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Electro-Assisted Leaching of Platinum-Group Metals: Interfacial Electron Transfer, In Situ Oxidant Generation, Redox-Mediator Regeneration, and Process Integration—A Critical Review

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Abstract

Electro-assisted leaching of platinum-group metals (PGMs) is often described as applied current or enhanced extraction. Yet, these observations do not clarify whether charge transfers at the PGM surface or is first converted into a soluble oxidant. This critical review examines Pt, Pd, and Rh dissolution alongside selected Ru-related mechanistic evidence by organizing published studies into direct anodic attack, electrogenerated lixiviants, redox-mediator regeneration, and electrochemical potential control. It links electrochemical surface behavior to chloride complexation, oxidant speciation, feed accessibility, electrode design, mass transfer, parasitic reactions, and downstream recovery. Across these configurations, electrode potential, cell voltage, current density, and transferred charge vary; extraction yield alone cannot establish efficient electrical utilization. The proposed assessment therefore combines element-resolved recovery, oxidant utilization, Faradaic accounting, specific energy per unit of recovered metal, material balances, and reactor stability. Direct mechanistic evidence is distinguished from conventional chemical leaching comparisons and from downstream separation studies. The analysis identifies real-feed repeatability, Rh dissolution, chloride containment, electrode stability, and continuous operation as priority validation gaps. A closed-loop process is promising only when its improved selectivity and reagent recirculation outweigh electrical losses and additional separations.

Keywords: Electro-assisted leaching; Platinum-group metals; Electrogenerated chlorine; Redox mediators; Dissolution kinetics; Process integration

Highlights

- Direct PGM electron transfer is distinct from indirect electrogenerated oxidants.
- Electrode potential and applied cell voltage must not be conflated.
- Metal recovery must be normalized to charge, energy, and oxidant use.

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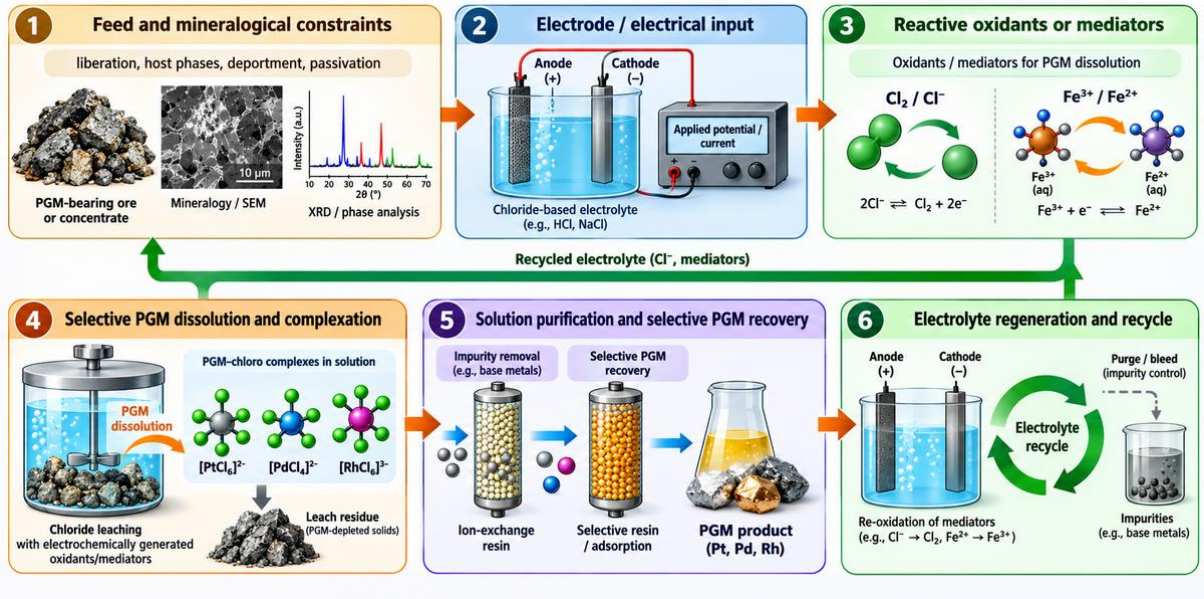
• Integrated electrolyte recycling requires full process and safety balances.

Graphical abstract



Graphical abstract. Conceptual coupling of feed accessibility, electrical input, PGM oxidation, separation, and oxidant regeneration; original design.

1. Introduction

Platinum-group metals combine strategic demand with high corrosion resistance, low natural abundance in viable concentrates, and dispersion across end-of-life catalysts. Leaching is governed not simply by oxidant strength, but by the coupled requirements of interfacial charge transfer, aqueous coordination, metal exposure, and product transport. The central premise of this review is that adding current to a leach vessel does not in itself establish direct electrochemical dissolution.

The review distinguishes direct electron transfer from electrogenerated reactive chlorine, soluble redox mediators, and electrochemical maintenance of a selected potential window. Figures 1–8 map these processes, their competing reactions, real-feed treatment, and integration; Tables 1–8 compare classifications, redox chemistry, feed behavior, hardware,

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efficiency measures, and evidence gaps. The displayed schematics are conceptual and deliberately do not imply a universal operating flowsheet.

A comparison of chemical catalyst treatment, electrochemical Pt corrosion, and recovered-PGM products becomes meaningful only after specifying the electron pathway, metal speciation, and system boundary. The analysis below consequently avoids treating catalyst stability experiments as demonstrated industrial-scale leach processes.

The review triangulates mechanistic electrode-corrosion evidence with studies of real catalyst treatment and separation. Potential-dependent Pt dissolution observed on model surfaces should not be converted into a predicted recovery yield for a ceramic-supported, multi-metal feed without independent tests. This evidence hierarchy informs the route classification in Table 1 and the direct-versus-indirect mechanism in Figure 1. (Cherevko et al., 2015; Duan et al., 2021; Fuchs et al., 2023; Wiecka et al., 2023; Xia et al., 2023; Yakoumis et al., 2020).

2. Review Methodology and Evidence Classification

2.1 Evidence scope and reproducibility

The evidence inventory supplied with the manuscript originally comprised 144 bibliographic records spanning mainly 2010–2026, including fundamental studies and technological analogs. The present bibliography preserves the 144 supplied records. The source compilation acknowledges that the bibliography was not independently audited in full. This manuscript therefore constitutes a critical narrative synthesis of the supplied records, not a registered systematic review, and does not claim exhaustive Google Scholar coverage or independently validated individual numerical extraction yields.

Screening logic grouped records by title and stated technical subject into mechanistic dissolution, chloride or mediator chemistry, real-feed treatment, kinetics, and downstream integration. Direct evidence denotes deliberate PGM electroleaching or quantitatively observed dissolution at an electrode; analogous evidence denotes electrochemical corrosion, fuel-cell

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degradation, or electrosynthesis; contextual evidence denotes purely chemical leaching, feed pretreatment, or separation. This tiering prevents mechanistic conclusions from being inferred from an unrelated end-point recovery.

2.2 Four electro-assisted route classes

Table 1 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 1. Classification of electro-assisted dissolution routes

Route	Electron transfer	Decisive verification
Direct anodic dissolution	PGM exchanges charge at an electrode	Electrical contact; metal-resolved current balance
Electrogenerated lixiviant	Electrode forms Cl_2 or other reagent	Oxidant speciation; spatial separation
Mediator regeneration	Electrode reoxidizes Fe, Ce, or related shuttle	Mediator cycling; crossover and losses
Potential control	Bias maintains solution redox envelope	Potential measured versus reference electrode

Note. Author-developed classification; direct dissolution should not be equated with indirect electro-assisted leaching.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

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Figure 1 illustrates direct and indirect mechanisms; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

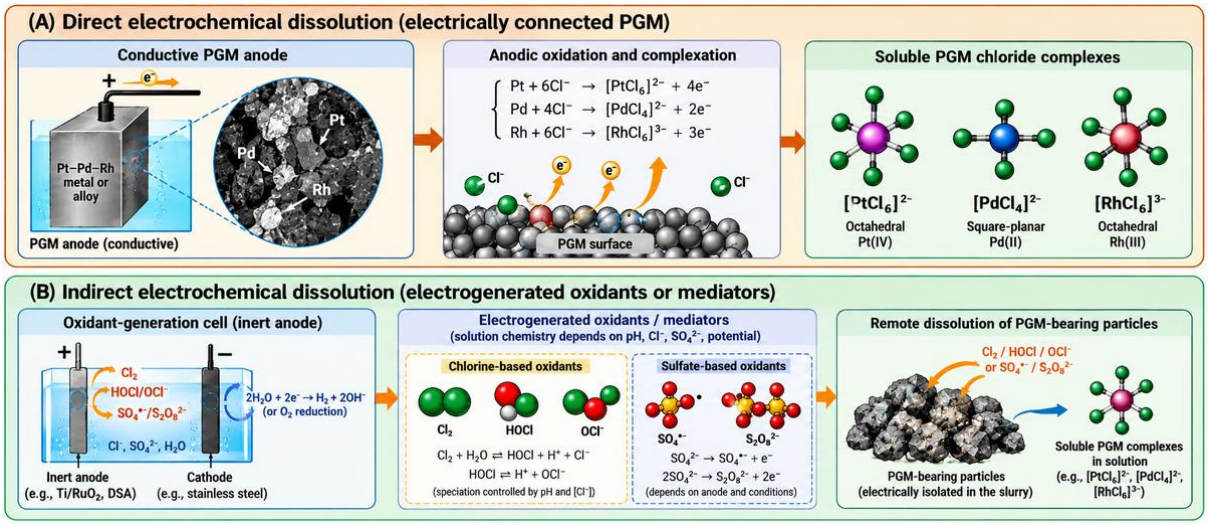

Figure 1. Direct, indirect, and mediator-assisted routes for PGM dissolution.
Note. Original conceptual diagram developed for this review from the mechanisms discussed in the cited literature; not reproduced or adapted from a specific published figure.

The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

3. Electrochemical Fundamentals

3.1 Electrode potential, voltage, and interfacial kinetics

For a half-reaction, the Nernst relation connects equilibrium potential to activities and reaction quotient; it does not define an applied full-cell voltage. The measured cell voltage includes reversible thermodynamic contributions, anodic and cathodic overpotentials, and ohmic drops. For complex-forming PGM ions, changes in free-ion activity shift formal redox behavior, while kinetic barriers and surface oxides may dominate a nominally favorable reaction.

The Butler–Volmer and Tafel frameworks are useful only within their domain of validity; oxide evolution, heterogeneous catalyst surfaces, gas formation, and time-dependent

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active area may invalidate single-slope interpretation. A potentiostat setting also cannot replace independently measured local potentials throughout an industrial slurry.

Figure 2 illustrates the separation between applied voltage and reactive chemical conversion; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

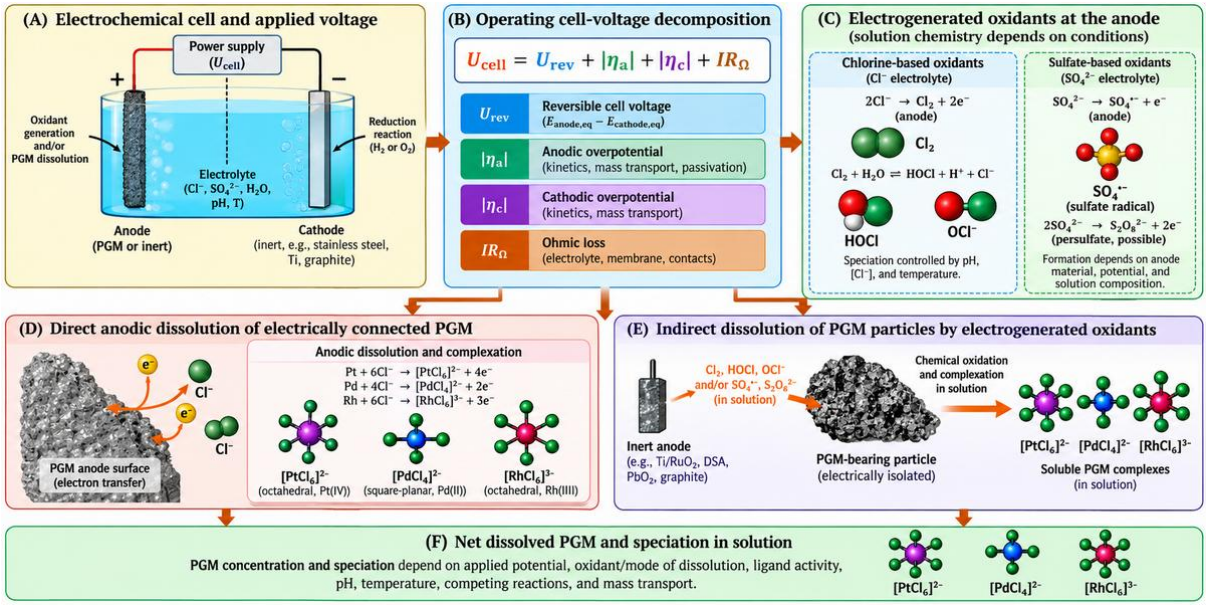

Figure 2. From cell power to interfacial oxidation and product formation.
Note. Original conceptual diagram developed for this review from the mechanisms discussed in the cited literature; not reproduced or adapted from a specific published figure.

The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

A process report should record reference scale, ohmic compensation, electrode area definition, current history, ionic composition, temperature, and electrode aging. Without these elements, apparent current-density trends cannot be compared across publications.

The central methodological limitation is that transient dissolution during potential cycling is not interchangeable with steady-state anodic recovery. Oxide coverage, electrode history, dissolved chloride, and transport interact, making potential traces, dissolution flux, and

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independently quantified dissolved mass jointly necessary. Mechanistic data therefore indicate plausible reaction pathways rather than optimized ore-processing conditions. (Bae et al., 2017; Briega-Martos et al., 2024; Cherevko et al., 2015; Duan et al., 2021; Fuchs et al., 2020; Fuchs et al., 2023; Geiger et al., 2015; Hodnik et al., 2016; Topalov et al., 2014).

4. Direct and Indirect Electro-Assisted Dissolution

4.1 Contact, conductivity, and suspended particles

Direct anodic dissolution requires sustained electrical contact between the metal phase and the circuit. A conductive metallic coupon behaves differently from nanometre-scale PGM particles isolated within an oxide washcoat. A suspended catalyst may dissolve predominantly through an oxidant generated at a separate anode, even when the experiment is labeled electrochemical leaching.

4.2 Mediated and potential-controlled configurations

An insoluble feed can be reached chemically by soluble oxidizing species formed remotely. Evidence for genuine electrochemical benefit requires control experiments at matched solution composition and oxidant exposure, as well as recorded current and charge. If applied current only reproduces a pre-existing chemical oxidant, the claim should be reagent-management value rather than intrinsically faster PGM surface kinetics.

An oxidation-enhanced batch must be evaluated against an oxidant-matched chemical blank and an electrode-material blank. A conductive catalyst coating may exhibit direct charge transfer, whereas insulating washcoat particles primarily respond to soluble oxidants. Discrimination requires spatially separating solids from the electrode, reference-electrode measurements, and quantitative electrode-loss analysis. (Cho et al., 2023; Chung et al., 2024; Cui et al., 2023; Cui et al., 2024; Diac et al., 2020; Guillet et al., 2024; Klemm et al., 2012).

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5. Electro-Assisted Chloride Leaching

5.1 Chloride ligands and chlorine speciation

Chloride stabilizes multiple dissolved PGM complexes while anodic chloride oxidation may generate chlorine-containing oxidants. The relevant reactive pool depends on chloride activity, acidity, temperature, dissolved gas, and local hydrodynamics. A free-chlorine reading is not by itself a quantitative measure of the species that reacted with Pt, Pd, or Rh.

Figure 3 illustrates the interdependence of chloride regeneration, complexation, and containment; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

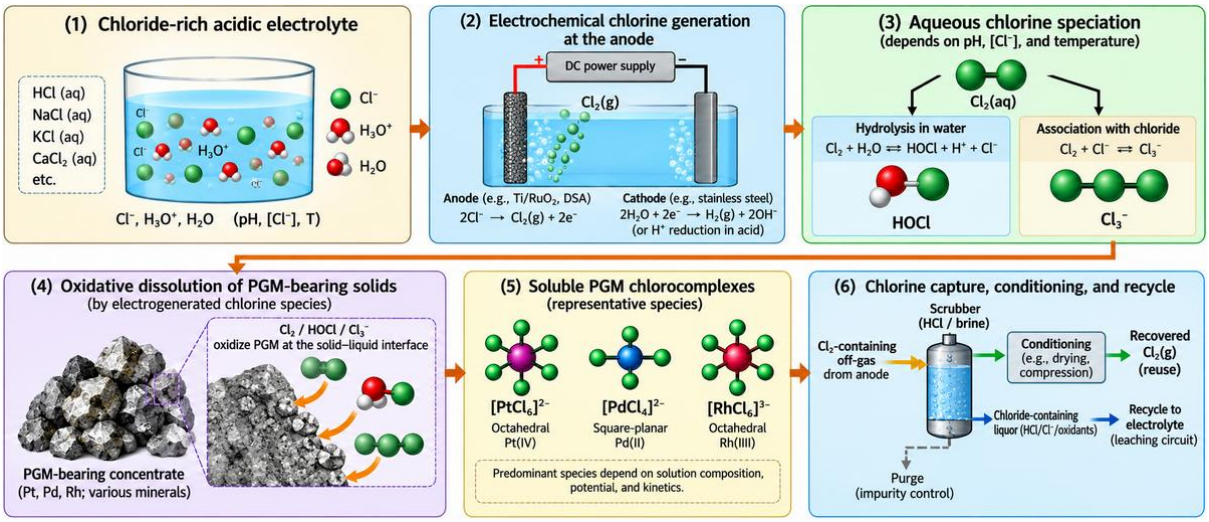

Figure 3. Chloride-based electrogeneration and PGM chlorocomplex formation.
Note. Original conceptual diagram developed for this review from the mechanisms discussed in the cited literature; not reproduced or adapted from a specific published figure.

The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

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Table 2 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 2. Key chemical actors in electro-assisted chloride circuits

Species/couple	Beneficial function	Primary caveat
Cl^- / Cl_2 / HOCl	Oxidant generation and complexation	Gas emissions and speciation shifts
Fe^{2+} / Fe^{3+}	Potentially recyclable oxidizing shuttle	Impurity buildup and Fe coprecipitation
Ce^{3+} / Ce^{4+}	High-potential oxidizing mediator	Reagent losses, acidity, and cost
Cu^+ / Cu^{2+}	Electron-transfer mediator candidate	Cu contamination and downstream load

Note. Illustrative redox roles; the ability to dissolve a particular PGM must be established experimentally under specified ligands, pH, and potential.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

5.2 Chlorine accounting and closed-loop claims

Mass balance must account for chloride in fresh feeds, leach solution, wash streams, solid residues, off-gas capture, and purge. Claims of chlorine-free emission or zero discharge cannot follow solely from electrogeneration: volatilization, membrane crossover, and electrolyte accumulation require measurements. The preferred operating envelope balances oxidant flux against capture capability and selective complex formation.

High chloride concentrations may stabilize dissolved chlorocomplexes but also shift chlorine/HOCl distributions and increase materials-of-construction demands. Oxidant generation, transfer into slurry, chemical consumption, off-gas stripping, and destructive cathodic reactions must be represented as separate fluxes. Studies relying on externally dosed chemical oxidants offer conditional chemical context, not proof of electrogeneration. (Abo Atia et al., 2021; Cui et al., 2023; Cui et al., 2024; Demarco et al., 2020; Forte et al., 2020; Geiger et al., 2015; Kim et al., 2025a; Kim et al., 2025b).

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6. Electrogenerated Oxidants and Redox Mediators

6.1 Mediator generation and regeneration

Fe, Cu, and Ce redox pairs can relocate oxidation from the electrode surface to the dispersed solids. Mediator cycling may make nonconductive feeds accessible, but high mediator current efficiency is not equivalent to high PGM extraction efficiency. Measure the oxidation step independently of subsequent chemical consumption and irreversible side reactions.

Figure 4 illustrates a representative mediated redox loop; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

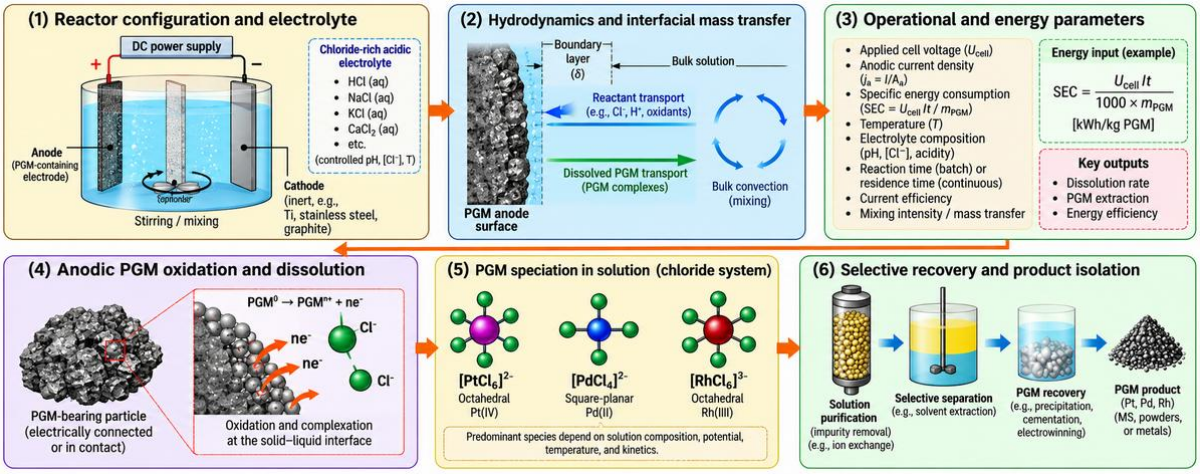

Figure 4. Regeneration and consumption of a soluble oxidizing mediator.
Note. Original conceptual diagram developed for this review from the mechanisms discussed in the cited literature; not reproduced or adapted from a specific published figure.

The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

Table 3 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 3. Minimum reporting for electrogenerated oxidants

Quantity	Preferred measurement	Interpretation

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Total transferred charge	Time-integrated current	Electrical reagent input
Useful oxidant produced	Species-resolved chemical assay	Oxidant generation yield
Oxidant consumed by PGMs	Oxidant and elemental balances	Useful chemical allocation
Crossover and gas release	Separate compartment and exhaust analysis	Reagent and safety losses

Note. Original assessment matrix; reaction stoichiometries must be defined for each actual redox couple.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

6.2 Mediator degradation and crossover

A separator can prevent cathodic destruction of an anodically generated oxidant, but adds electrical resistance, membrane fouling, and maintenance demand. The evaluation must therefore compare total circuit electricity and replacement costs, not only higher instantaneous oxidant concentration in a divided cell.

Mediator feasibility depends on turnover rather than merely the formal potential of the oxidized species. The oxidation current must be reconciled with mediator accumulation, decomposition, crossover, PGM oxidation, and impurity oxidation. Ce(IV), Fe(III), and copper-based shuttles differ in acidity, chloride complexation, precipitation risk, and downstream purification burden; none is universally superior. (Berretti et al., 2022; Chung et al., 2024; Kasuya et al., 2022; Khanipour et al., 2020; Lopes et al., 2020).

7. Metal-Specific Dissolution and Feed Interactions

7.1 Platinum and palladium

Pt behavior is strongly influenced by transient surface oxidation and reduction, and electrochemical corrosion studies provide mechanistic insight but do not guarantee efficient bulk leaching. Pd can show distinct dissolution and coordination behavior, and therefore needs

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its own kinetic and mass-balance model. Bulk Pt/Pd extraction ratios cannot be predicted safely from standard potentials alone.

7.2 Rhodium, other PGMs, and galvanic effects

Rh is often a particularly challenging component because of slow ligand exchange, resistant surface states, and heterogeneous encapsulation. Observations on Ru, Ir, or alloyed nanoscale catalysts can clarify potential-controlled dissolution but should not be projected unchanged to real Rh-rich washcoats. Mixed-metal galvanic coupling also changes when conductive contact is absent.

Table 4 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 4. Element-specific interpretation of electro-assisted dissolution

Metal	Dominant interpretation issue	Required discriminating evidence
Pt	Oxide-mediated dissolution and redeposition	Potential-cycle dependence and Pt balance
Pd	Variable aqueous complexation and oxidation	Speciation and Pd-resolved kinetics
Rh	Low accessibility and kinetic inhibition	Residual phase mapping and Rh-specific balance
Ru / Ir	Possible passivity and oxidized species	Safe speciation and electrochemical verification

Note. Mechanistic comparison rather than universal ranking; Os is excluded from proposed bench testing because potentially hazardous volatile Os oxides require dedicated safety control.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

Reported dissolution behavior is element- and matrix-specific: Pt passivation/oxide transients, Pd coordination chemistry, and kinetically resistant Rh cannot be collapsed into a bulk “PGM recovery” value. Residual elemental mapping and element-resolved kinetics are necessary before concluding that improvements for Pt apply to Rh-rich spent catalysts. (Bawari

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et al., 2023; Briega-Martos et al., 2024; Furuya et al., 2015; Ranninger et al., 2021; Ranninger et al., 2022; Sandbeck et al., 2019; Sandbeck et al., 2020; Zlatar et al., 2025).

8. Electrode Materials and Cell Architecture

8.1 Anode, cathode, and separator choice

Graphite, metal-oxide-coated titanium, and dimensionally stable anodes differ in chlorine evolution selectivity, chemical durability, surface fouling, and cost. Platinum-bearing electrodes create a specific analytical risk: their own dissolution may contaminate measured PGM values. Check for cathodic redeposition and reduction of reactive chlorine, particularly in undivided cells.

Table 5 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 5. Electrode and cell selection criteria

Design variable	Potential benefit	Validation requirement
Anode coating	Selected oxidant generation	Corrosion and active-area stability
Divided compartments	Lower cathodic oxidant loss	Membrane resistance and crossover
Gap and flow	Lower ohmic losses; higher transfer	Residence-time and distribution mapping
Slurry conductivity	Effective current transport	Short circuits and solids abrasion

Note. Conceptual engineering selection table; no universal optimal electrode is asserted.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

Cell architecture governs both selectivity and long-term cost. A membrane can suppress oxidant destruction at the cathode, but its voltage penalty and fouling susceptibility may outweigh the chemical savings. Electrode erosion is especially consequential when the electrode itself contains a PGM: reagent recovery assays may otherwise overestimate feed

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dissolution. (Diac et al., 2020; Ehelebe et al., 2021; Guillet et al., 2024; Sandbeck et al., 2019; Sandbeck et al., 2020; Schalenbach et al., 2018).

9. Dissolution Kinetics, Mass Transfer, and Current Distribution

9.1 Reaction and transport limitations

Overall extraction can be controlled by external liquid-film transport, diffusion through washcoat pores, chemical surface conversion, or electron transfer. The observed limiting step may change during a batch because reacted outer layers expose new phases while pores clog with insoluble products. Comparing fitted shrinking-core parameters without independent microstructural evidence risks false mechanistic attribution.

Figure 5 illustrates serial and parallel limitations governing observed leach kinetics; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

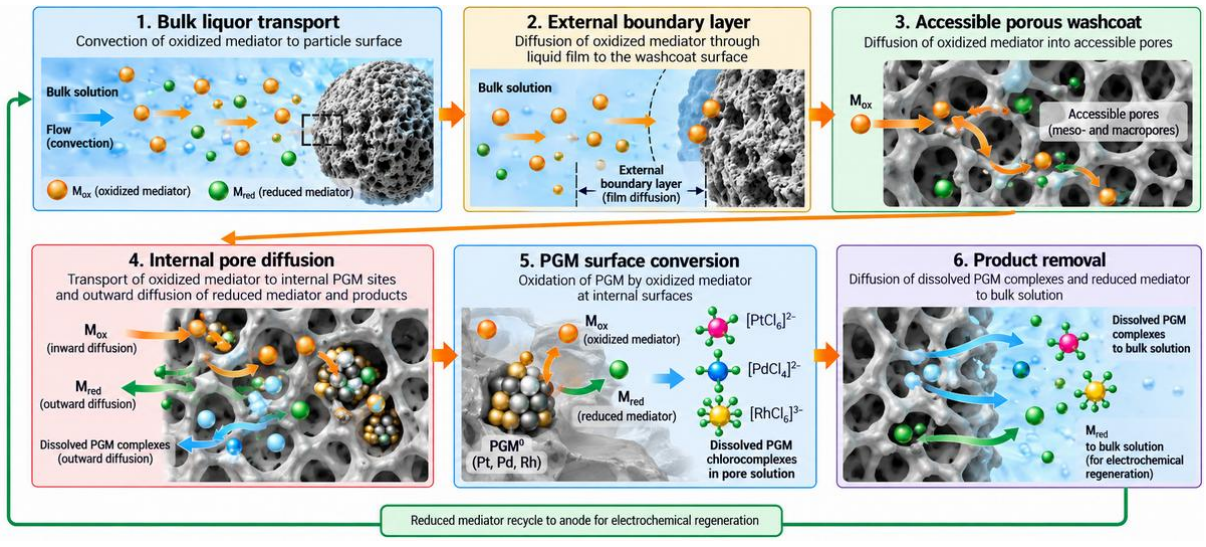

Figure 5. Mass-transfer and surface-conversion resistances in a porous catalyst particle.
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The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

9.2 Current distribution and reactor hydrodynamics

Current does not distribute uniformly over rough, aging electrodes; local bubble coverage and electrolyte resistivity distort effective area. For particulate feeds, mixing should be selected to suspend solids and supply oxidant while limiting electrode abrasion. A controlled-potential trial should therefore report bulk and local observables, rather than interpreting nominal current alone as the actual oxidant supply rate.

Table 6 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 6. Operating variables and competing interpretations

Variable	Useful trend to measure	Main confounder
Current density	Oxidant flux; extraction response	Oxygen evolution and passivation
Chloride concentration	Complexation and conductivity	Chlorine speciation and corrosion
Temperature	Reaction and diffusion acceleration	Gas loss and material degradation
Solids loading	Productivity per reactor volume	Suspension, short circuit, and transport

Note. Changes must be evaluated using matched controls and measured interfacial or mediator chemistry.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

Transient current and shrinking-core fits are ambiguous when dissolution changes particle porosity, washcoat exposure, and bubble coverage simultaneously. Test mechanistic assignments by varying stirring and particle size independently, measuring dissolved oxidant concentration versus time, and analyzing sectioned residual particles rather than relying on fit quality alone. (Atlan et al., 2023; Fuchs et al., 2020; Fuchs et al., 2023; Roiron et al., 2024; Topalov et al., 2014; Xu et al., 2023).

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10. Passivation, Side Reactions, and Charge Efficiency

10.1 Accounting for electrons

The fraction of current reaching useful chemistry can be much smaller than the share of dissolved metal recovered. Competing oxygen evolution, hydrogen evolution, metal re-plating, unwanted electrode corrosion, and oxidant crossover consume charge without adding net product. Report three quantities separately: oxidant-generation Faradaic efficiency, useful oxidant utilization, and recovered-PGM-normalized electrical demand.

Figure 6 illustrates the main desired and parasitic electron sinks; the arrows indicate a conceptual dependency, not a quantified reaction rate or experimentally validated mass balance.

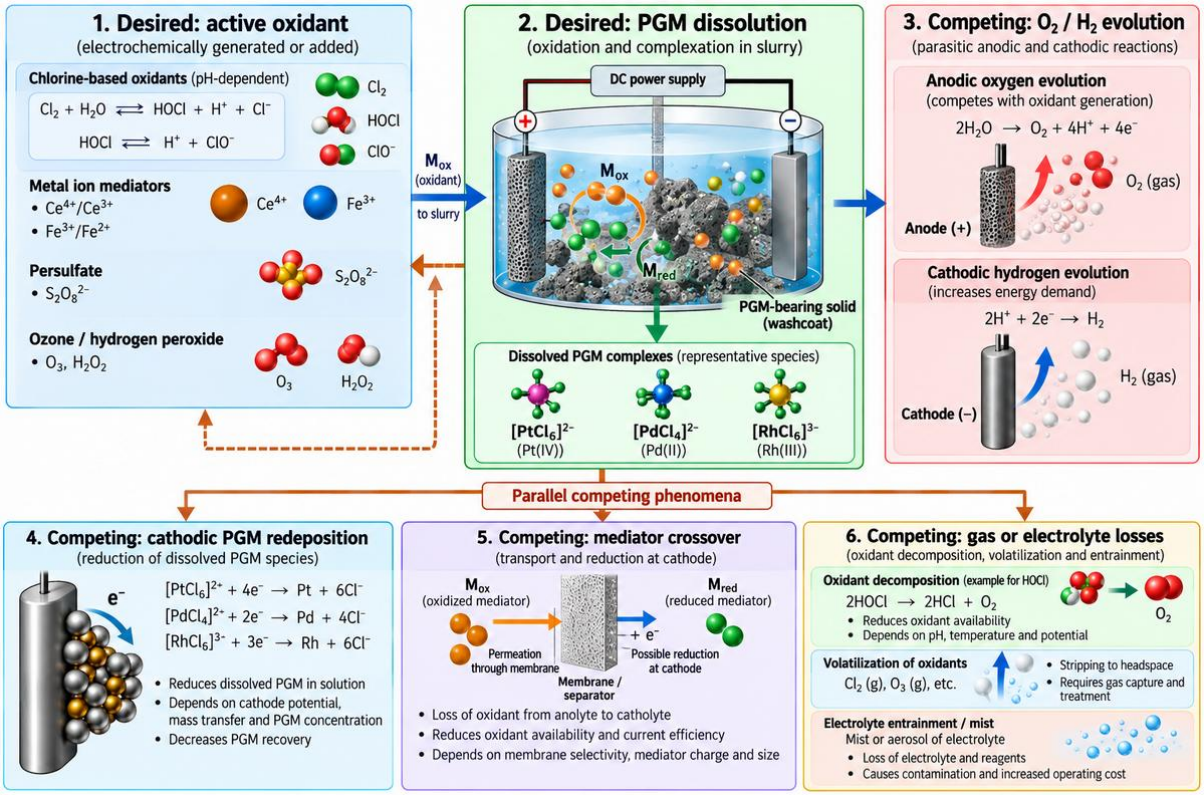

Figure 6. Competing reactions that determine practical electrochemical efficiency.
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The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

Table 7 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 7. Quantitative metrics required for process comparison

Indicator	Definition or unit	Reporting caution
PGM recovery	Recovered metal/feed metal (%)	Include residue and solution closure
Oxidant Faradaic efficiency	Useful oxidant equivalents/charge equivalents (%)	Specify stoichiometry and assay
Specific electric energy	kWh per kg recovered PGM	Use full-cell voltage integral
Charge-normalized dissolution	mol metal / C	Do not assume one oxidation state
Process selectivity	Recovered PGM / impurity dissolution	Specify impurity and product specification

Note. Original proposed metric framework; integrated energy is $\int U(t)I(t)dt$, not necessarily constant UIt.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

10.2 Passivation and deposition

Transiently oxidized noble-metal surfaces can undergo simultaneous dissolution and oxide stabilization. Such countervailing reactions mean that a monotonic increase in applied voltage need not improve net dissolution. Analytical protocols should distinguish true feed dissolution from electrode-origin contamination and particulate reprecipitation.

No single Faradaic efficiency accounts for an indirect circuit. Oxidant-generation selectivity, its useful consumption by a target metal, product recovery, and gross electric input form distinct denominators. A defensible comparison reports the energy integral $\int U_{cell}(t)I(t)dt$ and reconciles the charge equivalents potentially consumed by gas evolution, dissolved impurities, electrode attack, and cathodic destruction. (Cherevko et al., 2015; Cho et al., 2023;

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Fuchs et al., 2020; Fuchs et al., 2023; Geiger et al., 2015; Pavlišič et al., 2018; Tian et al., 2016).

11. Electro-Assisted Processing of Real PGM Feeds

11.1 Automotive and fuel-cell catalysts

Spent automotive catalysts contain PGM particles distributed in ceramic or oxide washcoats; fuel-cell catalysts contain nanoscale Pt on carbon-bearing supports. Particle size, binders, washcoat accessibility, and operating aging differ, so rates measured with polished Pt or virgin nanoparticles are rarely directly transferable. A representative sample must be split for feed assays, controlled chemical leaching, and electro-assisted tests.

Figure 7 illustrates an integrated real-feed verification sequence; the arrows indicate conceptual dependencies, not a quantified reaction rate or an experimentally validated mass balance.

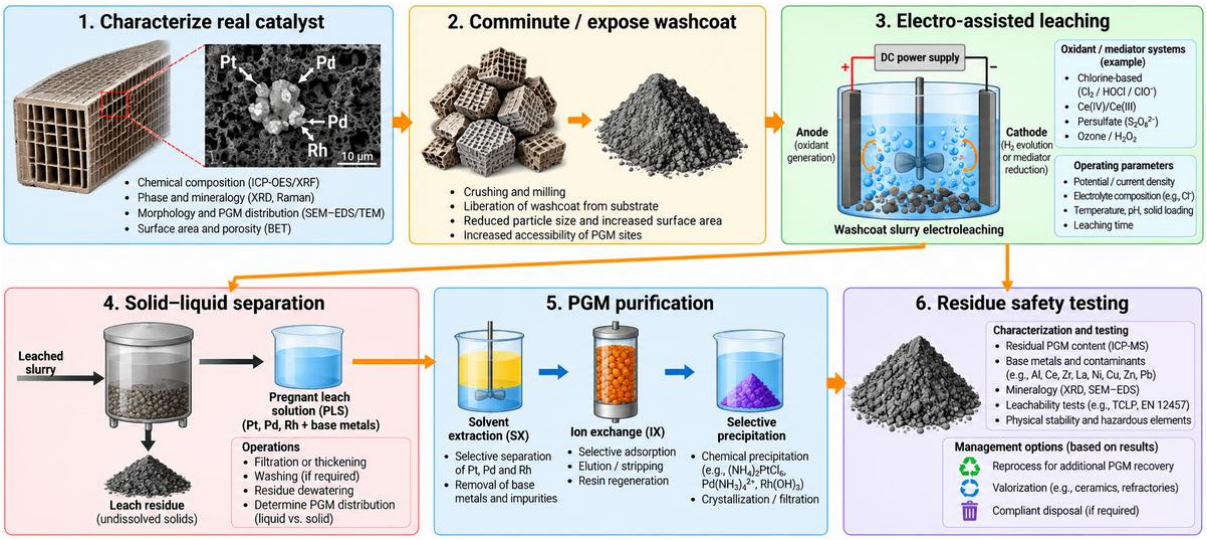

Figure 7. Pretreatment, electroleaching, and elemental closure for spent catalysts.
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11.2 Primary feed, impurities, and pretreatment

Matte and primary concentrates introduce sulfides and base metals that consume oxidants and modify electrolyte chemistry. Pretreatment is justified when it improves actual PGM accessibility without losing PGMs to fines or adding an excessive impurity load. Real-feed evaluation requires elemental deportment to each residue and liquor, plus sufficient replicates to separate analytical uncertainty from process response.

Real catalyst lots differ in washcoat mineralogy, PGM grade, alumina/ceria-zirconia content, and thermal history. Chemical extraction reports and pretreatment studies help bound dissolution chemistry. Still, direct comparisons require a common representative split, an identical assay basis, measured losses during grinding, and elemental closure across liquor, wash, precipitate, and residue. (Chidunchi et al., 2024; Ge et al., 2023; Ilyas et al., 2021; Morcali, 2020; Sharma et al., 2023; Wiecka et al., 2023; Xia et al., 2023; Yakoumis et al., 2020).

12. Reactor Design, Process Integration, and Critical Outlook

12.1 Batch versus continuous configurations

Batch experiments can isolate electrode chemistry, but continuous stirred, flow-through, or recirculating configurations are needed to determine reagent inventory, operational stability, and actual electricity cost. The active electrode area, hydraulic residence distribution, solids holdup, temperature control, membrane replacement, and corrosion management must all be scaled together.

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Figure 8 illustrates a conceptual closed-loop PGM treatment train; the arrows indicate conceptual dependencies, not a quantified reaction rate or an experimentally validated mass balance.

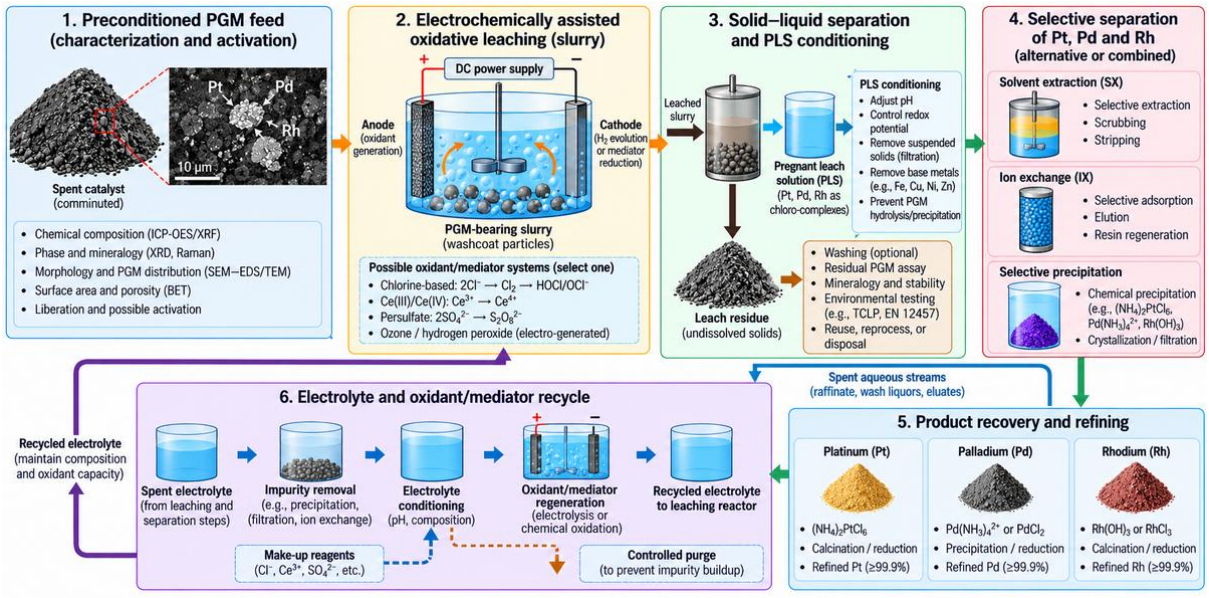

Figure 8. Integrated electroleaching, purification, recovery, and electrolyte recirculation.
Note. Original conceptual diagram developed for this review from the mechanisms discussed in the cited literature; not reproduced or adapted from a specific published figure.

The diagram distinguishes established chemical or electrochemical mechanisms from route-specific assumptions; interpretation requires feed-specific experimental verification.

Table 8 summarizes the principal comparison criteria and the interpretive limitations relevant to this section.

Table 8. Process integration and evidence-to-scale assessment

Circuit element	Data requirement	Scale-up risk
Feed conditioning	Representative assays; liberation	Variable washcoat and PGM grade
Electroleaching	Stable current and oxidant balance	Electrode failure and off-gas containment
Solid-liquid separation	Wash recovery; entrainment	Secondary loss of dissolved PGMs
SX / IX/precipitation	Purity and recovery per element	Competing base metals and reagent load

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Recycle and purge	Salt inventory; impurity accumulation	Gradual chemistry drift

Note. TRL should be assigned only to specifically documented integrated operations; isolated laboratory tests do not establish an overall flowsheet TRL.

These criteria are not a universal performance ranking: interpretation depends on feed assay, operating conditions, reporting boundaries, and the required purified product.

12.2 Specific energy, material balance, and cost

Normalize electricity as the time integral of full-cell power divided by the mass of recovered saleable PGM, not the total mass of leached catalyst. Energy comparison should include auxiliary pumping, agitation, gas handling, and downstream circuits where boundaries permit. Higher leaching recovery has limited value if electrode replacement, acid control, membrane fouling, and refining costs outweigh additional metal revenue.

A quantitative reporting hierarchy distinguishes (i) feed-based extraction, (ii) liquid-to-product recovery, and (iii) overall saleable-metal recovery. The numerator for useful energy performance must be saleable PGM mass, whereas the electrical input is the measured full-cell energy integral. Full material closure includes sampling losses, wash liquors, electrode-derived contamination, purge, captured off-gas, and spent membranes.

12.3 Proposed verification program

A defensible first-stage program would compare an electrochemical treatment with an oxidant-matched chemical control, plus open-circuit and electrode-blank tests. Report Pt, Pd, and Rh separately; full solution-and-solid inventories; current and voltage histories; active oxidant assays; reference-electrode potential; gas captures; and endpoint metal purity. A second stage would test continuous operation, electrode lifetime, purge control, and integrated separation; discuss technology readiness only when documented whole-route evidence exists.

Process integration can reverse a laboratory ranking. The best apparent extraction may demand excessive chloride inventory, oxidant off-gas control, membrane maintenance, or complex polishing of the pregnant leach solution. An integrated route should therefore be

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compared on saleable Pt, Pd, and Rh recovered per tonne of feed; energy per kilogram of recovered metal; reagent makeup; secondary waste; and documented operating hours. (Baleti et al., 2025; Fajar et al., 2021; Gibson et al., 2023; Granados-Fernández et al., 2021; Grilli et al., 2023; Kang et al., 2024; Niu et al., 2024; Pereira, 2026a; Pereira, 2026b; Sun et al., 2022; Sun et al., 2023; Wen et al., 2020).

Priority research design should separate electrical and chemical attribution. A first stage should determine the electron/oxidant balance and selective dissolution on characterized coupons and representative catalyst powders; a second stage should test a recirculating cell with gas capture, variable solids loading, and impurity accumulation; only then should techno-economic comparison and scale-specific maturity be assessed.

13. Conclusions and Future Research Priorities

Electro-assisted PGM dissolution is best interpreted as an electrode–electrolyte–feed interaction rather than an ordinary chemical leach with added current. Its principal potential advantage is the precise location and replenishment of oxidizing capacity, but the benefit depends on metal-specific speciation and material accessibility. Direct anodic corrosion, electrogenerated chlorine, mediator regeneration, and potential control require separate experimental identification.

Future work should prioritize Rh-resolved kinetics, reference-electrode measurements in representative reactors, comprehensive oxidant and chloride balances, Faradaic allocation, and specific energy per kilogram of recovered PGM. Long-duration tests with realistic solids loading and integrated product recovery are essential to distinguish promising chemistry from robust processing. The principal unresolved challenge is demonstrating an improvement over optimized chemical leaching after including full electricity, materials, safety, and downstream burdens.

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