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Rhodium Recovery from Primary Ores and Secondary Resources: A Critical Review of Geochemistry, Thermodynamics, Extractive Metallurgy, Selective Separation, and Sustainable Process Integration

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Abstract

Rhodium is both technologically indispensable and difficult to recover because of its low abundance in primary ores, its dispersed distribution in secondary feedstocks, its resistance to dissolution, and its kinetically inert aqueous coordination chemistry. This critical review integrates geochemistry, primary-resource beneficiation, secondary-resource characterization, thermal concentration, chloride-based leaching, Rh(III) speciation, selective extraction, refining, and system-level sustainability. A bibliography of 153 records defines the literature considered; we assess eligibility and bibliographic metadata separately from scientific interpretation, and we do not claim a fully systematic review or an industrially validated meta-analysis. We compare mechanisms governing rhodium deportment through ore and waste pretreatment, collector smelting, oxidative leaching, interfacial transfer, and product isolation. Distinguishing leaching yield from plant-wide metal recovery exposes the importance of fine-particle losses, intermediate handling, and stripping efficiency. Preferential rhodium recovery before conventional end-stage refining emerges as a conditional design hypothesis rather than an established universal advantage. Robust deployment requires controlled feed characterization, complete rhodium balances, reproducible species identification, comparable recovery metrics, independently documented demonstration scale, and uncertainty-aware techno-economic and life-cycle assessment.

Keywords: Rhodium; Platinum-group metals; Secondary resources; Chloride speciation; Selective separation; Process integration

Highlights

• Rhodium deportment depends on mineral hosts, feed heterogeneity, and preparation losses.

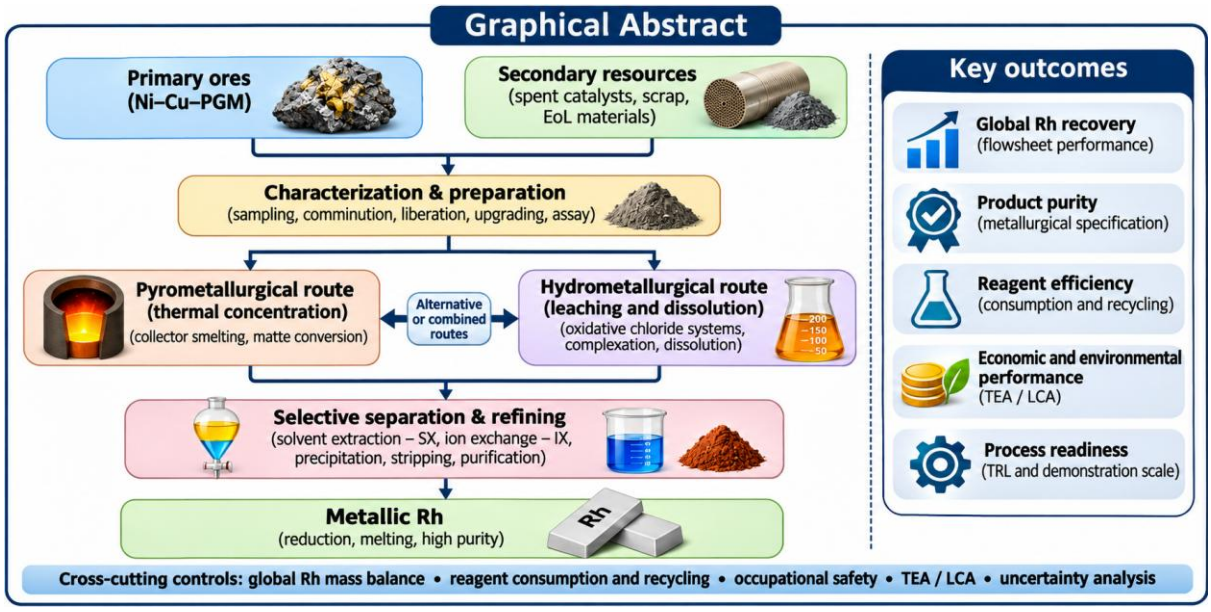
• Rh(III) chloro-aqua speciation and ligand-exchange inertia constrain selective refining.

• Collector smelting and oxidative leaching require whole-flowsheet rather than single-step comparisons.

• Preferential Rh recovery requires demonstration of global recovery, cost, and environmental gains.

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Pages: 1-35

Graphical Abstract



1. Introduction and Critical Review Methodology

Rhodium is predominantly obtained as a coproduct within platinum-group-metal (PGM) value chains. Its industrial importance is disproportionately large relative to its supply size and geological concentration. Unlike a generic survey of PGM recycling, this work asks whether Rh's chemical and physical properties create unique recovery bottlenecks, and whether intentionally shifting its position in a refinery sequence can improve global recovery. The conceptual chain starts with resource and process characterization (Figure **1**), extends to oxidation and aqueous coordination (Figure **2**), compares thermal and aqueous routes (Figure **3**), and culminates in selective separation (Figure **4**) and uncertainty-aware decision-making (Figure **5**).

The bibliographic corpus was assembled using topic-specific Boolean searches across primary deposits, spent catalysts, chloride dissolution, separation, thermal processing, and sustainability. The intended priority was publications from 2020–2026, with relevant foundational papers from 2010–2019. This article is a critical, mechanism-based narrative review, not a PRISMA-compliant systematic review: reproducible retrieval counts, screening decisions, independent assessors, and full-text eligibility logs are not documented in the review materials. Thus, the review reports no pooled extraction rates or unsupported comparative statistics. Evidence types include industrial operating reports, pilot or

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Pages: 1-35

demonstration studies, controlled experiments, simulations, and narrative reviews. These categories are not numerical quality scores, and bibliographic inclusion alone is not evidence of a validated operating result.

A key methodological distinction is between single-operation performance and total flowsheet recovery: R_global = m(Rh in saleable product) / m(Rh entering the defined battery limits). An apparent increase in leaching yield has no assured economic or environmental value if the preceding pretreatment or subsequent separation loses additional Rh. The observations are interpreted against mechanism, feed chemistry, reagent consumption, competing PGMs, and reporting scale, with the relevant economic and environmental comparisons condensed in Table 1.

Table 1 sets out the minimum evidence needed to compare technologies across feed characterization, global metal accounting, separation, demonstration scale, and environmental boundaries. Apply these dimensions jointly rather than treating a high single-step extraction percentage as a proxy for plant recovery.

Table 1. Evaluation framework for comparing Rh recovery technologies

Dimension	Minimum evidence required	Comparison limitation
Feed and host	Representative assay, size distribution, Rh deportment	Primary and secondary resources are not interchangeable
Metallurgical performance	Step recovery and measured total Rh balance	Do not equate dissolution with saleable Rh yield
Separation	Product purity, D-values, stripping, recycle	Synthetic solutions may overstate selectivity
Maturity	Scale, run length, feed variability, control data	Publication alone does not establish TRL
Sustainability	Energy, reagent, emissions, waste and uncertainty	Functional units and system boundaries differ

Note. Original evaluation framework developed for this critical review; no numerical performance values are inferred.

The framework makes transparent why the apparent best step in a laboratory study can be inferior when it includes material losses, reagent regeneration, and downstream refining obligations.

2. Geochemistry, Mineralogy, and Primary Rhodium Resources

Primary Rh is generally dispersed among sulfide-related PGM assemblages rather than hosted in a single ubiquitous mineral. The mode of occurrence and association with Ni–

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Pages: 1-35

Cu sulfides and discrete PGM minerals determine liberation, flotation response, and downstream concentrate composition. Deposits in the Bushveld Complex, Great Dyke, and Norilsk-related systems cannot be assumed to show the same mineralogical deportment, even when their bulk Rh assays appear similar. Detailed microscopy and deportment methods are therefore prerequisites to credible process comparisons.

Figure 1 traces the progression from Rh-bearing mineral hosts through liberation, flotation, and collector-metal formation. Its main implication is that the mineralogical distribution of Rh must be established before interpreting process recovery.

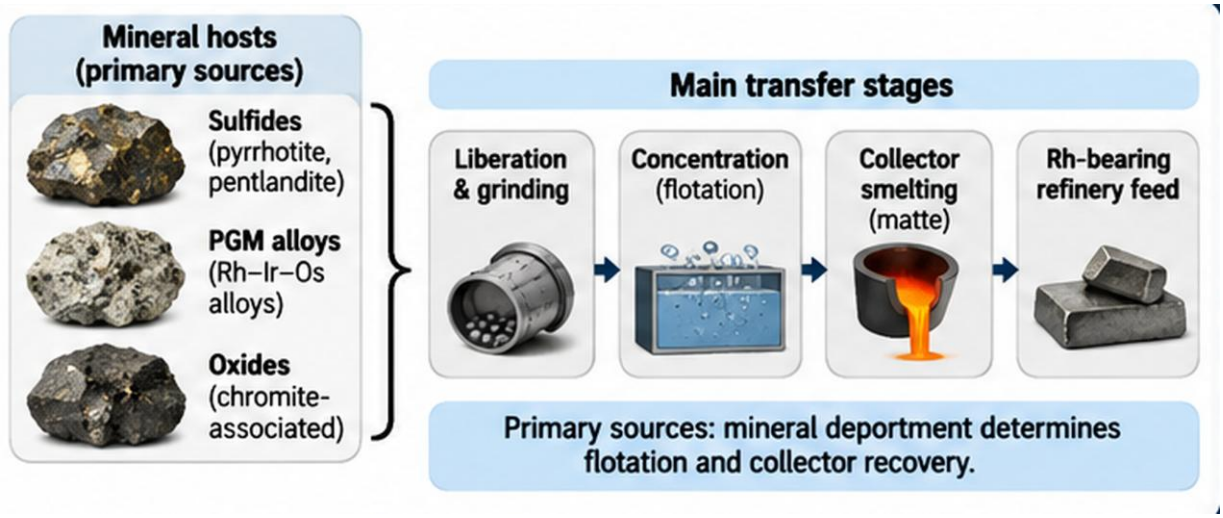


Figure 1. Primary-source mineral association and the main metallurgical transfer stages for Rh.
Note. Conceptual illustration generated with AI assistance from the review framework; no experimental values are represented. Scientific content and provenance require final author verification.

The primary-resource chain must distinguish Rh in floatable sulfide grains, discrete liberated PGM inclusions, and partially exposed composite particles. Coarse grinding may conserve energy, but increase locked Rh losses; indiscriminate fine grinding may improve liberation yet create slimes, entrainment, and downstream handling losses. Consequently, optimum grind size and collector chemistry are ore-specific, and recovery should be assessed separately for individual PGMs rather than extrapolated from combined PGM grades.

Evidence from the geology and flotation literature supports a critical comparison of deposit-specific recovery, whereas the presence of rich high-tenor assemblages does not automatically imply commercial recoverability. Concentrate transport, metal accounting, and

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eventual refinery penalties are additional determinants. Table **2** presents the host-related decisions to record before selecting a flowsheet.

Table 2 separates the analytical priorities for primary ores, flotation tailings, automotive catalysts, homogeneous catalyst residues, and metallic scrap; no single sampling or assay protocol is adequate for all these materials.

Table 2. Ore and secondary-feed characterization considerations

Feed family	Rh association/challenge	Essential analytical controls
Ni–Cu–PGM primary ores	Sulfide-hosted and discrete PGM grains	Automated mineralogy; phase association; flotation assays
PGM flotation tails	Locked or poorly recovered particles	Size-by-size Rh accounting; regrind response
Spent three-way catalysts	Low-volume coatings on refractory substrates	Representative lot sampling; PGM assay; ceramic fraction
Homogeneous catalyst residues	Organometallic species in complex liquor	Metal speciation; organics; solvent inventory
Alloys and process scrap	Pt–Rh solid solution and metallic dilution	Bulk assay; corrosion and alloy identification

Note. Original typology drawn from the scope of supplied studies; concentrations omitted because no common assay basis is available.

A feed-specific decision should only follow a material-deportment study. This contrasts with route-first approaches that optimize one chemical operation while leaving liberation or feed heterogeneity uncontrolled.

3. Secondary Resources and Rhodium-Bearing Waste Characterization

Spent automotive three-way catalysts represent a major secondary pathway, but their Rh concentration depends on vehicle class, catalyst history, original formulation, and physical damage. Chemical-production catalysts, Rh carbonyl residues, Pt–Rh fabrication scrap, and selected complex aqueous waste streams require fundamentally different preparation. In ceramic-supported catalysts, robust lot subdivision, dust containment, and representative fire assay or validated elemental analysis are critical because sampling uncertainty can exceed an apparent incremental process improvement.

Industrial homogeneous catalyst wastes introduce additional challenges from organic ligands, dissolved salts, high ionic strength, and catalyst-deactivation by-products. A Rh-rich liquid residue may bypass collector smelting, whereas ceramic autocatalysts often justify thermal concentration if direct leaching becomes oxidant-intensive. Contaminants such as Fe, Al, Ni, Cu, Ce, and dissolved organics alter reagent demand and the speciation entering

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separation circuits; the same quoted Rh extraction percentage is therefore non-comparable across unlike feeds.

The wider secondary-resource literature includes plating streams, refining residues, and special nuclear-associated Rh-bearing materials. These niche feedstocks should not be merged into conventional automotive-catalyst economics. The practical screening hierarchy is: sample validity; accessible Rh phases; hazardous constituents; product potential; and feasible residue management. Only then should extraction reagents and equipment be selected.

4. Thermodynamics, Aqueous Speciation, and Dissolution Kinetics

The dissolution of Rh metal is constrained by oxidation kinetics and the stability of oxide or surface species; thermodynamic feasibility alone does not establish a practical dissolution rate. In acidic chloride systems, low-spin d^6 Rh(III) forms octahedral chloro-aqua complexes that may coexist and interchange slowly. Consequently, the distribution observed at a given analytical HCl concentration may reflect reaction history rather than an immediately reached equilibrium state. This directly affects Rh transfer from aqueous phases to amines, ligands, resins, and other selective media.

Figure 2 distinguishes the chemical oxidation needed to solubilize Rh from the subsequent formation and slow exchange of Rh(III) chloro-aqua complexes. An extractant cannot overcome an unfavorable species distribution by increasing its equilibrium affinity alone.

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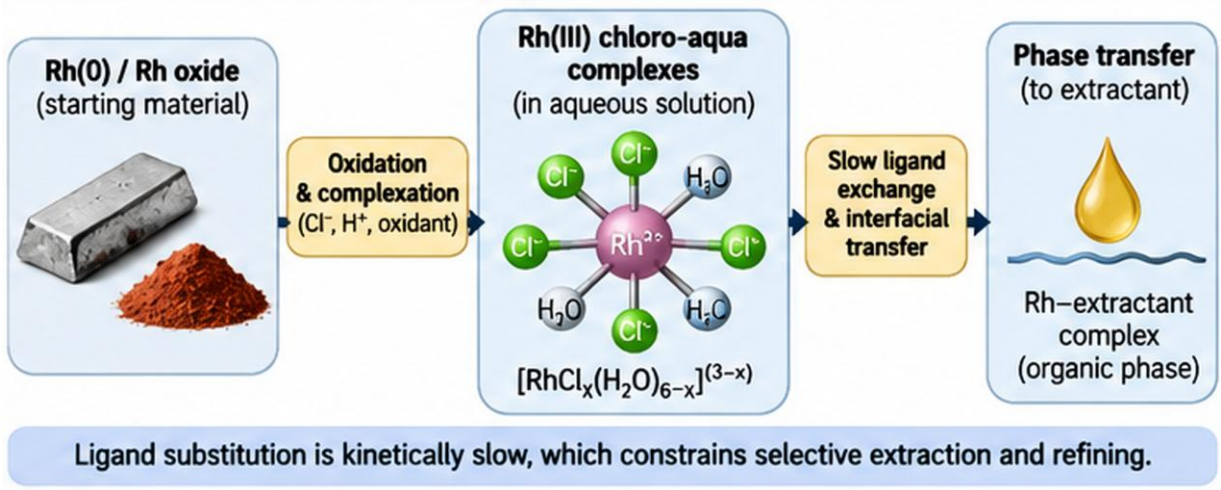


Figure 2. Conceptual relationship between Rh oxidation, chloro-aqua complexes, and the kinetic barrier to phase transfer.
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An instructive conceptual ligand-substitution step is $[RhCl_5(H_2O)]^{2-} + Cl^- \rightleftharpoons [RhCl_6]^{3-} + H_2O$. The equation is a mass- and charge-balanced representation, not evidence that one particular species dominates under all process conditions. Direct comparisons require measurements or models of chloride activity, acidity, temperature, aging, and redox state. Similarly, Eh–pH sketches cannot by themselves capture sluggish Rh ligand substitution or determine plant residence time.

The central critical question is whether an extractant improves equilibrium partitioning, accelerates species conversion, or changes the oxidation state. These claims require different experimental controls: time-resolved spectroscopy and speciation, extraction kinetics, metal balances, and repeated stripping. Treating all increases in aqueous removal as "selectivity" conflates irreversible adsorption, transient complexation, and useful recoverable Rh.

5. Pyrometallurgical Processing and Thermal Pretreatment

Collector smelting concentrates PGMs from refractory and dilute solid matrices into a more manageable metal or matte phase. Fe- and Cu-bearing collectors are commonly discussed; however, the optimum system depends on collector chemistry, slag basicity, liquidus constraints, furnace atmosphere, viscosity, entrainment, and downstream dissolution of the collector alloy. A high collector-stage Rh capture fraction is necessary but not

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sufficient for strong final recovery, since secondary oxidation, dusting, slag retention, and metal handling can create losses.

Figure 3 locates collector smelting and direct leaching within alternative integrated processing sequences. When comparing the two routes, include Rh retained in slag, dust, or intermediate alloys.

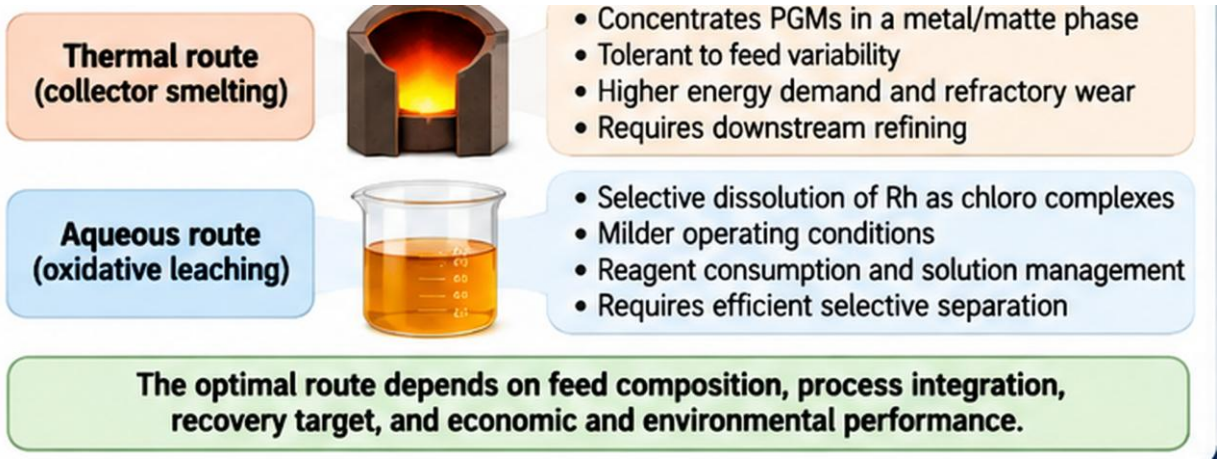


Figure 3. Alternative process integration and intermediate accounting in pyrometallurgical and hydrometallurgical Rh recovery.
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A published iron-melting investigation reports high PGM collection from spent automotive catalysts under its experimental conditions, but scale, feed nature, and later separation must be retained when interpreting its results. Thermal pretreatments can increase accessibility by removing organics, transforming the matrix, or forming soluble intermediates, but they may increase energy demand and introduce chloride-containing off-gases. Thermodynamic mass-partition analysis should therefore be linked to emission controls, recoverable residues, and an explicit Rh input–output balance.

One crucial trade-off is the cost of making the Rh-rich collector alloy versus the benefit of avoiding aggressive direct leaching of inert ceramic matrices. The apparent advantage disappears if collector dissolution consumes disproportionate chemicals or transfers large base-metal loads to solvent extraction. Thermal route comparisons should therefore report collector composition, slag mass, metal droplets in slag, dust Rh assays, and the assay of the final saleable product.

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Pages: 1-35

6. Hydrometallurgical Extraction and Leaching Technologies

Hydrometallurgical options include chloride–oxidant mixtures, combined microwave-assisted leaching, thermochemical activation followed by aqueous dissolution, chlorination, selected electrochemical methods, and emerging alternative solvent systems. These options should be evaluated by Rh-specific dissolution under realistic feed conditions, not by aggregate Pt + Pd + Rh extraction. Rh is especially vulnerable to low recovery when oxidant strength and temperature are optimized for Pd or Pt.

Oxidation and complexation are coupled. A leachant may be sufficiently oxidizing on paper, but may be limited by surface passivation, mass transfer across catalyst washcoats, chloride speciation, and local reagent depletion. Microwave irradiation can accelerate heating or cause beneficial local effects, but comparisons must use consistent temperature histories and energy accounting. Biological and mechanochemical approaches offer interesting intensification mechanisms, although continuity, residence time, contamination tolerance, and downstream recovery must be demonstrated.

A suitable comparative experiment should record the initial Rh content of the solid and solution, slurry density, size distribution, pH and free acidity, chloride activity, temperature, oxidant dosing, treatment time, solid residue assays, and dissolved concentrations after each unit. Any reported leaching rate without closure of solution and residue inventories should be treated as a preliminary indication, not a validated recovery claim.

7. Selective Separation, Purification, and Metallic Rhodium Production

Selective separation is often a more demanding operation than dissolution. Complexes of Pt(IV), Pd(II), Ir(IV), and Rh(III) can display markedly different extractability, while iron and other base metals may load the solvent or adsorbent. Rh(III) ligand-exchange inertia creates a mechanism-specific problem: an extraction solvent may thermodynamically favor a species that forms too slowly to sustain a practical contactor residence time. In consequence, conventional end-stage Rh precipitation, selective extraction, and direct preferential capture must be compared on cycle time, product purity, and achievable stripping.

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Pages: 1-35

Figure 4 contrasts two possible sequences for treating multimetallic chloride liquors. The proposed earlier Rh-capture branch should be tested against a conventional flowsheet using measured multi-cycle extraction and stripping yields.

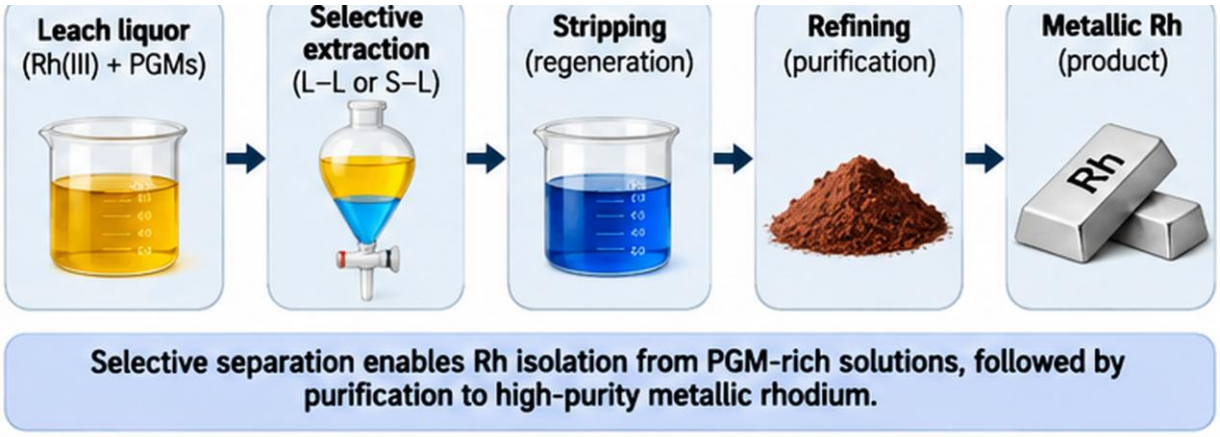


Figure 4. Alternative sequence for Rh selective recovery from multimetallic chloride liquors.
Note. Conceptual illustration generated with AI assistance from the review framework; no experimental values are represented. Scientific content and provenance require final author verification.

Synergistic solvent extraction with amides or amines, ion-exchange resins, functional sorbents, and ionic liquids are reported as potential ways to control Rh selectivity. Extraction into a loaded organic phase is not a final recovery operation: Rh must subsequently be stripped or irreversibly recovered in an accessible product form. Regeneration losses, degradation of organic extractants, chloride carry-over, and recovery from loaded adsorbents can dominate the flowsheet even where one cycle shows strong Rh removal.

Preferential Rh capture ahead of conventional removal of other PGMs remains a conditional hypothesis, not a generally demonstrated industrial advantage. It can be favorable when competing metals have separable speciation, and Rh enters a capture pathway with efficient elution; it can be detrimental if the selective medium fouls quickly or if activation chemistry requires expensive treatment. Comparisons should use separation factors, mass balance over multiple cycles, phase ratios, impurity profiles, Rh product assay, and continuous-pilot operation.

8. Integrated Flowsheets, Process Intensification, and Technology Readiness

An integrated flowsheet should define battery limits before benchmarking. For primary feeds, the boundary may span flotation through collector alloy refining; for spent

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Pages: 1-35

catalysts, it may begin with collection, decanning, crushing, and sample preparation. A fair comparison requires explicit intermediate Rh inventories and rejects at each stage. Conflating flowsheets with different boundaries creates artificial differences in recovery and cost.

The sequence may contain optional roasting, chlorination, acid leaching, oxidation control, selective extraction, stripping, Rh precipitation, washing, reduction, and metal consolidation. Stream recycles must be modeled because reagent accumulation and by-product bleed influence ion strength, ligand composition, and wastewater burden. The importance of precursor purity is amplified by the difficulty of separating Rh from other PGMs after complex formation.

Technology readiness level (TRL) cannot be inferred from the existence of a publication. A report of a bench experiment establishes only that the described experiment was performed; industrial status requires documented processing capacity, feed variation, reliability, product specification, safety management, and operating duration. Table **3** provides a structured maturity test without assigning unsupported TRL integers to individual articles.

Table 3 defines the documentary requirements for laboratory, integrated-bench, pilot, and industrial maturity. These evidence tiers are descriptive and should not be converted into numerical TRL values without further substantiation.

Table 3. Minimum evidence required to advance a proposed Rh recovery route

Evidence tier	Expected information	Unresolved risk
Laboratory	Reproducible controls, Rh and impurity assays	Representativeness and reagent recycling
Integrated bench	Connected stages and total metal balance	Cycle losses and recycle accumulation
Pilot/demonstration	Real-feed campaigns, duration, operability	Scale-related mass transfer and safety
Industrial	Commercial output and product QA over time	Economic resiliency and wider feed envelope

Note. Original classification framework. No numbered TRL is asserted without verified demonstration evidence.

A robust development decision combines independent experimental reproduction, feed variability, and an engineered control plan; a numerical TRL label should follow those facts, not precede them.

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Pages: 1-35

9. Techno-Economic Assessment, Life-Cycle Assessment, and Circularity

Rhodium economics are sensitive to feed grade, metal price, recovery losses, treatment charges, and working capital. For secondary feeds, collection and sampling costs may be as influential as chemical extraction. For primary feeds, mining and concentration infrastructure must be allocated to coproducts through an explicitly stated economic or physical basis. Without harmonized coproduct allocation, primary production and secondary recycling cannot be compared with a single universal carbon footprint.

A coherent techno-economic assessment (TEA) requires mass and energy balances, equipment capacities, reagent make-up and regeneration, labor, materials of construction, off-gas systems, effluent treatment, maintenance, and product payability. A life-cycle assessment (LCA) should state functional units, system boundaries, regional power mix, avoided-burden assumptions, catalyst collection pathways, and the treatment of secondary wastes. Environmental benefit from recycling is plausible but must not be assumed independent of oxidant intensity and thermal operations.

Figure 5 connects measured recovery and product purity with reagent demand, techno-economic analysis, life-cycle assessment, and documented technology maturity. The figure is a decision framework, not evidence that any process is commercially superior.

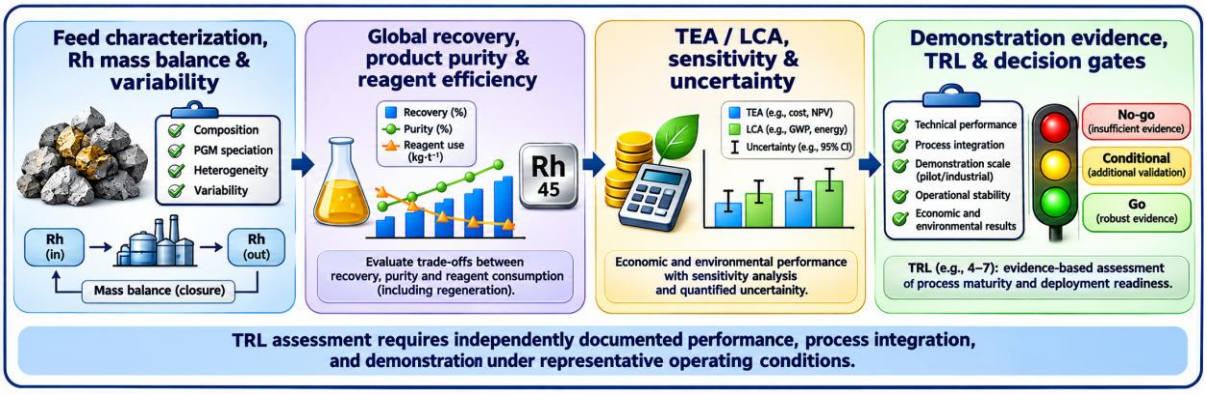


Figure 5. Evidence and uncertainty gates linking metallurgical performance to TEA, LCA, and technological maturity.
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Without a harmonized dataset, the defensible comparison is qualitative and conditional. Sensitivity should be evaluated against at least Rh price, collection yield, global

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Pages: 1-35

metal recovery, power intensity, acid and oxidant consumption, reagent recycling, and disposal costs. A useful next step would be a transparent process inventory against which competing flowsheets can be compared on equivalent system boundaries.

10. Environmental, Occupational, and Process Safety Challenges

Primary and secondary Rh processing poses material-specific hazards. Crushing and handling spent autocatalysts can release fine particulate containing PGM-bearing washcoat and other constituents; oxidizing chloride circuits introduce corrosion and may release chlorine-containing fumes under some operating conditions. Thermal routes can require high-temperature dust capture, off-gas cooling, and controlled treatment of chloride-bearing emissions. Evaluate occupational hazards through exposure pathways and containment design rather than inferring them solely from Rh content.

Mixtures of Rh with base metals and other PGMs can produce hazardous waste streams in purge liquor, spent organic solvent, adsorbents, slags, and filter cakes. Classification and final destination must align with local regulatory requirements and chemical characterization. Closing the reagent loop can lower material consumption but can also concentrate impurities, alter chloride chemistry, or create unstable waste mixtures if impurity removal is neglected.

Preferred safety controls include enclosed sampling and powder handling, ventilation, corrosive-liquid-compatible materials, gas detection where appropriate, robust spill containment, waste segregation, and analytical verification before recycling or discharge. Environmental risk is inseparable from metal recovery because uncontrolled dust and residues represent both hazard and loss of Rh value.

11. Critical Synthesis, Knowledge Gaps, and Future Research Priorities

The central scientific synthesis is that Rh extraction bottlenecks are sequential and interactive: ore and residue associations determine accessibility; oxidation and slow ligand exchange determine solution composition; phase-transfer kinetics and impurity competition determine extractant performance; and refining losses determine actual product recovery. The strongest individual operation cannot be selected independently of these interfaces. This

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favors integrated experimental programs rather than isolated screening of high extraction percentages.

The most important research gaps are (i) validated Rh speciation under process-relevant chloride activities and aging histories; (ii) comparable whole-flowsheet recoveries for real heterogeneous feeds; (iii) collector-smelting versus direct-leaching datasets on common boundaries; (iv) multi-cycle stripping and extractant regeneration; (v) Rh–Ir and Rh–Pt–Pd separations at realistic impurity loads; and (vi) pilot-level energy, reagent, and environmental inventories. Equally important is an experimental demonstration showing whether earlier Rh capture offers a net recovery advantage, rather than merely changing the sequence of refinery operations.

Prioritization should therefore begin with paired baseline and modified flowsheets for at least two feed classes, one solid catalyst or concentrate and one Rh-rich solution. Analyze all Rh-bearing inputs, saleable outputs, wash liquors, recycled intermediates, sludges, dusts, and final rejects. The resulting total-recovery, impurity, safety, and economic dataset would constitute a strong basis for industrial route selection.

12. Evidence Integration Across the Supplied Bibliography

12.1 Primary-resource evidence

Mineralogical and flotation studies address orebody-specific association, liberation, and processing response. In this review, they establish feed constraints; they do not directly measure Rh purification from chloride solutions.

The cited contributions address mineral occurrence, sulfide association, liberation, and flotation performance across different primary resources. Their value to this review lies in defining ore-specific constraints rather than establishing a transferable Rh recovery factor. Cross-deposit comparisons require comparable deportment methods, grind size, feed assay, and Rh-specific balances. (Cabri, 2023; Canham et al., 2025; Engelbrecht & Cloete, 2022; Gibson et al., 2023; Kabemba & Waters, 2025; Maier et al., 2023).

These deposit and flotation references span different mineral hosts and operating contexts. Interpretation should therefore separate Rh-specific deportment and analytical

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losses from the response of combined PGM concentrates. (McFadzean et al., 2024; Notole et al., 2025; O'Connor & Alexandrova, 2021; Pereira, 2026; Taguta & Ross, 2022).

12.2 Feed and waste streams

Studies on catalyst material, industrial residues, and Rh-bearing wastes define feed diversity and analytical boundaries—some address recovery of a mixed PGM inventory rather than Rh alone, which limits cross-study comparisons.

The referenced work spans spent catalysts, industrial waste streams, sampling and analytical methods, and several different recovery strategies. These sources should not be ranked by a single PGM-extraction metric: feed heterogeneity, Rh assay basis, pretreatment, and residual-solid accounting differ. Only directly comparable experimental datasets can support a quantitative claim. (Ding & Zhang, 2020; Emmons-Burzyńska et al., 2025; Guo et al., 2023; Ho & Lee, 2026; Hosseinzadeh & Petersen, 2024; Ibrahim & Abolhasani, 2022).

For primary and secondary feedstocks alike, validation must include representative sampling, independent Rh assays where possible, and closure of solids and solution inventories; the cited work does not establish transferable recovery values.

A second group of publications broadens the range of residues and processing approaches investigated. Before quantitative comparison, their sample preparation, Rh assay methods, and reporting boundaries require source-level verification. (Leon-Fernandez et al., 2026; Morcali, 2020; Nguyen & Riaño, 2023; Nguyen et al., 2021; Nicol et al., 2021; Nogueira et al., 2020).

The methodological comparison remains incomplete where article-level experimental datasets and uncertainty estimates are unavailable. This limitation affects the strength of route ranking rather than establishing that the technologies perform equivalently.

Evidence from the following references may help define research coverage, although its strength cannot be determined without checking the complete experiments and operating boundaries. (Saguru & Moropeng, 2018; Spathariotis et al., 2026; Spooren & Abo Atia, 2020; Tokoro et al., 2024; Trinh et al., 2020; Van den Bossche et al., 2021).

JIRRS
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The publications listed here should be screened for Rh-specific rather than aggregate PGM metrics, including metal fate in residue and final product. (Wang et al., 2025; Wang et al., 2023; Wiecka et al., 2023; Xu et al., 2022; Xv et al., 2025; Yakoumis et al., 2020).

Additional studies in this topic area can support a synthesis only where the experimental basis, analytical uncertainty, and phase accounting are explicitly available. (Yan et al., 2025; Ye et al., 2025; Yi et al., 2021; Yousif, 2019; Zabielska-Konopka et al., 2026; Zabielska-Konopka et al., 2025).

These records complete part of the subject-specific bibliography; no common quantitative result is attributed to them without source-level verification. (Zambrzycka-Szelewa & Godlewska-Żyłkiewicz, 2024).

12.3 Aqueous chemistry evidence

Thermodynamic and chemical-mechanism literature highlights the need to distinguish formation of soluble Rh species from experimentally demonstrated reversible capture. Speciation claims require direct aqueous characterization.

The listed literature is relevant to coordination chemistry, ligand environment, and interfacial recognition. For Rh(III), measured chloride activity, aging, temperature, and equilibration time are essential descriptors because a nominally similar acid concentration need not produce the same extractable species. (Zardkhoshouei et al., 2026; Zhou et al., 2024).

12.4 High-temperature evidence

Thermal collection and smelting reports concern transfer of PGM into collector phases or pretreatment intermediates. These cannot independently establish final pure-Rh yield without downstream balance data.

These sources address thermal collection, slag and alloy behavior, and related process configurations. The key distinction is between capturing Rh in an intermediate phase and recovering purified Rh after processing that intermediate. Reported metal-collection performance should be interpreted together with dust, slag, and subsequent refining losses.

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Vol: 1.11
DOI: 10.66104/xyv6xq81
Pages: 1-35

(Ding et al., 2020; He et al., 2024; Huang et al., 2024; Jin et al., 2025; Liu et al., 2021; Pereira, 2026).

Collector-stage reporting is useful only when it reconciles Rh transfer to alloy, slag, flue dust, and subsequent refining products. The referenced publications do not, by their bibliographic presence alone, establish a common metallurgical recovery benchmark.

12.5 Dissolution evidence

Leaching and chemical activation publications support testing alternative dissolution pathways. The main limitation is variable feed chemistry, contact time, reagent loading, and reporting of Rh-specific rather than total-PGM recovery.

The cited studies cover oxidative dissolution and activation approaches. Their results are not inherently comparable without consistent feed composition, solid-to-liquid ratio, reagent loading, oxidation conditions, residence time, and a Rh-specific solution–residue balance. Accelerated dissolution alone does not establish a higher saleable-metal yield. (Abo Atia & Spooren, 2021; Atia et al., 2021; Chen et al., 2021; de Aberasturi et al., 2011; Ding et al., 2023; Feng et al., 2025).

The effects of pretreatment and oxidant chemistry cannot be isolated without comparable feed and reaction histories. Differences in Rh dissolution should therefore be interpreted alongside reagent consumption and Rh remaining in undissolved solids.

Additional dissolution studies enlarge the set of candidate operations but cannot yet support a single performance ranking without common Rh-specific material-balance boundaries.

12.6 Separation evidence

Separation studies concern extractants, adsorbents, resins, precipitation, and interfacial recognition. For process selection, selectivity must be combined with stripping or regeneration, purity, and cycle stability.

These contributions examine extraction media, sorbents, resin systems, precipitation, and selective transport. Process value requires recoverable Rh, not merely depletion from the aqueous phase. Useful comparisons therefore need distribution and separation factors,

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 20/11/2026
Vol: 1.11
DOI: 10.66104/xyv6xq81
Pages: 1-35

stripping yields, product purity, impurity competition, reagent recycling, and multiple-cycle data. (Biswas et al., 2024; Carrick et al., 2021; Carrick et al., 2024; Dai et al., 2026; Deng et al., 2026; Firmansyah & Goto, 2018).

Selective capture must be differentiated from a recoverable Rh product. Differences in elution, regeneration, competitive co-extraction, and accumulated cycle losses may reverse a ranking based only on first-contact aqueous removal.

Other separation reports cover heterogeneous solution compositions and contact modes. Their industrial implications depend on the kinetics of extractable Rh formation and on the stability of the recovery medium during repeated cycles.

Source-level verification is particularly important when the reported measurement represents loaded-organic Rh, sorbed Rh, stripped Rh, or final metallic Rh; these quantities are not interchangeable recovery endpoints.

When authors report distribution coefficients, selectivity factors, or uptake capacities, the comparison should also record acidity, chloride loading, contact time, phase ratio, and competing elements.

Rh(III) coordination kinetics impose a separate limitation from equilibrium separation factors. Data on conditioning time and subsequent elution are needed before high apparent selectivity can be interpreted as operable process selectivity.

Literature coverage should not be mistaken for validated performance: without accessible full-text experimental conditions, relevant studies remain candidates for detailed comparison rather than quantitative benchmarks.

12.7 Integrated process evidence

Broader technology reviews and process integration studies help place individual operations within battery limits and indicate engineering priorities. Review-level proposals must not be equated with industrial verification.

The cited process-oriented publications place individual operations in broader resource-recovery and refinery contexts. Their implications are conditional on feedstock and battery limits: proposed integrated sequences cannot be assigned industrial maturity without

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 20/11/2026
Vol: 1.11
DOI: 10.66104/xyv6xq81
Pages: 1-35

traceable demonstration campaigns and complete metal balances. (Chen et al., 2021; E et al., 2025; Jia et al., 2022; Liu et al., 2026; Pereira, 2026).

The industrial relevance of process integration reports depends on explicit feed boundaries, Rh losses through intermediate handling, and the proven scale of each connected operation. (Pereira, 2026; Ryu et al., 2024; Wajima & Hashikawa, 2024; Xia & Ghahreman, 2023; Yoshii & Mizuhashi, 2022).

12.8 TEA, LCA, and circularity evidence

Resource, circularity, and techno-economic studies frame Rh supply risk and environmental trade-offs, but system boundaries and co-product allocations vary and require harmonization.

This literature provides a basis for examining resource efficiency, environmental burdens, and economic sensitivity. Comparative conclusions must disclose coproduct allocation, functional unit, collection and transport assumptions, power mix, reagent regeneration, and waste-treatment boundaries. (Cespi et al., 2025; Hughes et al., 2021; Karim & Ting, 2024; Li et al., 2024; Madani et al., 2024; Nag et al., 2026).

Economic and environmental comparisons must retain the same functional unit and account for secondary-material collection and metal allocation. Otherwise, differences in system boundaries can exceed the apparent advantage of a particular extraction route.

12.9 Safety and environmental evidence

Risk, environmental, and special-residue studies highlight safety and waste constraints; they do not provide universal emission factors across distinct Rh recovery routes.

These sources highlight characterization, environmental control, and responsible residue management. Hazard assessment should distinguish actual exposure pathways from bulk-metal concentration, and route comparisons should include contained dust, chloride-bearing gas, effluent, and spent-media inventories. (Bahaloo-Horeh & Mousavi, 2020; Hodgson & Holdsworth, 2023; Murtaza et al., 2025; Petrović et al., 2025; Sun et al., 2022; Weng et al., 2023).

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 20/11/2026
Vol: 1.11
DOI: 10.66104/xyv6xq81
Pages: 1-35

13. Conclusions

A credible Rh recovery strategy must connect mineral and waste characterization, physical concentration, oxidation and aqueous chemistry, selective separation, and validated metallic product yield. Dissolution is not synonymous with global metallurgical recovery, and recovery metrics from dissimilar feedstocks or laboratory configurations cannot be directly ranked. Collector smelting can efficiently concentrate some heterogeneous solids, whereas direct hydrometallurgical processing can be advantageous for suitable solutions and accessible residues; the decision depends on complete material balances, safety and environmental controls, and reagent-recycle performance. The kinetic inertia of Rh(III) coordination chemistry remains a central challenge for selective separation. Earlier preferential Rh capture is a promising but unproven general strategy that deserves controlled process-scale testing. Future work should emphasize Rh-specific measurements, operationally validated multimetal selectivity, repeatable product purity, and harmonized TEA/LCA assumptions.

Declarations

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Conflict of Interest

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This narrative review relies on the bibliography provided with the manuscript. No original experimental dataset is presented.

Author Contributions

Sole authorship is indicated in the manuscript; the final CRediT role statement requires author verification before submission.

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Vol: 1.11
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