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Iridium Extraction and Recovery from Primary Ores and Secondary Materials: Process Chemistry, Metallurgical Routes, Selectivity, and Industrial Scale-Up—A Critical Review

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Abstract

Iridium is recovered mainly through platinum-group-metal production and specialized secondary-processing circuits, yet its chemical resistance, heterogeneous occurrence, and difficult separation from associated noble metals complicate process selection. This critical review compares primary concentrates, refinery intermediates, industrial catalyst scrap, and end-of-life proton-exchange-membrane electrolyzer components across mineralogical characterization, thermal activation, dissolution chemistry, selective refining, and industrial integration. A structured bibliography covering 1960–2026 contrasts process mechanisms and evidence quality, without interpreting isolated laboratory dissolution as industrial recovery. The synthesis identifies mineral deportment, feed-specific oxidation requirements, chloride-complex speciation, separation from rhodium and ruthenium, and complete-circuit material accounting as decisive variables. Thermochemical and electrochemical strategies offer different trade-offs in selectivity, corrosion, safety, energy intensity, and reagent recirculation. Product specifications, secondary-residue handling, and functional recovery yields must be considered jointly, not inferred from leachate concentration alone. The review proposes a feedstock-first decision framework and reporting criteria to compare routes and identify where independent scale-up evidence remains insufficient.

Keywords: Iridium recovery; Platinum-group metals; Primary resources; Secondary recycling; Selective separation; Process integration

Highlights

- Feed mineralogy and chemical form govern iridium accessibility.
- Dissolution yield alone is not an industrial recovery metric.
- Selective Ir–PGM separation is a central flowsheet bottleneck.
- Evidence quality and closed-loop burdens determine route readiness.

JIRRS
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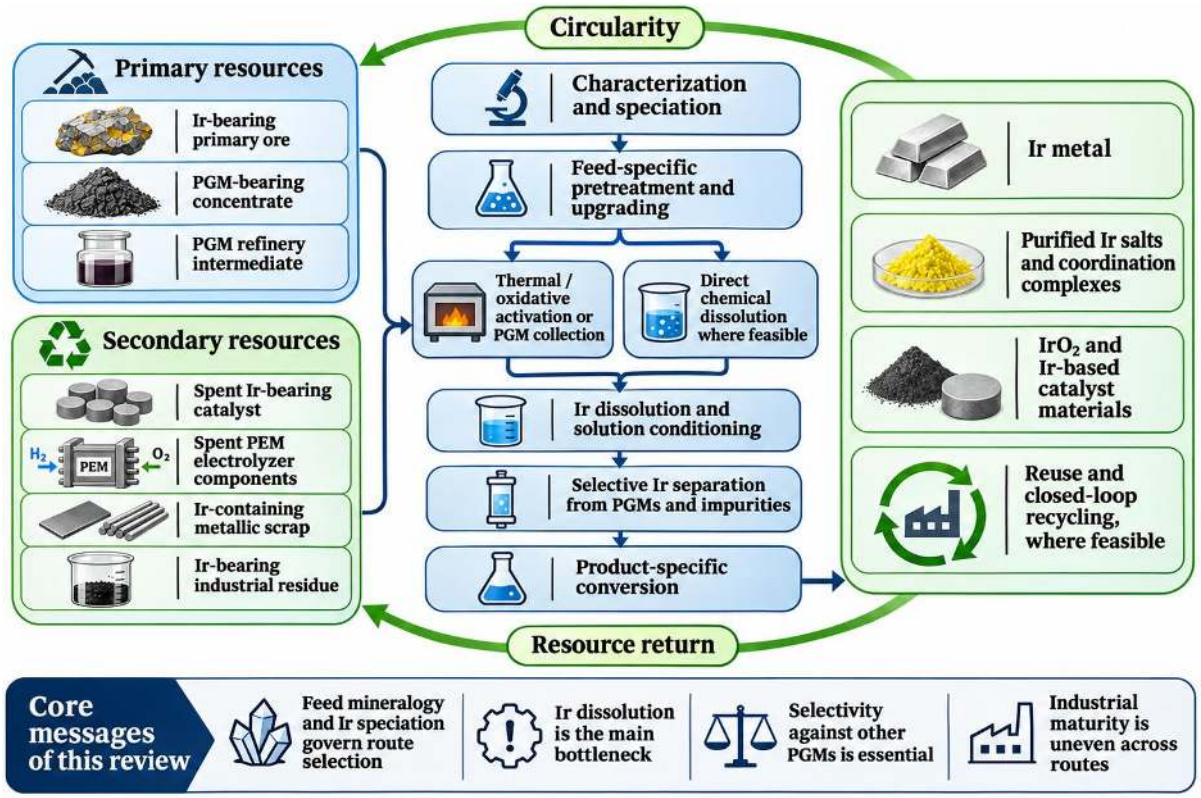
Graphical Abstract



1. Introduction

Iridium has a small, coproduct-dominated supply chain and is increasingly relevant to oxygen-evolution catalysis in proton-exchange-membrane (PEM) electrolysis. Supply risk cannot be reduced to crustal abundance alone: refinery recoverability, competing PGM economics, inventory holding, product specification, and end-of-life collection contribute to available metal (Beamish, 1966; Fu et al., 2026; Minke et al., 2021).

Primary and secondary resources must be evaluated on a common metallurgical basis, but their unit operations differ markedly. In mineral-derived streams, the metal may occur in complex PGM minerals, alloys, or fine inclusions; in manufactured scrap, its phase may be metallic, oxidic, or embedded in multicomponent coatings (Wortmann et al., 2026; Zhen et al., 2025).

This analysis links the mineralogical origin of Ir to the sequence of operations required to obtain a specification-compliant product. Figure 1 and Tables 1 and 2 introduce

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Pages: 1-30

the distinctions between concentrate recovery, dissolution, and final refining that underpin subsequent comparisons.

Unlike broad platinum-group-metal processing reviews, including the author's earlier PGM-wide synthesis (Pereira, 2026d), and Ir-focused discussions emphasizing secondary-resource purification (Fan et al., 2023) or catalyst dissolution chemistry (Ho & Lee, 2026), this review integrates primary and secondary material classes within an explicitly feedstock-first, feed-to-qualified-product framework. Its distinct contribution is to connect Ir deportment and accessibility, activation losses, dissolution, selective Ir/Rh/Ru separation, product-specific conversion, reagent and residue loops, and industrial evidence maturity using comparable mass-balance boundaries; it does not claim that reviewing Ir recovery per se is novel.

2. Review Methodology and Evidence Assessment

The scope follows a thematic critical-review design rather than a claimed exhaustive systematic review. The reference collection spans 1960–2026 and covers mineralogy, primary extraction, secondary feedstocks, dissolution, solvent extraction, electrochemistry, industrial implementation, and life-cycle considerations.

Literature is grouped by feed type, process mechanism, measured endpoint, and evidence level. Claims from a reported single-stage leach test are distinguished from full-circuit recovery, while commercial readiness requires direct industrial operating evidence rather than an inferred technology-readiness level.

Comparisons require consistent denominator definitions: initial Ir inventory, extracted Ir, purified Ir, and saleable product should be separately reported. Studies with incomplete feed assays, unresolved oxidation states, or missing reagent balances cannot support quantitative route rankings.

The bibliography was updated through 9 November 2026 for targeted identification of relevant 2026 publications, including refinery-intermediate chemistry and Rh/Ir separation. Representative search expressions for reproducible updating are (iridium OR Ir) AND (recovery OR refining OR recycling), (iridium AND rhodium) AND (solvent extraction OR separation), and (PEM electrolyzer OR membrane electrode assembly) AND (iridium recycling). This is a thematic narrative synthesis, not a PRISMA systematic review. The

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Pages: 1-30

original search platforms, historical search dates, exact screening counts, citation-chaining history, and full primary-source verification log were not available for independent confirmation during this revision and must be documented by the author before submission; these details must not be retrospectively represented as performed searches.

3. Iridium Geochemistry, Mineralogy, and Resource Characteristics

Iridium deportment depends upon whether the metal resides in natural alloys, sulfide-associated minerals, discrete microinclusions, or refractory grains. A mineralogical assay that reports only total Ir can underestimate the significance of textural locking and overestimate its immediate process accessibility (Cabri, 2023; Chernyshov & Ponamareva, 2015; Engelbrecht et al., 2022).

Automated mineralogy, quantitative phase identification, and targeted microanalytical methods should be linked to process observations. Key variables include mineral association, occurrence frequency, particle size, liberation, and behavior under flotation, matte smelting, and downstream refiner conditions (Garuti et al., 2012; Mohamed et al., 2021; Pereira, 2026c).

For a feed F divided among mineralogical or processing fractions k, Ir deportment may be defined as $D(Ir,k) = [m(k) \times C(Ir,k)]/[m(F) \times C(Ir,F)]$, where m is the dry mass and C is the Ir mass fraction on a consistent basis. The fractions should sum to unity within analytical uncertainty when the material balance is closed. Phase identity, abundance, association, liberation, grain size, and the share of total Ir inventory should accompany this calculation.

Table 1 separates resources by matrix and uncertainty; Table 2 connects representative phase types to likely recovery restrictions. These are conceptual comparisons, not universal ore-specific grade estimates (Stepanov et al., 2020; Taghipour & Ahmadnejad, 2018; Tertipis & Beamish, 1963).

Table 1. Resource classes and the principal uncertainties affecting Ir recovery.

Resource	Ir occurrence/matrix	Critical uncertainty
PGM ore	PGM minerals, alloys, fine inclusions	Liberation and deportment
PGM refinery intermediate	Complex mixed-metal solids	Individual Ir inventory
Spent industrial catalyst	Supported metallic/oxide particles	Substrate and poisons

JIRRS
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Resource	Ir occurrence/matrix	Critical uncertainty
PEM catalyst layer	Ir-based oxide in membrane-electrode assembly	Layer separation and losses

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

Table 2. Chemical forms and expected processing implications.

Form	Process issue	Evidence required
Ir metal / alloy	Resistance to dissolution	Surface chemistry, oxidant demand
IrO_2-rich oxide	Oxidation-state-dependent stability	Pretreatment and dissolution kinetics
Chloridoiridate solutions	Complexation and redox speciation	Cl activity and solution conditions
Mixed PGM precipitate	Competitive separations	Mass balance and purity

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

4. Primary Iridium Resources: Mining, Beneficiation, and Metallurgical Recovery

Primary Ir is commonly accessed through PGM-bearing ores and intermediate refinery products rather than dedicated iridium-only mining. The economic objective of flotation and smelting is generally to concentrate a suite of valuable metals and transfer them into refinery streams that permit subsequent impurity rejection.

Collector selection, mineral liberation, matte/slag partitioning, and base-metal removal all influence subsequent Ir availability. A metallurgical flowsheet that maximizes bulk PGM recovery may not maximize the recoverability of a specific minor constituent, particularly when associated phases partition differently.

Figure 1 presents the logical sequence from ore concentration to selective refining. Table 3 identifies the information needed to distinguish a real material balance from a simplified process diagram.

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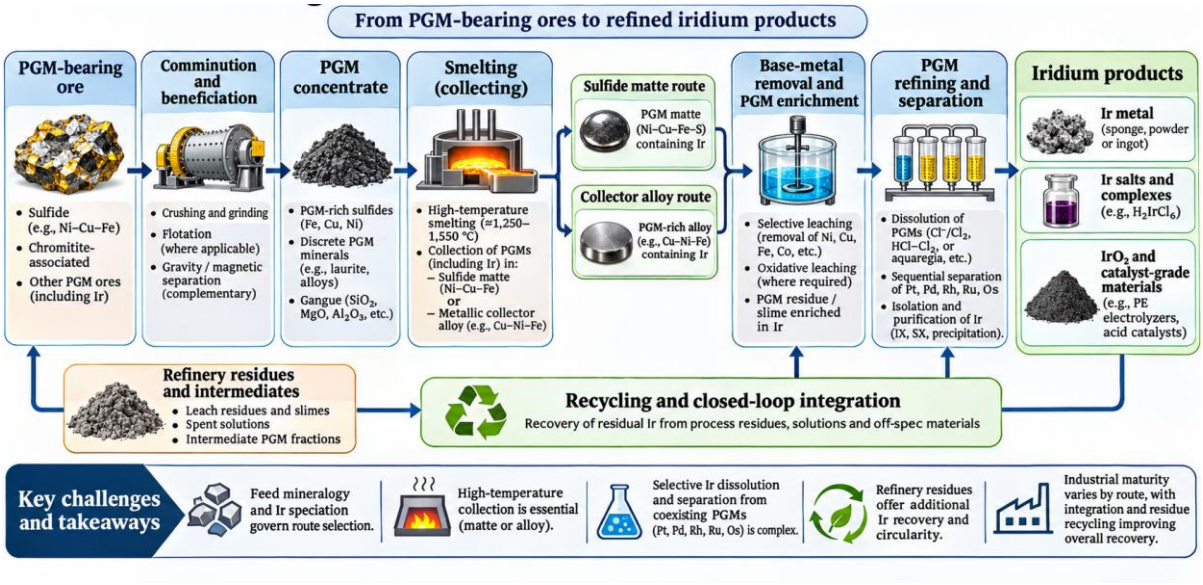

Figure 1. Integrated primary iridium recovery flowsheet and principal metal-loss control points.
Note. Original AI-assisted conceptual illustration prepared for this review; representative pathways are illustrative and do not depict a validated commercial flowsheet. Final journal-policy compliance and image-asset rights require author confirmation.

The flowsheet is intentionally simplified: individual mineral operations and refinery separations depend on feed-specific assays, product specifications, and accountable losses.

The existence of commercial primary PGM refining does not, by itself, establish publicly documented Ir-specific recovery at each stage. Publicly accessible, reconciled Ir balances across ore, concentrate, matte or collector, refinery intermediate, and saleable Ir products are comparatively scarce. Consequently, primary-route comparisons in this review are qualitative unless supported by independently reported, element-specific assays and loss inventories; numerical recovery rankings are not inferred from bulk PGM performance.

Table 3. Primary-route unit operations and essential Ir reporting.

Stage	Purpose	Required measurement
Flotation	PGM preconcentration	Ir distribution by product
Smelting	Collector/matte concentration	Ir in matte, slag, dust
Base-metal refining	Removal of major impurities	Ir in intermediates
PGM separation	Ir purification	Ir product recovery and purity

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

5. Secondary Iridium Resources: Sources, Characterization, and Pretreatment

Secondary feedstocks range from relatively concentrated production scrap to low-loading catalyst layers on polymeric or metallic supports. The substrate composition,

JIRRS
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Pages: 1-30

coatings, binders, and co-deposited metals determine whether direct dissolution, delamination, thermal treatment, or prior concentration is appropriate (Chen et al., 2023; Cherepakhin & Williams, 2024; Du et al., 2025).

End-of-life PEM components merit careful inventory definition because metal dissolved during operation, metal retained in catalyst particles, and metal embedded in membranes may require different recovery operations. Recycling reports should explicitly define the collection boundary and residual Ir in ancillary process streams. (Grilli et al., 2023; Ho & Lee, 2026; Hughes et al., 2021).

Figure 2 traces a simplified secondary-process decision pathway. A pretreatment method is not intrinsically preferable merely because it lowers dissolution time: entrainment, emissions, contamination, and losses to pretreatment residues must be included. (Ibrahim & Eggert, 2026; Jacinto et al., 2012; Karim & Ting, 2021).

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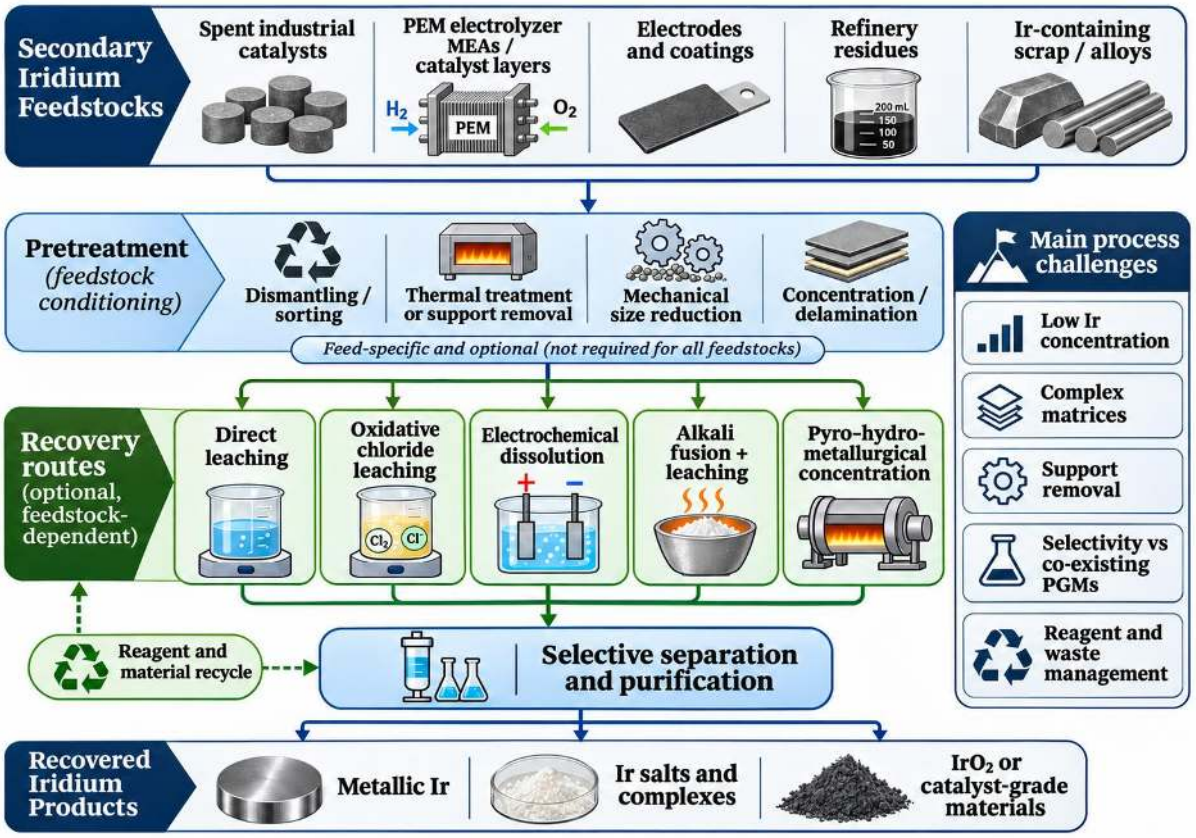

Figure 2. Secondary iridium recovery pathways, including feedstock conditioning and alternative treatment routes.

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The central decision is whether a feed can be dissolved directly or must first be concentrated or selectively activated. This choice must be based on the actual support and coating composition.

Secondary evidence is most informative when it states the physical form of Ir alongside the substrate and impurity inventory. Without those descriptions, a reported extraction percentage cannot be attributed confidently to a dissolution mechanism (Leon-Fernandez et al., 2026; Liu et al., 2021; Liu et al., 2026).

Dismantling losses and the Ir retained in spent supports must be counted before a leaching efficiency is used in a process balance. Recovery figures based only on the treated fraction may systematically overstate recovery from the received waste (Ma et al., 2026; Marinho et al., 2010; Mashiya et al., 2026).

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Pretreatment can reduce the mass delivered to leaching but also redistribute Ir between fines, liberated coatings, and discarded structural components. Sampling those fractions is a prerequisite for comparing alternative flowsheets (Nguyen et al., 2021; Otgonbayar et al., 2024; Paiva, 2017).

Studies comparing dissimilar secondary streams should use common boundaries rather than a single headline yield. The appropriate denominator is the Ir initially present in the collected feed, not merely the mass transferred into the dissolution reactor (Peng et al., 2017; Pereira, 2026d; Ryan et al., 2026).

Catalyst-layer recycling requires additional attention to membrane polymers, ionomers, and metallic supports. Removing them changes reagent demand and may introduce contaminants not found in concentrated metallic scrap (Son & Sohn, 2021; Son, 2025; Tang et al., 2023).

For PEM-derived streams, graded recovery can distinguish direct component reuse, reclamation of electrode or catalyst functions, and full elemental extraction. This hierarchy is a feed- and performance-dependent decision rather than evidence that any one recycling route is universally preferable (Ma et al., 2026).

Processing routes designed for individual materials cannot be assumed to tolerate mixed waste without additional separation stages. This matters particularly when the desired Ir product must satisfy catalyst-precursor purity limits (Wang et al., 2026; Wen et al., 2023; Xia & Ghahreman, 2023).

For any proposed circular route, the decisive demonstration is a reconciled balance of Ir across product, recycled liquors, solid residues, and purge streams. Recovery without disclosure of these outlets remains a partial-process result (Yakoumis et al., 2021; Ye et al., 2025; Zupanc et al., 2023).

Accepted-feed recovery must be distinguished from reactor-level extraction. Define $R(Ir,overall)\ (\%) = 100 \times m(Ir \text{ in qualified saleable products})/m(Ir \text{ in accepted end-of-life feed})$. The accepted-feed inventory includes Ir subsequently lost during dismantling, delamination, support removal, attrition and fines collection, thermal conditioning, washing, leaching, selective separation, stripping, precipitation, and finishing. Where direct reuse or regenerated catalyst is qualified for an intended service, the same accepted-feed denominator

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Pages: 1-30

defines functional recovery, R(functional) (%) = 100 × m(Ir in qualified reusable products)/m(Ir in accepted feed). Dismantling residues and all other losses are measured separately, not excluded by shifting the process boundary.

6. Thermodynamic, Chemical, and Kinetic Fundamentals of Iridium Dissolution

The high resistance of Ir metal and certain oxidized forms creates a distinction between possible equilibrium speciation and practical dissolution rates. Strongly oxidizing chloride chemistry may stabilize soluble species, yet real rates remain conditional on surface structure, electrochemical potential, transport, and passivation. (Biata et al., 2020; Chung et al., 2024; Dam et al., 2025).

Interpret oxidation states without directly transferring trends from Pt, Pd, or Rh to Ir. Ionic strength, chloride activity, hydrolysis, oxidant decay, and changes in metal valence can influence extraction or adsorption in later unit operations. (Hodgson et al., 2017; Ka et al., 2025; Kobayashi et al., 2019).

Figure 3 places oxidation/complexation, interfacial kinetics, and product separation in one causal chain. Mechanistic studies that do not close the metal inventory cannot establish a corresponding refinery yield. (Kong & Chai, 1990; Lee & Kim, 2011; Li et al., 2024).

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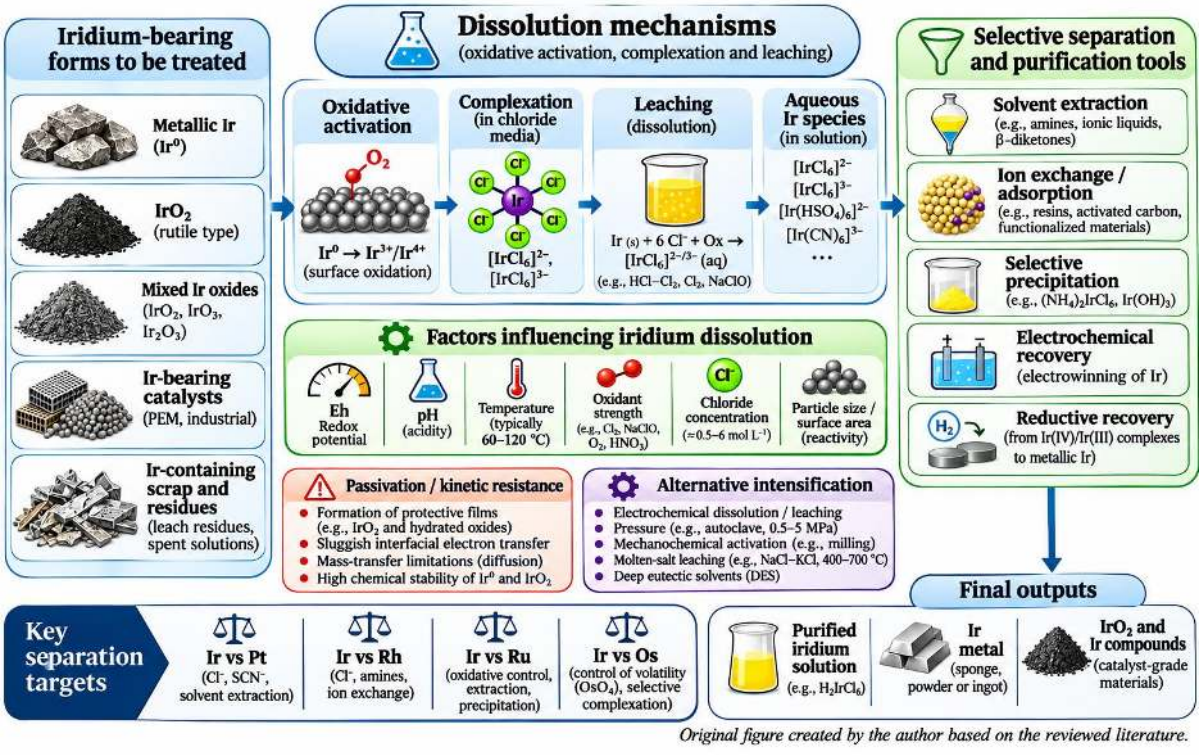

Figure 3. Iridium dissolution mechanisms and downstream selective separation strategies.
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A concentration change in solution is not necessarily a measurement of net Ir extraction: sampling, precipitation, adsorption, and losses must be reconciled.

A dissolution yield is Y(diss) (%) = 100 × m(Ir transferred to solution)/m(Ir entering the dissolution step), whereas the accepted-feed recovery denominator includes all upstream losses. Dissolved concentration alone does not validate species distribution: oxidation state, solution redox potential, acidity, chloride activity, ionic strength, water activity, temperature, counterions, and coexisting metals affect speciation and downstream extraction. Nominal HCl concentration should not be equated to thermodynamic chloride activity in concentrated multicomponent media.

7. Pyrometallurgical and Thermal Activation Routes

Thermal activation can increase subsequent chemical accessibility or concentrate noble metals in selected phases. Alkali fusion, reactive chlorination, oxidizing roasting, and collector-metal treatment should be understood as distinct chemical strategies rather than interchangeable methods (He et al., 2024; Yoshimura et al., 2024).

JIRRS
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Pages: 1-30

Industrial selection must account for matrix chemistry, refractory compatibility, off-gas capture, volatilization risk, and the potential to convert undesirable impurities into downstream solution contaminants. A high laboratory dissolution fraction after thermal treatment does not by itself establish the preferred route.

An activation-step Ir balance requires m(Ir, feed) = m(Ir, activated solids) + m(Ir, dust) + m(Ir, gas/condensate) + m(Ir, other outlets), within measurement uncertainty. Off-gas capture and trace-metal accounting are particularly important for high-temperature treatment and reactive chlorination; we assume no unmeasured volatile Ir loss.

Table 4 contrasts the key burdens of activation routes and highlights the need for complete gas and residue balances.

Table 4. Comparative functions and constraints of activation routes.

Route	Principal objective	Dominant constraint
Collector smelting	Concentrate dispersed PGM	Slag/dust losses; energy
Alkali fusion	Alter chemical accessibility	Reagent load and solids washing
Oxidative roasting	Adjust phase chemistry	Volatilization and gas treatment
Reactive chlorination	Enable chloro-complex formation	Corrosion and chlorine management

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

8. Hydrometallurgical Recovery and Dissolution Technologies

Acidic chloride oxidizing systems, electrochemical dissolution, and alternative solvents address different feed states. Surface oxidation, complexation, temperature, effective reagent activity, and particle-scale access may jointly govern recovery, while pre-reduction or pretreatment can change the apparent selectivity (Alexiou et al., 2026; Heshmatpour & Heestand, 1985; Kim & Ahn, 2025).

The most defensible comparison distinguishes a primary Ir solid from IrO_2 catalyst layers, mixed PGM residues, and organometallic scrap. Reagent consumption per unit feed often obscures the actual cost of a trace-metal recovery process; normalization per kilogram of recovered Ir is more useful when mass balances are available. (Moriau et al., 2023; Rzelewska-Piekut et al., 2021; Saguru et al., 2018).

To compare reagent burdens on a common product basis, define I(reagent) = m(fresh reagent)/m(Ir in qualified saleable product) and I(oxidant) = m(fresh oxidant)/m(Ir in

JIRRS
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Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

qualified saleable product), expressed in kg/kg. Report gross recirculating flow separately from fresh make-up, purge, solvent degradation, and impurity accumulation. A large internal recycle volume does not demonstrate low net reagent intensity or a closed mass balance.

Table 5 presents a reporting framework for leaching comparisons without manufacturing unreported experimental values. (Sato et al., 2024; Sharma et al., 2025).

Table 5. Minimum comparability criteria for Ir leaching studies.

Variable	Report	Reason
Feed assay	Ir and accompanying metals	Valid extraction denominator
Chemical system	Acidity, Cl^-, oxidant concentration	Reproducible speciation
Conditions	T, time, S/L, particle size	Rate and mass-transfer context
Outputs	Ir in solution, solid, losses	Mass closure
Downstream	Recovery after purification	Industrial relevance

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

9. Selective Separation, Purification, and Final Iridium Products

Evaluate separation mechanisms under prevailing chloride activity and oxidation-state distributions. Historical liquid-anion-exchange and solvent-extraction studies establish the sensitivity of Ir–Rh partitioning to solution chemistry. In contrast, modern process studies must additionally resolve stripping, solvent stability, and impurity accumulation. Accordingly, apparent selectivity from a synthetic binary solution cannot be equated with performance in a multi-PGM refinery liquor (Kanert & Chow, 1974; Kanert & Chow, 1975; Carrick et al., 2024).

Dissolving Ir is only an intermediate step. Selective extraction, ion exchange, precipitation, and electrodeposition must address strong chemical similarities among PGM ions while respecting differences in redox chemistry and complex stability. (Al-Bazi & Chow, 1984; Beamish, 1960; Beamish, 1967).

Competition among Ir, Rh, Ru, Pt, and Pd creates a circuit-design problem: extraction capacity, phase disengagement, loaded-organic cleanup, stripping, recycling, and final product contamination are interconnected. Published separation factors are conditional on the exact aqueous medium and should not be transferred between matrices without verification. (Carrick et al., 2024; Desai & Shinde, 1979; Diamantatos & Verbeek, 1977).

JIRRS
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Pages: 1-30

For solvent extraction, D(Ir) = C(Ir, organic)/C(Ir, aqueous) under the specified equilibrium conditions, and the separation factor against metal M is beta(Ir/M) = D(Ir)/D(M). These ratios require stated phase composition, oxidation state, acidity, chloride activity, and loading. They do not translate to commercial yield without stripping efficiency, phase disengagement, solvent loss, organic stability, regeneration, and impurity build-up. Ion-exchange comparisons likewise require dynamic capacity, breakthrough, loading rate, elution, and multicycle regeneration; single-contact removal from synthetic binary solutions cannot predict multimetal refinery behavior (Carrick et al., 2024; Zhou et al., 2026).

Table 6 distinguishes technologies by controlling mechanism, operational burden, and the residual evidence needed for product-grade demonstration (El-Maghrabey et al., 2026; Fan et al., 2023; Fan et al., 2022).

An emerging product-directed example is isolating crystalline $K_2[Ir(OH)_6]$ from both defined chloroiridate salts and crude refinery chloroiridate streams, then converting it into selected Ir(III) coordination compounds (Willans et al., 2026). This demonstrates a plausible route from mixed refinery intermediate to a compositionally defined platform intermediate and application-specific products, rather than requiring metallic Ir as the default endpoint for every circuit. It is not evidence of a universally validated continuous industrial flowsheet. Recent ionic-liquid reviews also underline the need for regeneration, chemical stability, and realistic multimetal-feed data before claims of scale-up readiness (El-Maghrabey et al., 2026).

Table 6. Selective refining options and principal decision criteria.

Method	Primary selectivity basis	Key limitation
Solvent extraction	Complex affinity/redox state	Strip and organic stability
Ion exchange	Resin sites and chloride complexes	Breakthrough/regeneration
Selective precipitation	Solubility and oxidation state	Coprecipitation
Electrodeposition	Electrochemical potential	Side reactions/product purity

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

10. Integrated Processing Flowsheets and Industrial Technology Readiness

An integrated circuit should trace feed receipt, pretreatment, activation, dissolution, impurity management, Ir-rich intermediate recovery, refining, and product conditioning. Any claim of commercial feasibility requires an identified materials boundary, product purity

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requirement, and management of secondary residues (Hudson & Thorns, 1983; Pereira, 2026d, 2026e).

A particularly important accounting distinction is between metal extraction and product recovery: R_total = R_pretreatment × R_dissolution × R_separation × R_finishing, where each recovery is a dimensionless fraction calculated on its own appropriate inlet. This expression is a bookkeeping identity for sequential non-recycling stages, not a reported process yield (Sinisalo & Lundström, 2018; Williams et al., 2026).

For an individual non-recycling stage, yield is defined on its own inlet Ir inventory, so the product of fractional step recoveries is a bookkeeping identity only for strictly sequential non-recycling paths. With recycle, purge, bypass, and repeated extraction, overall recovery must instead be obtained from a reconciled network: R(Ir, overall) (%) = 100 × Σm(Ir in qualified final products)/m(Ir in accepted feed). Industrial operation on one feed does not establish performance on another, and neither publication wording nor the existence of a commercial PGM refinery independently demonstrates an Ir-specific numerical TRL or stagewise Ir recovery.

Figure 4 classifies primary and secondary iridium resources by material origin and highlights feed-specific criteria relevant to technological screening. Table 7 distinguishes laboratory concepts from industrial evidence.

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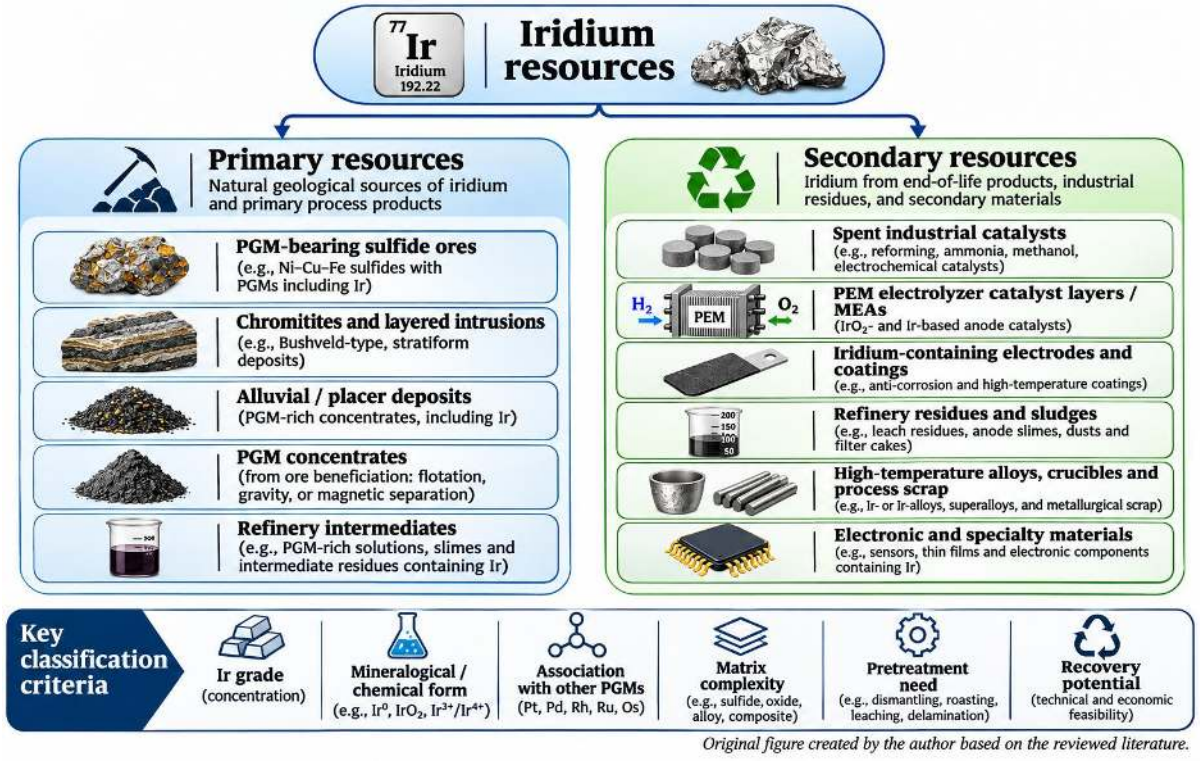

Figure 4. Classification of primary and secondary iridium resources and key feedstock-screening criteria.

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The evidence framework does not assign a technology readiness level automatically: site-specific pilot and commercial records are required for such a determination.

Table 7. Evidence thresholds for Ir recovery process assessment.

Evidence level	What it demonstrates	What it does not establish
Bench chemistry	Feasibility on tested material	Industrial operability
Continuous pilot	Selected stability and recycle behavior	Commercial economic performance
Commercial operation	Performance under documented conditions	Transfer to dissimilar feeds

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

11. Techno-Economic Assessment, Environmental Performance, and Circularity

Because Ir may be a minor constituent of a multi-metal feed, allocating mining, smelting, reagent, and refinery burdens matters. Primary-versus-secondary comparisons can reverse when transport, pre-concentration, support removal, oxidant consumption, wastewater

JIRRS
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DOI: 10.66104/weke5g87
Pages: 1-30

treatment, and coproduct credits are treated inconsistently (Bossi & Gediga, 2017; Wei et al., 2024).

A techno-economic assessment should identify the production basis, recovery yield, commodity-value assumptions, reagent recycle, utility intensities, equipment corrosion allowance, waste disposal, and sensitivity to throughput. A life-cycle assessment should report the system boundary and functional unit, not only a headline energy or emissions reduction.

Transparent TEA reporting also requires a defined cost year and currency, geographic location, plant design throughput, accepted-feed Ir grade, product specification, project lifetime, discount rate, and uncertainty bounds. At minimum, low/reference/high Ir-price scenarios and, where applicable, coproduct-PGM price sensitivities should be tested. Utility requirements, corrosion-resistant construction, solvent replacement, waste-treatment costs and net fresh-reagent demands must be included rather than assuming internal circulation is free of cost.

Table 8 defines the information needed for a transparent comparative environmental and economic synthesis.

Table 8. Functional indicators and disclosure requirements.

Indicator	Preferred basis	Boundary to disclose
Overall Ir recovery	% of Ir in accepted feed	All solids/liquids and product
Specific oxidant use	kg/kg Ir recovered	Make-up vs recycle
Electricity/fuel	kWh or MJ/kg Ir recovered	Allocated unit operations
Residues	kg/kg Ir recovered	Class and disposal route
Climate impact	kg CO_2-eq/kg Ir recovered	LCA allocation and credits

Note. The table is an original qualitative synthesis; conditions and efficiencies vary with feed and must be confirmed in primary publications.

Comparative LCA should define a common functional unit (for example, kg CO_2-equivalent per kg of qualified Ir product), matched product quality and consistent system boundaries. Primary-production results depend on how mining and refinery burdens are allocated among coproduced PGMs and other metals (mass, economic allocation or system expansion). At the same time, secondary scenarios should transparently address collection, transport, dismantling, pretreatment, purification, effluents and residue treatment. Secondary origin alone does not establish lower environmental burden. Circularity should distinguish material return, net reagent reuse, and product-quality retention. It should separate open-loop

JIRRS
Journal International Review of Research Studies
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Vol: 1.11
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Pages: 1-30

markets from industrial closed loops that may not appear in reported secondary-supply statistics.

12. Critical Synthesis, Knowledge Gaps, and Research Priorities

The literature is not comparable when feed compositions, oxidation states, leach times, and denominators differ. Consequently, route rankings should be feed-specific and conditional. Studies of pure Ir standards clarify mechanisms but cannot substitute for evidence from mixed refinery residues or polymer-supported catalyst layers (Chen et al., 2021; Stokley & Jacobs, 1963; Wang & Feng, 2024).

Priority research needs include systematic mineral deportment, reproducible oxidation-state measurements, kinetic modeling in representative matrices, robust Ir/Rh/Ru selectivity, solvent and oxidant recycling, impurity partitioning, corrosion performance, and independently audited continuous-circuit demonstrations (Zaccarini et al., 2026).

The overarching research agenda should move from isolated unit-operation optimization to verified integrated recovery, including complete material balances, product quality, recycle accumulation, environmental controls, and uncertainty disclosure.

13. Conclusions

Iridium extraction and recovery cannot be optimized independently of feed mineralogy and chemical form. Primary ore processing depends on PGM concentration and intermediate refining, whereas secondary treatment depends strongly on scrap composition, catalyst-layer architecture, and pretreatment losses.

Thermal activation, oxidative hydrometallurgy, electrochemical approaches, and selective separation serve different roles in viable flowsheets. Comparisons based solely on dissolution fraction are incomplete unless they quantify downstream losses, reagent demands, impurity partitioning, and final product specifications.

Future progress depends on reproducible, feed-specific evidence; experimentally validated metal balances; appropriate environmental boundaries; and demonstration of complete-circuit performance under representative operating conditions.

Declarations

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Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

References

Al-Bazi, S. J., & Chow, A. (1984). Polyurethane foam for the extraction of rhodium and its separation from iridium. Talanta, 31(6), 431–435. https://doi.org/10.1016/0039-9140(84)80114-9

Alexiou, V., Zagoraiou, E., Moschovi, A. M., Yakoumis, I., & Chalaris, M. (2026). Life cycle assessment of closed-loop hydrometallurgical recovery of platinum group metals from PEM fuel cells and electrolyzers. Purification, 2(3), Article 12. https://doi.org/10.3390/purification2030012

Beamish, F. E. (1960). A critical review of methods of isolating and separating the six platinum metals. Talanta, 5(1), 1–35. https://doi.org/10.1016/0039-9140(60)80202-0

Beamish, F. E. (1966). A critical review of gravimetric methods for determination of the noble metals—II. Talanta, 13(6), 773–801. https://doi.org/10.1016/0039-9140(66)80282-5

Beamish, F. E. (1967). A critical review of methods of isolating and separating the noble metals—II. Ion-exchange and solvent extraction. Talanta, 14(9), 991–1009. https://doi.org/10.1016/0039-9140(67)80138-3

Biata, N. R., Jakavula, S., Mashile, G. P., Nqombolo, A., Moutloali, R. M., & Nomngongo, P. N. (2020). Recovery of gold(III) and iridium(IV) using magnetic layered double hydroxide (Fe3O4/Mg-Al-LDH) nanocomposite: Equilibrium studies and application to real samples. Hydrometallurgy, 197, 105447. https://doi.org/10.1016/j.hydromet.2020.105447

Bossi, T., & Gediga, J. (2017). The environmental profile of platinum group metals. Johnson Matthey Technology Review, 61(2), 111–121. https://doi.org/10.1595/205651317X694713

Cabri, L. J. (2023). Discovery of the six members of the platinum group and their mineralogical characterization. Johnson Matthey Technology Review, 67(2), 138–149. https://doi.org/10.1595/205651323X16570342480111

Carrick, A. I., Patrick, J., Schofield, E. R., O'Shaughnessy, P., Breeze, B., Love, J. B., & Morrison, C. A. (2024). Separation of rhodium from iridium through synergistic

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

solvent extraction. Separation and Purification Technology, 333, 125893. https://doi.org/10.1016/j.seppur.2023.125893

Chen, W.-S., Liu, W.-S., & Chen, W.-C. (2023). Leaching efficiency and kinetics of platinum from spent proton exchange membrane fuel cells by H2O2/HCl. Metals, 13(6), 1006. https://doi.org/10.3390/met13061006

Chen, Y., Qiao, Q., Cao, J., Li, H., & Bian, Z. (2021). Precious metal recovery. Joule, 5, 3097–3115. https://doi.org/10.1016/j.joule.2021.11.002

Cherepakhin, V., & Williams, T. J. (2024). Recycling organoiridium waste to [(1,5-cyclooctadiene)IrCl]$_2$. Green Chemistry, 26, 3146–3148. https://doi.org/10.1039/D4GC00151F

Chernyshov, N., & Ponamareva, M. (2015). Os-Ru-Ir and Os-(Ru)-Ir-Pt mineral phases from iron quartzites and weathered rocks of the Mikhailovka and Staryi Oskol KMA iron regions, central Russia. Doklady Earth Sciences, 460, 183–188. https://doi.org/10.1134/S1028334X1502018X

Chung, C., Cotty, S., Jeon, J., Elbert, J., & Su, X. (2024). Auto-oxidation of redox electrodes for the selective recovery of platinum group metals. Journal of Materials Chemistry A, 12, 15006–15018. https://doi.org/10.1039/D4TA01384K

Dam, A. P., Franz, T., Papakonstantinou, G., & Sundmacher, K. (2025). Catalyst dissolution in PEM water electrolysis: Influence of time, current density, and iridium ion transport in single-pass and recirculation water flow modes. Applied Catalysis B: Environment and Energy, 365, 124946. https://doi.org/10.1016/j.apcatb.2024.124946

Desai, D. D., & Shinde, V. M. (1979). Separation of osmium(VIII) from platinum group metals by extraction with liquid ion exchangers. Separation Science and Technology, 14(10), 947–951. https://doi.org/10.1080/01496397908058104

Diamantatos, A., & Verbeek, A. A. (1977). Method for the separation of platinum, palladium, rhodium, iridium, and gold by solvent extraction. Analytica Chimica Acta, 91(2), 287–294. https://doi.org/10.1016/S0003-2670(01)93671-2

Du, J., Zlatar, M., Zhang, D., Escalera-López, D., Quinson, J., Cherevko, S., & Arenz, M. (2025). Towards selective Ir/IrO$_2$ electrochemical dissolution of Ir-based electrocatalysts for enhanced proton exchange membrane water electrolyzer sustainability. Journal of Power Sources, 657, 238224. https://doi.org/10.1016/j.jpowsour.2025.238224

El-Maghrabey, M., Abourehab, M. A. S., Abdel-Hakim, A., Hetta, H. F., Hashem, H. M., & El-Shaheny, R. (2026). From extraction to closed-loop recovery: Recent advances in ionic-liquid-based recycling of platinum-group metals. RSC Advances. https://doi.org/10.1039/D6RA09002H

Engelbrecht, S., Jordaan, P., & Cloete, J. (2022). Investigating the recoveries and grades of individual platinum group and precious metals when alternative collector chemistries are used on UG2 ore. Minerals Engineering, 179, Article 107437. https://doi.org/10.1016/j.mineng.2022.107437

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Fan, C., Quan, K., Han, Z., Han, F., Li, Z., Liu, J., & Liu, X. (2023). Recovery and purification of iridium from secondary resources: A review. Journal of Sustainable Metallurgy, 9(3), 909–926. https://doi.org/10.1007/s40831-023-00697-y

Fan, M., Li, S., Deng, H., Zhang, X., Luo, G., Huang, Z., & Chen, M. (2022). Separation and recovery of iridium(IV) from simulated secondary resource leachate by extraction–electrodeposition. Separation and Purification Technology, 289, 120765. https://doi.org/10.1016/j.seppur.2022.120765

Faye, G. H., & Inman, W. R. (1963). A scheme for the separation of platinum, palladium, rhodium, and iridium by solvent extraction. Analytical Chemistry, 35(8), 985–988. https://doi.org/10.1021/ac60201a020

Firmansyah, M. L., Kubota, F., & Goto, M. (2018). Solvent extraction of Pt(IV), Pd(II), and Rh(III) with the ionic liquid trioctyl(dodecyl)phosphonium chloride. Journal of Chemical Technology & Biotechnology, 93, 1714–1721. https://doi.org/10.1002/jctb.5544

Fu, J., Zhang, Y., He, X., Zhang, S., & Ding, Y. (2026). Severe supply risk of iridium on hydrogen energy and its sustainable development strategy. Separation and Purification Technology, 380, 135429. https://doi.org/10.1016/j.seppur.2025.135429

Garuti, G., Zaccarini, F., Proenza, J. A., & Thalhammer, O. A. R. (2012). Platinum-group minerals in chromitites of the Niquelândia layered intrusion (central Goiás, Brazil): Their magmatic origin and low-temperature reworking during serpentinization and lateritic weathering. Minerals, 2(4), 365–384. https://doi.org/10.3390/min2040365

Goc, K., Kluczka, J., Benke, G., Malarz, J., Pianowska, K., & Leszczyńska-Sejda, K. (2021). Application of ion exchange for recovery of noble metals. Minerals, 11, 1188. https://doi.org/10.3390/min11111188

Grilli, M. L., Slobozeanu, A. E., Larosa, C., Paneva, D., Yakoumis, I., & Cherkezova-Zheleva, Z. (2023). Platinum group metals: Green recovery from spent auto-catalysts and reuse in new catalysts—A review. Crystals, 13(4), 550. https://doi.org/10.3390/cryst13040550

He, X., Ding, Y., Shi, Z., Ren, J., Zhao, B., Zhang, C., & Zhang, S. (2024). A comprehensive review on the distribution behaviors of precious metals through pyrometallurgical processes and implications for recycling. Minerals Engineering, 219, 108998. https://doi.org/10.1016/j.mineng.2024.108998

Heshmatpour, B., & Heestand, R. L. (1985). Recovery of iridium from scrap and residues. Journal of the Less Common Metals, 105(1), 119–128. https://doi.org/10.1016/0022-5088(85)90130-4

Ho, H. L., & Lee, M. S. (2026). A review of recent developments in the dissolution of rhodium and iridium metals from spent catalysts. Mineral Processing and Extractive Metallurgy Review, 47(1), 94–108. https://doi.org/10.1080/08827508.2024.2432667

Hodgson, A. P. J., Jarvis, K. E., Grimes, R. W., & Marsden, O. J. (2017). Advances in the development of a dissolution method for the attribution of iridium source materials. Journal of Radioanalytical and Nuclear Chemistry, 311, 1193–1199. https://doi.org/10.1007/s10967-016-5151-4

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Hudson, M. J., & Thorns, J. F. (1983). The concentration of rhodium and iridium during the final stages of the platinum group metals refining process using the co-polymer poly[(N-dithiocarboxylato)-iminoethenehydrogenoiminioethene]. Hydrometallurgy, 11(3), 289–295. https://doi.org/10.1016/0304-386X(83)90049-X

Hughes, A. E., Haque, N., Northey, S. A., & Giddey, S. (2021). Platinum group metals: A review of resources, production and usage with a focus on catalysts. Resources, 10(9), Article 93. https://doi.org/10.3390/resources10090093

Ibrahim, A. S. M., & Eggert, R. G. (2026). Recycling iridium and platinum from end-of-life technologies: A 2050 material-flow analysis. Resources, 15(8), 106. https://doi.org/10.3390/resources15080106

Jacinto, M. J., Silva, F. P., Kiyohara, P. K., Landers, R., & Rossi, L. M. (2012). Catalyst recovery and recycling facilitated by magnetic separation: Iridium and other metal nanoparticles. ChemCatChem. https://doi.org/10.1002/cctc.201100415

Jha, M. K., Gupta, D., Lee, J.-C., Kumar, V., & Jeong, J. (2014). Solvent extraction of platinum using amine-based extractants in different solutions: A review. Hydrometallurgy, 142, 60–69. https://doi.org/10.1016/j.hydromet.2013.11.009

Ka, S., Lee, Y., Lim, C., Kim, E.-D., Bang, H.-S., Kim, W., Choi, J.-Y., Oh, H.-S., & Lee, W. H. (2025). Accelerated dissolution of iridium anode in the presence of organic compounds. Nature Communications, 16, 8946. https://doi.org/10.1038/s41467-025-63992-0

Kanert, G. A., & Chow, A. (1975). The separation of rhodium and iridium by anion-exchange. Analytica Chimica Acta, 78(2), 375–382. https://doi.org/10.1016/S0003-2670(00)00157-4

Kanert, G., & Chow, A. (1974). Solvent extraction separation of rhodium from iridium with tri-n-octylamine as a liquid anion-exchanger. Analytica Chimica Acta, 69(2), 355–361. https://doi.org/10.1016/S0003-2670(01)80902-8

Karim, S., & Ting, Y.-P. (2021). Recycling pathways for platinum group metals from spent automotive catalyst: A review on conventional approaches and bio-processes. Resources, Conservation and Recycling, 170, 105588. https://doi.org/10.1016/j.resconrec.2021.105588

Khalili, M., Harameen, H. M. A., Choi, B., Bae, M., Lee, H., Kim, S.-K., & Lee, C. (2025). Sustainable PGM recovery processes for fuel cell and electrolyzer applications. ACS Applied Energy Materials, 8, 8641. https://doi.org/10.1021/acsaem.5c01074

Kim, H., & Ahn, J. (2025). A short review on hydrometallurgical recovery of iridium. Resources Recycling, 34(5), 3–17. https://doi.org/10.7844/kirr.2025.34.5.3

Kinas, S., Jermakowicz-Bartkowiak, D., Pohl, P., Dzimitrowicz, A., & Cyganowski, P. (2024). On the path of recovering platinum-group metals and rhenium: A review on the recent advances in secondary-source and waste materials processing. Hydrometallurgy, 223, 106222. https://doi.org/10.1016/j.hydromet.2023.106222

Knothe, M., Schwarz, K., & Förster, H. (1991). Iridium recovery from compact metal scrap. Journal of the Less Common Metals, 168(2), 249–255. https://doi.org/10.1016/0022-5088(91)90306-O

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Kobayashi, Y., Yamada, S., & Nagai, T. (2019). New dissolution process of iridium to hydrochloric acid. Rare Metal Technology 2019, 197–200. https://doi.org/10.1007/978-3-030-05740-4_19

Kong, P., & Chai, C. (1990). A new selective chemical dissolution procedure for chemical speciation studies of anomalous iridium in geological samples. Chemical Geology, 82, 51–56. https://doi.org/10.1016/0009-2541(90)90073-G

Koster, G., & Schmuckler, G. (1967). Separation of noble metals from base metals by means of a new chelating resin. Analytica Chimica Acta, 38(1), 179–184. https://doi.org/10.1016/S0003-2670(01)80575-4

Lanaridi, O., Schnürch, M., Limbeck, A., & Schröder, K. (2022). Liquid- and solid-based separations employing ionic liquids for the recovery of platinum group metals typically encountered in catalytic converters: A review. ChemSusChem, 15. https://doi.org/10.1002/cssc.202102262

Le, M. N., & Lee, M. S. (2018). Separation of iridium(IV) and rhodium(III) from hydrochloric acid solution by solvent extraction with Cyanex 921. Geosystem Engineering, 21(4), 210–216. https://doi.org/10.1080/12269328.2017.1392903

Le, M. N., Lee, M. S., & Senanayake, G. (2018). A short review of the separation of iridium and rhodium from hydrochloric acid solutions by solvent extraction. Journal of Solution Chemistry, 47, 1373–1394. https://doi.org/10.1007/s10953-018-0770-8

Le, M. N., Nguyen, T. H., & Lee, M. S. (2018). Comparison of separation behavior of Ir(IV) and Rh(III) between tin(II) chloride and ascorbic acid as a reducing agent in the extraction with Cyanex 921 and Cyanex 301. Solvent Extraction and Ion Exchange, 36(3), 272–285. https://doi.org/10.1080/07366299.2018.1478373

Lee, J., & Kim, Y. (2011). Chemical dissolution of iridium powder using alkali fusion followed by high-temperature leaching. Materials Transactions, 52(11), 2067–2070. https://doi.org/10.2320/matertrans.M2011202

Lee, J.-C., Kurniawan, K., Kim, S., Nguyen, V. T., & Pandey, B. D. (2023). Ionic liquids-assisted solvent extraction of precious metals from chloride solutions. Separation and Purification Reviews, 52, 242–261. https://doi.org/10.1080/15422119.2022.2091458

Lee, M., Lee, J., & Sun, P. (2010). Solvent extraction of rhodium(III) and iridium(IV) from hydrochloric acid solution. Korean Journal of Metals and Materials, 48(5), 430–435. https://doi.org/10.3365/KJMM.2010.48.05.430

Leon-Fernandez, L. F., Kukurugya, F., Martinez-Mora, O., Mourdikoudis, S., Zeng, L., Parascanu, M. M., Saez, A., Fransaer, J., Spooren, J., & Dominguez-Benetton, X. (2026). Electrified, decentralized upcycling of platinum-group metals from spent automotive catalysts into functional electrocatalysts. RSC Sustainability, 4, 2729–2747. https://doi.org/10.1039/D6SU00190D

Lewis, P. A., Morris, D. F. C., Short, E. L., & Waters, D. N. (1976). Application of solvent extraction to the refining of precious metals IV. Practical and structural aspects of the separation of rhodium, palladium, iridium and platinum with organic sulphoxides. Journal of the Less Common Metals, 45(2), 193–214. https://doi.org/10.1016/0022-5088(76)90267-8

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Li, A., Kong, S., Adachi, K., Ooka, H., Fushimi, K., Jiang, Q., Ofuchi, H., Hamamoto, S., Oura, M., Higashi, K., Kaneko, T., Uruga, T., Kawamura, N., Hashizume, D., & Nakamura, R. (2024). Atomically dispersed hexavalent iridium oxide from MnO2 reduction for oxygen evolution catalysis. Science, 384(6696), 666–670. https://doi.org/10.1126/science.adg5193

Liu, C., Sun, S., Zhu, X., & Tu, G. (2021). Metal smelting-collection method for recycling of platinum group metals from waste catalysts: A mini review. Waste Management & Research, 39(1). https://doi.org/10.1177/0734242X20969795

Liu, M., Yang, C., Tian, M., Zhao, Y., Liu, X., Zhan, C., Li, Z., Xue, T., He, F., & Yang, J. (2026). Recovery of platinum group metals from spent automotive catalysts: A review of processes and challenges. Materials, 19(12), 2491. https://doi.org/10.3390/ma19122491

Liu, W., Huang, Z., & Dong, J. (2013). Solvent extraction of iridium(IV) with the petroleum sulfoxide. Asian Journal of Chemistry, 25(13), 7131–7134. https://doi.org/10.14233/ajchem.2013.14462

Ma, L., Huang, M., Tao, J., Tao, H. B., & Zheng, N. (2026). Breaking resource bottleneck for proton exchange membrane water electrolysis by graded recycling strategy. International Journal of Hydrogen Energy, 227, Article 154640. https://doi.org/10.1016/j.ijhydene.2026.154640

Majavu, A., Ogunlaja, A. S., & Tshentu, Z. R. (2017). Separation of rhodium(III) and iridium(IV) chlorido complexes using polymer microspheres functionalized with quaternary diammonium groups. Separation Science and Technology, 52(1), 71–80. https://doi.org/10.1080/01496395.2016.1235051

Marinho, R. S., Afonso, J. C., & da Cunha, J. W. S. D. (2010). Recovery of platinum from spent catalysts by liquid–liquid extraction in chloride medium. Journal of Hazardous Materials, 179, 488–494. https://doi.org/10.1016/j.jhazmat.2010.03.029

Mashiya, N., Van Schalkwyk, F., Susac, D., Chamier, J., & Khotseng, L. (2026). Recovery of platinum and iridium metals from spent catalysts using potential cycling and square wave: A review. Energy & Environment. https://doi.org/10.1177/0958305X261418242

McKay, E. S., & Cordell, R. W. (1971). Separation of rhodium from iridium with sodium borohydride and standardization of rhodium(III) solutions. Talanta, 18(8), 841–845. https://doi.org/10.1016/0039-9140(71)80136-4

Minke, C., Suermann, M., Bensmann, B., & Hanke-Rauschenbach, R. (2021). Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? International Journal of Hydrogen Energy, 46(46), 23581–23590. https://doi.org/10.1016/j.ijhydene.2021.04.174

Mohamed, N., Rifai, K., Selmani, S., Constantin, M., Doucet, F. R., Özcan, L., Sabsabi, M., & Vidal, F. (2021). Chemical and mineralogical mapping of platinum-group element ore samples using laser-induced breakdown spectroscopy and micro-X-ray fluorescence. Geostandards and Geoanalytical Research, 45, 539–550. https://doi.org/10.1111/ggr.12385

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Moore, R. A., & Chow, A. (1980). The extraction of iridium and platinum from organic solvents by polyurethane foam. Talanta, 27(4), 315–319. https://doi.org/10.1016/0039-9140(80)80089-0

Moriau, L., Stojanovski, K., Jovanovič, P., Escalera-López, D., Cherevko, S., & Hodnik, N. (2023). Towards electrochemical iridium recycling in acidic media: Effect of the presence of organic molecules and chloride ions. RSC Advances, 13(12), 7980–7987. https://doi.org/10.1039/D2RA07142H

Morris, D. F. C., & Ritter, T. J. (1978). Separation of iridium by use of sodium tetrahydroborate. Hydrometallurgy, 3(3), 297–300. https://doi.org/10.1016/0304-386X(78)90030-0

Murawski, J., Scott, S. B., Rao, R., Rigg, K., Zalities, C., Stevens, J., Sharman, J., Hinds, G., & Stephens, I. E. L. (2024). Benchmarking stability of iridium oxide in acidic media under oxygen evolution conditions: A review part 1. Johnson Matthey Technology Review, 68(1), 121–146. https://doi.org/10.1595/205651323X16848455435118

Naito, T., & Takanabe, K. (2021). Recent advances in understanding oxygen evolution reaction mechanisms over iridium oxide. Inorganic Chemistry Frontiers. https://doi.org/10.1039/D0QI01465F

Nguyen, T. H., & Lee, M. S. (2016). Effect of HCl concentration on the oxidation of LIX 63 and the subsequent separation of Pd(II), Pt(IV), Ir(IV), and Rh(III) by solvent extraction. Korean Journal of Metals and Materials, 54(10), 768–774. https://doi.org/10.3365/KJMM.2016.54.10.768

Nguyen, T. H., Sonu, C. H., & Lee, M. S. (2016a). Separation of Ir(IV) and Rh(III) from strong hydrochloric acid solutions by solvent extraction with amines. Journal of Industrial and Engineering Chemistry, 36, 245–250. https://doi.org/10.1016/j.jiec.2016.02.006

Nguyen, T. H., Sonu, C. H., & Lee, M. S. (2016b). Separation of Pt(IV), Pd(II), Rh(III), and Ir(IV) from concentrated hydrochloric acid solutions by solvent extraction. Hydrometallurgy, 164, 71–77. https://doi.org/10.1016/j.hydromet.2016.05.014

Nguyen, V. T., Lee, J.-C., Chagnes, A., Kim, M.-S., Jeong, J., & Cote, G. (2016). Highly selective separation of individual platinum group metals (Pd, Pt, Rh) from acidic chloride media using phosphonium-based ionic liquid in aromatic diluent. RSC Advances, 6, 62717–62728. https://doi.org/10.1039/C6RA09328K

Nguyen, V. T., Riaño, S., Aktan, E., Deferm, C., Fransaer, J., & Binnemans, K. (2021). Solvometallurgical recovery of platinum group metals from spent automotive catalysts. ACS Sustainable Chemistry & Engineering, 9, 337–350. https://doi.org/10.1021/acssuschemeng.0c07355

Otgonbayar, U., Sandig-Predzymirska, L., Thiere, A., & Charitos, A. (2024). Solvent extraction of Pt, Ru, and Ir using Cyanex 923 in chloride media to develop a recycling route for spent polymer electrolyte membrane (PEM) electrolyzers. Hydrometallurgy, 226, 106303. https://doi.org/10.1016/j.hydromet.2024.106303

Paiva, A. P. (2017). Recycling of palladium from spent catalysts using solvent extraction—Some critical points. Metals, 7, 505. https://doi.org/10.3390/met7110505

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Peng, Z., Li, Z., Lin, X., Tang, H., Ye, L., Ma, Y., Rao, M., Zhang, Y., & Li, G. (2017). Pyrometallurgical recovery of platinum group metals from spent catalysts. JOM, 69, 1553–1562. https://doi.org/10.1007/s11837-017-2450-3

Pereira, A. C. (2026a). Aqua regia in metal processing: A critical review of reaction mechanisms, selectivity, and industrial applicability. IKR Journal of Engineering and Technology, 2(5). https://doi.org/10.5281/zenodo.23176166

Pereira, A. C. (2026b). Conventional ion-exchange and chelating resins for metal recovery: A critical comparison of selectivity, dynamic performance, regeneration, and process integration. International Journal of Current Science Research and Review, 9(9), 4916–4945. https://doi.org/10.47191/ijcsrr/V9-i9-08

Pereira, A. C. (2026c). From mineral liberation to metallurgical recovery: The role of automated mineralogy in sulfide ore processing. IKR Journal of Engineering and Technology, 2, 117–147. https://doi.org/10.5281/zenodo.20786643

Pereira, A. C. (2026d). Processing of platinum group metals: From primary ores to secondary resources and sustainable recovery strategies. IKR Journal of Engineering and Technology, 2, 73–104. https://doi.org/10.5281/zenodo.19670876

Pereira, A. C. (2026e). Scale-up in mineral processing: From mechanism preservation to flowsheet-scale transferability—A critical review and the MINESCALE framework. Journal of Advanced Multidisciplinary Studies, 1(III), 661–694. https://doi.org/10.68050/JAMS.2026.800

Petrov, G. V., Fokina, S. B., & Nikitina, T. Yu. (2021). Aspects of iridium extraction from chloride solution. Non-Ferrous Metals. https://doi.org/10.17580/nfm.2021.01.02

Pianowska, K., Kluczka, J., Benke, G., Goc, K., Malarz, J., Ochmański, M., & Leszczyńska-Sejda, K. (2023). Solvent extraction as a method of recovery and separation of platinum group metals. Materials, 16(13), 4681. https://doi.org/10.3390/ma16134681

Raju, P. V. S., Merkle, R. K. W., Babu, E. V. S. S. K., Satyanarayanan, M., Anjaiah, K. V., & Mohanthy, S. K. (2010). Isotope dilution with high-pressure asher acid digestion for the determination of platinum group elements in chromitite from Katpal chromite mine in the Sukinda Ultramafic Complex, Eastern India. Journal of Geology and Mining Research, 2(4), 93–100. https://doi.org/10.5897/JGMR.9000043

Rane, M. V. (2019). PGM ore processing: LIX reagents for palladium extraction & platinum stripping from Alamine 336 using NaOH–NaCl. Minerals Engineering, 138, 119–124. https://doi.org/10.1016/j.mineng.2019.04.044

Ryan, M., Gerosa, A. Z., Raithatha, R., Brown, S., Cowley, A., Fujita, M., Girardot, N., & Wang, A. (2026). Reassessment of recycling rates of platinum group metals (PGMs) and their impact on sustainability models. ACS Omega, 11(22), 31813–31819. https://doi.org/10.1021/acsomega.5c11916

Rzelewska-Piekut, M., Paukszta, D., & Regel-Rosocka, M. (2021). Hydrometallurgical recovery of platinum group metals from spent automotive converters. Physicochemical Problems of Mineral Processing, 57, 83–94. https://doi.org/10.37190/ppmp/132779

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Röttcher, N. C., Zhou, J., Löttert, L., Mayrhofer, K. J. J., & Dworschak, D. (2025). Tracing iridium dissolution pathways in proton exchange membrane water electrolyzers at relevant current densities in real time. ChemElectroChem, 12. https://doi.org/10.1002/celc.202500098

Saguru, C., Ndlovu, S., & Moropeng, D. (2018). A review of recent studies into hydrometallurgical methods for recovering PGMs from used catalytic converters. Hydrometallurgy, 182, 44–56. https://doi.org/10.1016/j.hydromet.2018.10.012

Sandig-Predzymirska, L., & Charitos, A. (2025). Closing the recycling loop of PEM electrolyzer: Synthesis of Ir precursor from spent electrocatalyst. Chemical Technology and Engineering: Proceedings, 360–363. https://doi.org/10.23939/cte2025.01.360

Sanekata, R., Takahashi, K., Yamada, S., & Nagai, T. (2023). Volatile separation and recovery of iridium using rare earth oxides to form complex oxides for effective solubilization. Metallurgical and Materials Transactions B, 55, 64–71. https://doi.org/10.1007/s11663-023-02936-9

Sato, K., Yamazaki, S., Takahashi, K., & Nagai, T. (2024). Recovery of iridium from electrode for oxygen generation by using strontium carbonate. Resources Processing, 70(3), 121–124. https://doi.org/10.4144/rpsj.70.121

Schalenbach, M., Wolf, N., Poc, J.-P., Heume, C., Basak, S., Schierholz, R., Karl, A., Jodat, E., & Eichel, R.-A. (2025). Accelerated iridium dissolution in proton exchange membrane (PEM) water electrolyzers by inert mobile anions adsorbed in the double layer. Journal of The Electrochemical Society, 172, 064509. https://doi.org/10.1149/1945-7111/ade0ef

Sen, K., Acharyya, B. R., Siladitya, B., & Bag, S. P. (1991). Liquid-liquid extraction-separation of iridium in the presence of rhodium and ruthenium with salicylhydroxamic acid in iso butanol. Indian Journal of Chemistry, Section A, 30A(5), 437–440. https://nopr.niscpr.res.in/handle/123456789/41904

Sharma, R., Morgen, P., & Andersen, S. M. (2025). Dissolution of nanoparticulate IrO_2 in dilute acidic baths through a pre-reduction step: A method to recover Ir from electrocatalytic/catalytic bodies. Applied Surface Science, 681, 161553. https://doi.org/10.1016/j.apsusc.2024.161553

Sharma, R., Morgen, P., Makovec, D., Gyergyek, S., & Andersen, S. M. (2024). Enhanced electrochemical dissolution of iridium oxide in acidic electrolytes through the presence of metal ions: Shortened lifetime and hope for recovery. RSC Sustainability, 2, 2225–2238. https://doi.org/10.1039/D4SU00257A

Sinisalo, P., & Lundström, M. (2018). Refining approaches in the platinum group metal processing value chain—A review. Metals, 8, 203. https://doi.org/10.3390/met8040203

Smith, W., Maier, W., Barnes, S., Moorhead, G., Reid, D., & Karykowski, B. (2021). Element mapping the Merensky Reef of the Bushveld Complex. Geoscience Frontiers, 12, 101101. https://doi.org/10.1016/j.gsf.2020.11.001

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Son, I., & Sohn, H.-S. (2021). Smelting of platinum group metals and recycling of spent catalyst. Resources Recycling, 30(3), 18–29. https://doi.org/10.7844/kirr.2021.30.3.18

Son, M.-K. (2025). Research trends on recycling of membrane electrode assembly in polymer electrolyte membrane water electrolysis. Journal of Hydrogen and New Energy, 36, 832. https://doi.org/10.7316/JHNE.2025.36.6.832

Stepanov, S. Y., Palamarchuk, R. S., Antonov, A. V., Kozlov, A. V., Varlamov, D. A., Khanin, D. A., & Zolotarev, A. A., Jr. (2020). Morphology, composition, and ontogenesis of platinum-group minerals in chromitites of zoned clinopyroxenite–dunite massifs of the Middle Urals. Russian Geology and Geophysics, 61(1), 47–67. https://doi.org/10.15372/RGG2019089

Stokley, J. R., & Jacobs, W. D. (1963). Simultaneous spectrophotometric determination of rhodium and iridium with 1-(2-pyridylazo)-2-naphthol. Analytical Chemistry, 35(2), 149–152. https://doi.org/10.1021/ac60195a013

Sun, P., & Lee, M. (2011). Separation of Ir(IV) and Rh(III) from mixed chloride solutions by solvent extraction. Hydrometallurgy, 105(3–4), 334–340. https://doi.org/10.1016/j.hydromet.2010.11.008

Taghipour, B., & Ahmadnejad, F. (2018). Platinum-group elements geochemistry and chromian spinel composition in podiform chromitites and associated peridotites from the Cheshmeh-Bid deposit, Neyriz, southern Iran: Implications for geotectonic setting. Acta Geologica Sinica (English Edition), 92(1), 183–209. https://doi.org/10.1111/1755-6724.13501

Takahashi, K., Sanekata, R., & Nagai, T. (2023). Volatile separation and recovery of iridium from oxygen evolution electrodes using calcium oxide. Journal of the Japan Institute of Metals and Materials, 87(9), 243–248. https://doi.org/10.2320/jinstmet.J2022044

Takahashi, K., Sanekata, R., & Nagai, T. (2024). Volatile separation and recovery of iridium from oxygen evolution electrodes using calcium oxide. Materials Transactions, 65(1), 71–75. https://doi.org/10.2320/matertrans.MT-M2023140

Tang, H., Peng, Z., Tian, R., Ye, L., Zhang, J., Rao, M., & Li, G. (2023). Platinum-group metals: Demand, supply, applications and their recycling from spent automotive catalysts. Journal of Environmental Chemical Engineering, 11, 110237. https://doi.org/10.1016/j.jece.2023.110237

Tertipis, G. G., & Beamish, F. E. (1960). Separation of rhodium from iridium by copper powder. Analytical Chemistry, 32(4), 486–489. https://doi.org/10.1021/ac60160a010

Tertipis, G. G., & Beamish, F. E. (1962). Solvent extraction separation and spectrophotometric determination of rhodium and iridium. Analytical Chemistry, 34(6), 623–625. https://doi.org/10.1021/ac60186a011

Tertipis, G. G., & Beamish, F. E. (1963). The recovery of rhodium, iridium, palladium and platinum from ores and concentrates by wet assay and a comparison with recovery by fire assays. Talanta, 10(11), 1139–1151. https://doi.org/10.1016/0039-9140(63)80165-4

Tso, K.-C., Chen, C.-H., Chen, P.-C., Li, S.-S., Chen, J.-L., Ohta, J., & Wu, P.-W. (2024). Reuse of sodium–doped iridium oxide nanoparticles as a bio–stimulating electrode by

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

a chemical and electrochemical recovery process. Ceramics International, 50(4), 6220–6228. https://doi.org/10.1016/j.ceramint.2023.11.344

Turnbull, S., Clauss, D., Martin, V., Magnin, J.-P., Dubau, L., & Maillard, F. (2025). An aqua regia-free chemical recovery and reprecipitation of Ir from IrOx catalysts: Optimization of the extraction efficiency using surface response methodology. RSC Sustainability, 3, 1741–1750. https://doi.org/10.1039/D5SU00038F

Wang, C., & Feng, L. (2024). Recent advances and perspectives of Ir-based anode catalysts in PEM water electrolysis. Energy Advances, 3, 14–29. https://doi.org/10.1039/D3YA00492A

Wang, L., Yu, J., Yang, L., Ye, X., Hou, M., Gao, L., Sun, Q., Shao, X., & Guo, S. (2026). Synergistic smelting and recovery of platinum group metals from metallurgical by-products and spent catalysts: A review of traditional technologies and microwave metallurgy. Metals, 16(2), Article 205. https://doi.org/10.3390/met16020205

Wang, Y., Song, Y., Li, Y., Li, J., Bao, J., Zhang, X., & Li, B. (2023). Study on the extraction and separation of precious metals from wastewater using a hydrophobic deep eutectic solvent. Journal of Environmental Chemical Engineering, 11(5), 111102. https://doi.org/10.1016/j.jece.2023.111102

Wei, Y., Zhang, W., & Gao, J. (2024). Trash or treasure? Sustainable noble metal recovery. Green Chemistry, 26, 5684–5707. https://doi.org/10.1039/D3GC04950G

Wen, J., Wang, X., Yu, F., Tian, M., Wang, C., Huang, G., & Xu, S. (2023). Recovery and value-added utilization of critical metals from spent catalysts for new energy industry. Journal of Cleaner Production, 419, 138295. https://doi.org/10.1016/j.jclepro.2023.138295

Williams, E. J., Racz, D. G., Perry, K. A., Fassbender, M. E., & Chaple, I. F. (2026). Processing iridium foil targets for the production of radioplatinum isotopes. Applied Radiation and Isotopes, 230, 112441. https://doi.org/10.1016/j.apradiso.2026.112441

Wilson, R. B., & Jacobs, W. D. (1961). Separation of iridium from rhodium by extraction with tributyl phosphate. Analytical Chemistry, 33(12), 1650–1652. https://doi.org/10.1021/ac60180a012

Wortmann, B., Stolten, D., & Heinrichs, H. (2026). Critical iridium demands arising from global expansion of proton exchange membrane electrolysis. Journal of Industrial Ecology, 30(4), 1299–1314. https://doi.org/10.1007/s44498-026-00088-y

Wu, Y.-H., Lee, J. G., Cho, J., Choi, C. H., & Cherevko, S. (2026). Effect of electrolyte on the dissolution of electrocatalysts. Current Opinion in Electrochemistry, 57, 101850. https://doi.org/10.1016/j.coelec.2026.101850

Willans, R. M., Heaton, J. H., Altus, K. M., Beaumont, S. K., Edwards, A. J., Hayward, M. A., Freeman, B., Lazarov, V. K., Muresan, N. M., Thompsett, D., Mosely, J. A., & Weller, A. S. (2026). $K_2[Ir(OH)_6]$: An isolable platform intermediate for the refining of complex chloroiridate mixtures to synthetically useful Ir(III) coordination complexes. Chemical Science, 17, 17990–18000. https://doi.org/10.1039/D6SC05573G

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/weke5g87
Pages: 1-30

Xia, J., & Ghahreman, A. (2023). Platinum group metals recycling from spent automotive catalysts: Metallurgical extraction and recovery technologies. Separation and Purification Technology, 311, 123357. https://doi.org/10.1016/j.seppur.2023.123357

Yakoumis, I., Panou, M., Moschovi, A. M., & Panias, D. (2021). Recovery of platinum group metals from spent automotive catalysts: A review. Cleaner Engineering and Technology, 3, 100112. https://doi.org/10.1016/j.clet.2021.100112

Ye, Q., Yu, F., Ma, X., Wang, J., Cai, K., Wang, L., & Zou, J.-P. (2025). An electrometallurgical and mechanochemical approach for the recovery of platinum group metals from spent automotive catalysts. Hydrometallurgy, 237, 106537. https://doi.org/10.1016/j.hydromet.2025.106537

Yoshimura, A., Komatsuda, H., & Matsuno, Y. (2024). Establishment of a novel recycling process for iridium using “dry aqua regia”. Materials Transactions, 65(1), 49–53. https://doi.org/10.2320/matertrans.MT-M2023084

Zaccarini, F., Garuti, G., Economou-Eliopoulos, M., Bowles, J. F. W., Hughes, H. S. R., Andersen, J. C., & Suárez, S. (2026). Overview of platinum group minerals (PGM): A statistical perspective and their genetic significance. Minerals, 16(1), 108. https://doi.org/10.3390/min16010108

Zhang, L., Li, N., Fan, P., Chu, X., An, S., Zhang, J., & Wang, X. (2012). Rapid and selective separation of iridium ions from aqueous solutions using nano-Al_2O_3. Hydrometallurgy, 127–128, 8–15. https://doi.org/10.1016/j.hydromet.2012.06.012

Zhen, Z., Wu, H., Lyu, B., Gu, A., & Zhou, S. (2025). The supply of critical metals could constrain China’s low-carbon transition in hydrogen production. Resources, Conservation and Recycling, 219, 108295. https://doi.org/10.1016/j.resconrec.2025.108295

Zlatar, M., Escalera-López, D., Simon, C., Briega-Martos, V., Stojanovski, K., & Cherevko, S. (2025). pH dependence of noble metals dissolution: Iridium. Electrochimica Acta, 513, 145450. https://doi.org/10.1016/j.electacta.2024.145450

Zhou, H., Yang, Z., Meng, X., Zou, X., Jiang, Y., & Huang, K. (2026). Selective preferential separation and extraction of rhodium: A review. Metals, 16(6), 612. https://doi.org/10.3390/met16060612

Zupanc, A., Install, J., Jereb, M., & Repo, T. (2023). Sustainable and selective modern methods of noble metal recycling. Angewandte Chemie International Edition, 62, e202214453. https://doi.org/10.1002/anie.202214453