factor with composition	Prevents qmax from being interpreted outside its chemical window
Kinetics	Agitation/flow; particle size; temperature; transport-model assessment	Separates chemical affinity from rate limitation
Column/reactor	Bed height; diameter; velocity; EBCT; breakthrough criterion; pressure drop; mass-transfer-zone behavior	Provides usable capacity and hydraulic basis for scale-up
Regeneration	Eluent composition and volume; fraction purity; concentration factor; rinse demand; reagent reuse	Closes the chemical and water balance
Durability	At least multi-cycle capacity/selectivity retention; fouling or degradation diagnostics	Supports resin-life assumptions
Process integration	Upstream conditioning; downstream product step; recycle/purge logic	Shows whether selectivity creates a flowsheet advantage
Economics/environment	Resin inventory/life; reagents; water; energy; waste; displaced operations; sensitivity analysis	Prevents unsupported “low-cost” or “green” claims

Note. Proposed by this review as a practical minimum for studies that make scale-up, sustainability, or industrial-readiness claims.

Finally, the field would benefit from deliberately comparative studies in which a conventional exchanger, a chelating resin, and a hybrid or impregnated material are tested under the same real feed, particle-size range, contact time, and regeneration objective. Such designs would reveal when added ligand complexity creates real process value and when it merely shifts cost from one part of the flowsheet to another. This type of comparative evidence is the clearest route to moving the discussion from material novelty toward process selection.

13. CONCLUSIONS

Conventional ion-exchange and chelating resins should not be treated as interchangeable adsorbent categories or as a simple hierarchy in which stronger binding is automatically superior. Conventional exchangers remain attractive for robust bulk exchange, impurity removal, guard-bed service, and polishing, whereas chelating resins can provide greater chemical discrimination when ligand–metal coordination is matched to the actual aqueous species. The same selectivity that creates this advantage also increases sensitivity to protonation, competing complexes, pore accessibility, mass transfer, and stripping chemistry.

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The central methodological conclusion is that batch capacity alone is not a reliable measure of process value. Working capacity under representative competition, dynamic breakthrough, product purity, regenerant demand, multicycle stability, and compatibility with the surrounding flowsheet provide a more defensible basis for scale-up assessment. The literature contains increasingly strong examples of fixed-bed, resin-in-leach, multicolumn, pilot, and industrial operation, but long-term resin-life data and complete reagent, water, cost, and environmental balances remain much less consistently reported.

The most defensible process strategy emerging from the reviewed evidence is therefore not the universal replacement of conventional ion exchange by chelating materials, but the deliberate allocation of separation duties according to the mechanism that provides the greatest process-level advantage. High-load impurities can be removed by robust exchange or pretreatment, selective ligands can capture high-value or difficult targets on a protected stream, and downstream precipitation, solvent extraction, electrowinning, or polishing can operate on a smaller and more concentrated volume. Hybrid flowsheets can therefore convert selectivity into process value while limiting unnecessary exposure of sophisticated resins to foulants and bulk competitors.

This review consequently proposes a minimum evidence and reporting framework for scale-up-relevant resin studies. Future work should prioritize representative feed chemistry, clearly defined breakthrough criteria, transport-aware dynamic testing, quantitative regenerant and rinse balances, product purity and concentration factor, extended cycling with physical and chemical diagnostics, and integrated techno-economic and environmental assessment. Materials that satisfy these requirements are more credible candidates for industrial translation than materials supported only by high equilibrium capacities or single-cycle selectivity.

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Data Availability
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