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Aqua Regia in Platinum-Group Metal Processing: Reaction Chemistry, Chloride Speciation, Dissolution Mechanisms, Selectivity, and Recovery Challenges—A Critical Review

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Abstract

Aqua regia remains an important benchmark lixiviant for platinum-group metals (PGMs), yet the shorthand HCl: HNO_3 = 3:1 obscures its time-dependent oxidant chemistry and the decisive influence of support materials and chloride speciation. This critical review examines aqua-regia formation, oxidation–complexation coupling, dissolution mechanisms for Pt, Pd, Rh, Ru, Ir, and Os, operating conditions, feed-matrix effects, kinetic interpretation, co-dissolution, separation, and reagent management. A curated body of 145 cited publications spanning 2010–2026 provides the documentary basis, supplemented by qualitative process-chemistry analysis. The literature indicates that a nominal acid ratio is not a transferable measure of leaching severity: absolute concentration, acid age, oxidant volatilization, accessible metal surface, matrix consumption, and reactor configuration must also be stated. The markedly different responses of individual PGMs and the speciation dependence of downstream separation preclude a universal maximum-extraction flowsheet. The review proposes a reporting framework linking effective oxidant availability and free chloride activity to metal-specific dissolution, impurity loading, and refined-metal yield. It identifies in situ speciation, gas quantification, selective rhodium recovery, and integrated techno-economic evaluation as priorities.

Keywords: aqua regia; platinum-group metals; chloride speciation; oxidative leaching; selective recovery; process integration

Highlights

- A nominal 3:1 acid ratio does not define effective aqua regia leaching intensity.
- Oxidation, chloride complexation, and feed-matrix demand jointly control recovery.
- Pt, Pd, Rh, Ru, Ir, and Os require metal-specific mechanistic interpretation.
- Leaching performance must be reconciled with separation, emissions, and acid demand.

The graphical abstract summarizes the relationship between evolving aqua regia chemistry, feed characteristics, platinum-group-metal dissolution, and downstream recovery. The illustration provides a conceptual overview rather than quantitative speciation or experimentally validated process performance.

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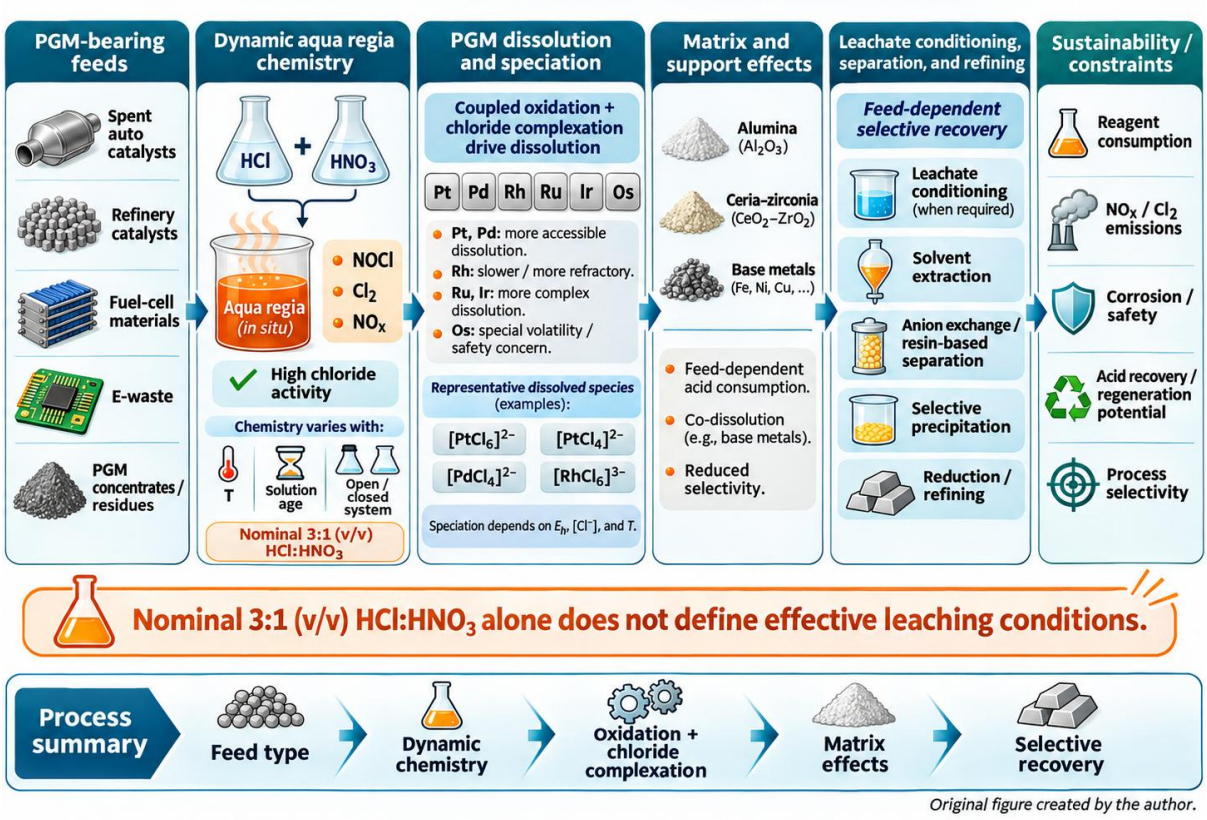
Graphical Abstract



Original figure created by the author.

1. Introduction

Aqua regia is not a reagent of constant oxidizing strength. After mixing hydrochloric and nitric acids, the system produces, consumes, and loses reactive chlorine- and nitrogen-containing species to the gas phase. The resulting solution chemistry therefore depends on preparation and residence history as well as on the nominal acid ratio. For platinum-group metals (PGMs), this distinction matters when comparing results from different feeds or reactor configurations.

This review examines how the changing oxidant inventory, metal-surface accessibility, chloride coordination, and dissolution of matrix constituents affect both PGM dissolution and subsequent purification. Automotive and fuel-cell catalysts, refinery residues, and primary intermediates provide useful but non-equivalent examples. Comparability requires reporting the chemical exposure the feed experienced, not merely the initial HCl: HNO_3 ratio.

The same nominal PGM assay may conceal either exposed crystallites or metal enclosed in refractory phases. Accordingly, establish feed mineralogy, support composition,

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and final product specifications before using a leaching result to select a process. (Ding et al., 2019; Dong et al., 2015; Grilli et al., 2023)

The distinction between leach extraction and refined recovery is equally important. Dissolved metal may subsequently be lost through transfers, co-extraction, stripping, and refining; a pregnant-liquor assay cannot account for these losses. (Hughes et al., 2021; Ilyas et al., 2021; Liu et al., 2024)

Comparisons across spent catalysts, refinery intermediates, and concentrates are conditional on the phases hosting each PGM, the exposed surface area, and the product specification. (Liu et al., 2026; Mvokwe et al., 2025; Sun et al., 2022)

For a full process comparison, the accounting boundary must therefore extend from feed inventory to saleable product and include residues, washes, and discarded solutions. (Xv et al., 2025; Yakoumis et al., 2021)

2. Review Methodology

This article is a structured critical narrative review, not a systematic review or meta-analysis. The manuscript reference list contains 145 bibliographic entries (counted in the supplied DOCX); 145 have publication years within 2010–2026, 0 precede 2010, and 0 postdate 2026, based solely on the years displayed in the entries. The collection was supplied to the author for thematic synthesis; this revision did not include the original search logs, database identities, execution dates, screening decisions, deduplication records, or the precise selection cutoff. Consequently, we do not claim a reproducible database search, exhaustive coverage, an independently verified DOI set, or a retrospective PRISMA screening sequence. Thematic inclusion was based on relevance to aqua-regia formation, oxidative chloride dissolution of PGMs, matrix effects, downstream recovery, or relevant chemical/process analogies. References to other metals and other lixiviants are identified as indirect evidence, not converted into direct aqua-regia–PGM experiments. The 145 entries are an identifiable bibliographic listing, not an independently reconstructed search yield.

For critical interpretation, we classified source relevance as: (I) direct investigation of PGMs with aqua regia; (II) related chloride, alternate oxidant, analytical digestion, or other-metal system used only as an analogy; and (III) review or process synthesis used for context.

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Source titles and the manuscript record permit a preliminary categorization but cannot substitute for checking full experimental methods, operating conditions, numerical results, or DOI metadata. Supplementary Table S1 links selected central claims to source scope and explicitly records information not verified in the original articles. We did not pool recovery percentages because feed, acid inventory and history, operating temperature, gas transfer, and assay boundary vary across studies.

Selection and verification limitation. Inclusion reflects the supplied bibliographic corpus rather than a documented database screening campaign. Exclusion and duplicate-removal decisions cannot be reconstructed without the original bibliography/search file; accordingly, audit completeness, publication-year exceptions, and original study findings against that file before final editorial submission. This distinction prevents planned search strings or retrospective topic labels from being presented as searches actually performed.

Supplementary Table S1. Targeted evidence-to-claim matrix (bibliographic scope and directness; no new experimental extraction).

Reference	Reported system/feed	Evidence type	Supported use	Limit/verification status
Hasani, K., Koleini, S., & Meléndez (2017)	Automotive Pt/Pd/Rh; chloride-containing solutions	PGM leach, related chloride system	Context for multi-PGM chloride dissolution	Exact HNO_3 use, conditions and rates: not checked against full text
Hasani, K., Koleini, S., Pérez-Pacheco, & Meléndez (2017)	Automotive catalyst; platinum; aqua regia	Direct aqua-regia/Pt topic	Pt leaching applicability	Original conditions, rate model and recoveries unverified; no evidence for other five PGMs
Niemelä et al. (2012).	Catalyst samples; microwave-assisted aqua regia digestion	Analytical digestion analogy	Analytical preparation comparison	Not industrial PGM reactor kinetics
Elomaa et al. (2017)	Circuit boards, Au/Cu/Fe in aqua regia	Other-metal analogy	Context for oxidant consumption and matrix effect	Cannot establish PGM-specific rate constant
Liu, C., et al. (2024)	Spent automotive catalysts; metal capture	Secondary synthesis / alternative route	Integrated recovery context	No direct aqua regia rate evidence

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Liu, M., et al. (2024)	Fe–Si–PGM alloy; thermo-/mechanochemical route	Alternative PGM process	Feed-host accessibility comparison	Not transferable to aqua regia catalyst rate without original evidence
Seisko et al. (2018).	Gold leaching, ferric chloride	Other-metal / different oxidant analogy	Limits of apparent kinetic-model comparison	Does not establish PGM/nitrate chemistry
Xu et al. (2022)	Pd recovery review	Secondary literature	Separation route context	Not primary aqua regia speciation data
Ru — evidence gap	Ru-bearing solids; oxidizing chloride	Mechanistic risk hypothesis	Phase-specific Ru chloro/oxo and off-gas tests	Original feed-specific kinetics and gas quantification not established
Ir — evidence gap	Ir-bearing refractory phases; chloride	Mechanistic risk hypothesis	Host mineralogy, interfacial rate and ligand exchange	Do not infer Os-like volatility or universal rate
Os — evidence gap	Os phases in strong oxidants	Chemical hazard hypothesis	OsO_4 monitoring and gas containment	No quantified generation rate for studied feeds

Note. Categories are based on bibliographic descriptions; original experimental findings, conditions, and publication metadata have not all been independently verified.

The synthesis compares mechanisms and reporting conditions rather than averaging extraction percentages from experiments with different acid strengths, reagent ages, solid-to-liquid ratios, and gas exchange. These differences can change the chemical exposure and accessible surface simultaneously. (Kinas et al., 2024; Mpinga et al., 2015; Saguru et al., 2018)

A process review may establish which technologies have been investigated, but it cannot substitute for primary evidence on reaction orders, rate limitation, or PGM chloride speciation in aqua regia. This distinction constrains how the comparative literature is used below. (Xu et al., 2022)

3. Chemistry of Aqua Regia Formation

An illustrative net representation for aqua regia preparation is $HNO_3 + 3HCl \rightleftharpoons NOCl + Cl_2 + 2H_2O$. This is a bookkeeping relation for one possible overall pathway, not proof that the solution contains fixed stoichiometric proportions of NOCl and Cl_2. Subsequent equilibria and gas evolution produce a changing distribution of oxidants and nitrogen oxides.

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Consequently, the extent of headspace exchange, mixing, and residence time belongs in the definition of the leaching environment.

Freshly combined concentrated acids and a hot solution held in an open vessel should not be presumed chemically equivalent, even at the same nominal HCl: HNO_3 ratio. Higher temperature may accelerate heterogeneous reaction while simultaneously increasing losses of volatile oxidant species. A closed apparatus can retain some volatile species but introduces pressure, materials, and off-gas hazards; safety constraints therefore preclude treating closure as an unqualified improvement.

Figure 1 follows reactive-species formation, loss, and consumption rather than assuming a fixed aqua-regia composition.

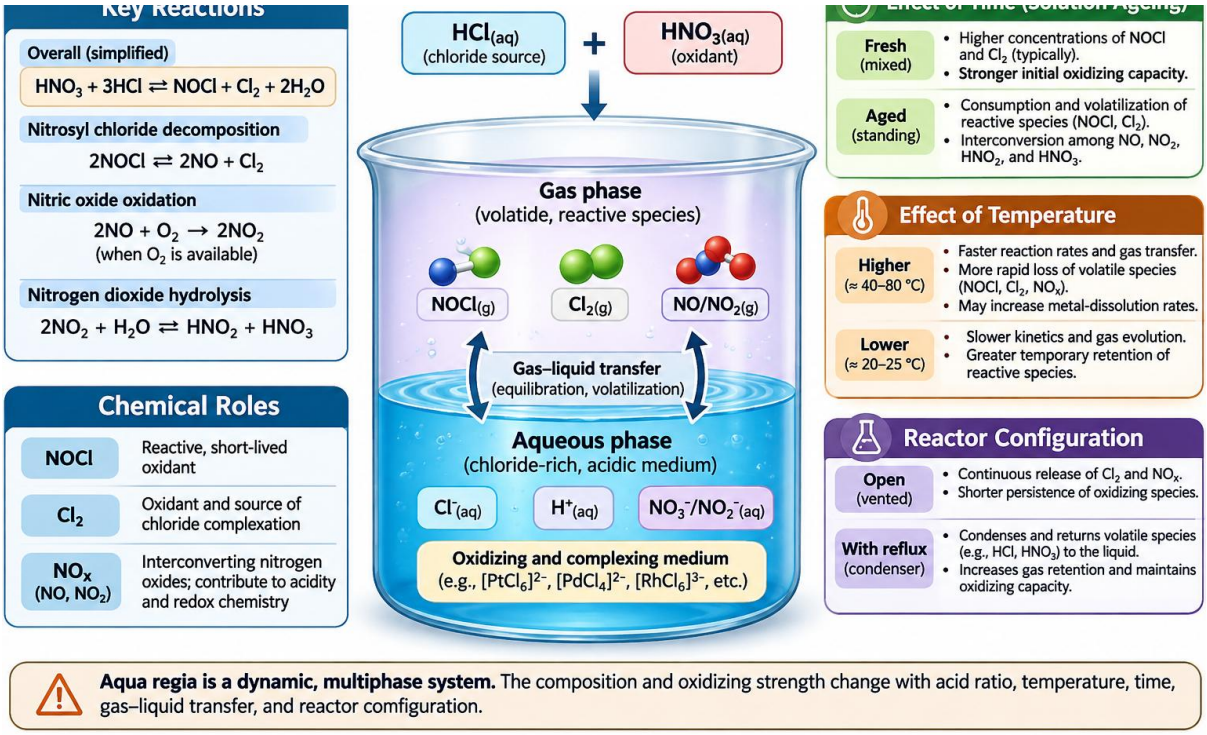

Figure 1. Reaction network and time-dependent gas–liquid chemistry of aqua regia.
Note. Original conceptual illustration generated with AI assistance. Its chemical species and graphical relationships are illustrative, not quantified speciation or kinetic results; the accompanying text governs interpretation. Independent validation of species and source-level mechanistic details remains required before publication.

Figure 1 separates preparation, volatile-species transfer, and reagent consumption. It does not imply fixed concentrations of NOCl, Cl_2, or nitrogen oxides: these require measurement or a validated reactive-speciation model.

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Two reactors charged with the same nominal HCl: HNO_3 ratio can expose the solid to different oxidant inventories as volatile species escape, gangue reacts, and nitric acid is depleted. (Abbas et al., 2025; Bae et al., 2020; Elomaa et al., 2017)

The oxidant supply mode is a relevant comparison variable. Still, evidence from gold recycling in aqua regia (Karamanoğlu & Aydın, 2016) and microwave-assisted analytical digestion of catalyst samples (Niemelä et al., 2012) must be treated as process and analytical analogies, respectively, not as direct measurements of PGM dissolution under an electrochemical oxidant-supply regime. The two distinct Hasani studies (2017) concern catalyst leaching in chloride media and platinum in aqua regia; their bibliographic scope cannot by itself substantiate a generalized electrochemical rate claim.

The acid mixing ratio is an initial condition, not a measure of oxidant activity during leaching; vessel closure, heating, feed demand, and reagent dosing alter that activity. (Pereira, 2026a; Rocky et al., 2024; Yoshimura & Matsuno, 2019)

Replacing nitrate oxidation with chlorine dosing changes gas handling, oxidant regeneration, and potentially the composition of the pregnant liquor; transferability cannot be presumed. (Yoshimura et al., 2021; Zhu & Huang, 2022)

4. Redox Thermodynamics of PGM Dissolution

Noble metal dissolution requires an oxidizing pathway that converts the solid to dissolved oxidation states, with complexing ligands stabilizing those states. In concentrated chloride solutions, potential–pH diagrams constructed for dilute idealized solutions must be treated cautiously: ionic strength, activity coefficients, and multinuclear or mixed-ligand complexes can alter chemical boundaries. A favorable net driving force does not guarantee an accessible surface reaction pathway.

Platinum and palladium commonly form stable chloride complexes under sufficiently oxidizing conditions, whereas rhodium and iridium may display slower apparent dissolution related to surface history and kinetic inertness. Ruthenium and osmium demand explicit evaluation of possible high-oxidation-state volatile products. Ranking metal leachability solely by equilibrium potential is therefore misleading without considering phase form, passivation, and gas-phase hazards.

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Table 1 summarizes illustrative oxidation states, chloride species, and key kinetic considerations. The table is not a speciation calculation; the actual distribution requires feed-specific and solution-specific evidence.

Table 1. Representative oxidation and chloride-coordination considerations

Metal	Relevant dissolved forms (illustrative)	Main interpretive limitation
Pt	Pt(IV), e.g. $[PtCl_6]^{2-}$	Verify oxidation state, accessible surface and matrix demand
Pd	Pd(II), e.g. $[PdCl_4]^{2-}$	Record oxidation state, chloride dependence and competitors
Rh	Rh(III) chloro/aqua species (conditional)	Resolve host phase, conversion, slow exchange and solution aging
Ru	Ru chloro/oxo species (conditional)	Evaluate feed phase, high-valence oxide pathways and off-gas separately
Ir	Ir(III/IV) chloro species (conditional)	Evaluate refractory host phase and slow surface/ligand-exchange kinetics
Os	Os chloro/oxo species; possible OsO_4	Separate hazardous OsO_4 formation and vapor monitoring from aqueous dissolution

Note. Conceptual chemistry synthesis; representative forms are not a calculated distribution for a specific solution.

Table 1 distinguishes plausible coordination chemistry from the factors that control whether each metal actually dissolves. Its illustrative formulas must not be read as a calculated speciation distribution for an operating leachate.

A stable dissolved chlorocomplex provides only a thermodynamic driving force; the passivated solid interface and ligand substitution may remain kinetically restrictive. (Ding et al., 2020; Kim & Hong, 2024; Pereira, 2026d)

Redox diagrams and chloride-complex calculations apply only within the stated temperature, chloride activity, ionic-strength, and species assumptions. When cited, comparisons with gold systems offer a chemical analogy but do not establish PGM-specific dissolution equilibria or interfacial rate behavior (Song et al., 2024; Wu & Zha, 2025; Zheng et al., 2021).

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Complex stability should not be confused with metal accessibility: refractory mineral associations or low surface reaction rates can prevent dissolution despite favorable aqueous speciation. (Zhou et al., 2026)

5. Chloride Complexation and PGM Speciation

Operational status of the framework. Total dissolved chloride is a directly measurable analytical inventory, whereas free chloride concentration requires a selective measurement or defensible speciation estimate. Free chloride activity further requires a declared activity-coefficient convention and standard state; it is not numerically interchangeable with either chloride assay. An effective oxidant-availability descriptor is proposed as a time series of initial charge, residual oxidizing reagents, reagent additions and measured gas losses, supplemented by electrode-referenced ORP as a proxy. A single ORP reading does not identify NOCl, Cl_2, NO_x, nitrate, or a transferable oxidizing capacity. Each recorded variable must be labeled measured, calculated/modelled, proxy,y or unavailable; Table 3 adds timestamps and uncertainty.

Chloride coordination couples oxidative dissolution to solution stability. Representative soluble species include $[PtCl_6]^{2-}$, $[PdCl_4]^{2-}$, and a family of hydrated or chlorinated rhodium(III) complexes; the relative abundance depends on chloride activity, temperature, oxidation state, and time available for ligand substitution. The written formulas describe plausible species families, not measured compositions of every aqua-regia leachate.

For operational reporting, total analytical chloride (cCl, total) is the sum of chloride across measured dissolved forms, not the free chloride concentration. Free chloride concentration, cCl^-, free, is a model- or measurement-dependent uncomplexed-ion quantity; its thermodynamic activity is $aCl^- = \gamma Cl^- \times cCl^-, free / c^\circ$, with the activity coefficient and standard state stated. In concentrated aqua-regia leachates, a single nominal HCl inventory does not determine either cCl^-, free or aCl^-. If activity is unavailable, report measured total chloride explicitly as a proxy, not a substituted activity value. Effective oxidant availability is an operational time-dependent inventory or exposure index, not one unique thermodynamic species: specify acid dosing, residual nitrate/nitric acid where measured, redox potential with electrode/reference and temperature, measured reactive chlorine/nitrogen species where feasible, and cumulative off-gas losses. ORP alone cannot resolve the individual oxidants or

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quantify transferable oxidation capacity. These quantities are proposed descriptors; this review does not retrospectively measure them.

The ligand-exchange kinetics of Rh(III) and Ir species can impose a separation timescale distinct from metal dissolution. As a result, solvent extraction or ion-exchange data from equilibrated synthetic chloride solutions cannot automatically be transferred to recently produced aqua-regia liquors containing residual nitrate, nitric acid, mixed metal ions, and oxidation products.

Figure 2 distinguishes oxidative surface reaction from chloride coordination and migration into the bulk liquor.

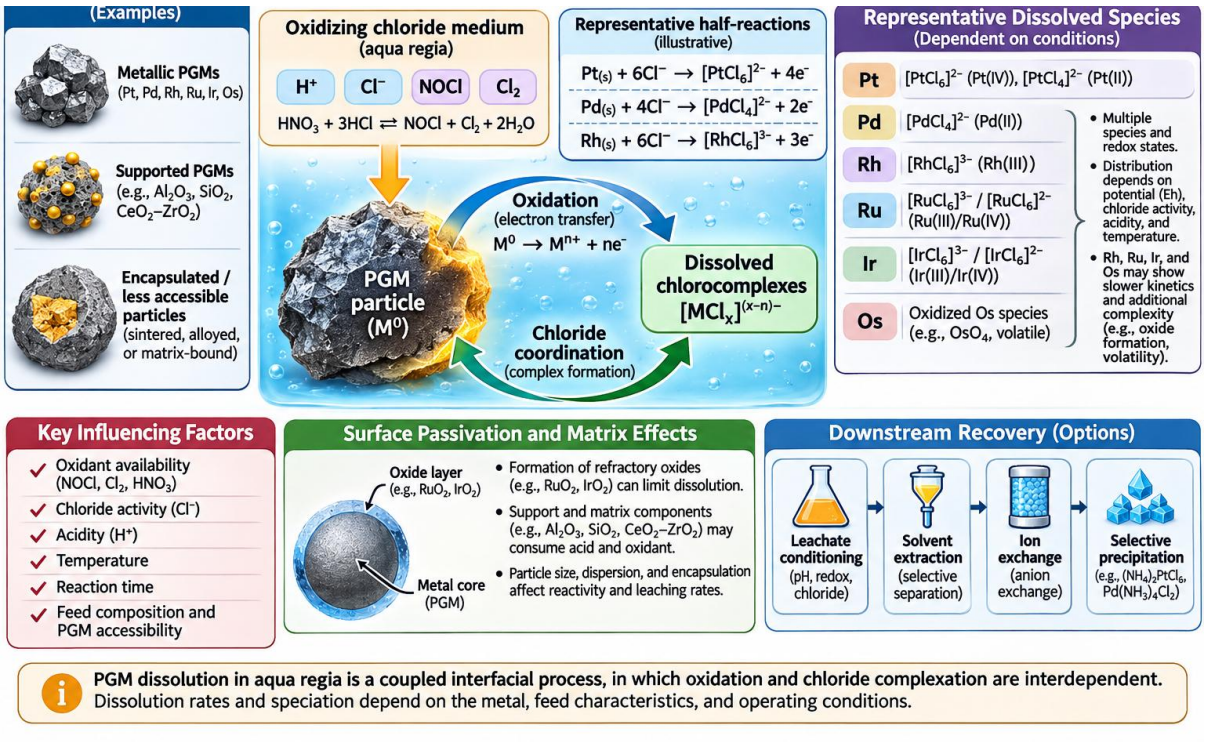

Figure 2. Coupled interfacial oxidation and chloride coordination during PGM dissolution.
Note. Original conceptual illustration generated with AI assistance. Its chemical species and graphical relationships are illustrative, not quantified speciation or kinetic results; the accompanying text governs interpretation. Independent validation of species and source-level mechanistic details remains required before publication.

Figure 2 emphasizes two coupled but separately testable steps: interfacial metal oxidation and stabilization of oxidized species by chloride coordination. Neither step can be inferred solely from total dissolved-metal concentration.

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Elemental analysis of a leachate gives total dissolved metal but not ligand occupancy; this distinction matters because competing separation reagents distinguish species, not only elemental identities. (Hosseinzadeh & Petersen, 2025; Kononova et al., 2011; Pietrantonio et al., 2025)

Rhodium and iridium may require additional attention to ligand-exchange kinetics. Measurements taken after prolonged equilibration may not represent the species present immediately after oxidative dissolution. (Raju et al., 2012; Shen et al., 2010b; Wang et al., 2021)

A chemically conditioned synthetic liquor may differ from fresh aqua-regia solution even at the same Pt/Pd/Rh concentration, since aquated and chlorinated complexes need not partition identically. (Zhang et al., 2023)

6. Dissolution Mechanisms of Individual PGMs

Pt, Pd, and Rh are not interchangeable reaction substrates. Particle surface exposure, metal crystallite size, oxidation state, and support bonding can change both dissolution rate and extent. Pt and Pd may respond readily to oxidative chloride chemistry in some feeds, while refractory Rh-containing phases and poorly accessible particles often require additional activation or treatment. Such statements require feed-specific evidence rather than a single assumed hierarchy.

Ruthenium (Ru) must be assessed in relation to the Ru-bearing feed phase, accessible surface, and oxidation-state-dependent aqueous chloro/oxo chemistry; under sufficiently strong oxidizing conditions, potential high-valence oxide formation also calls for off-gas assessment. The present bibliography does not establish a general Ru volatilization fraction or nitric-acid–chloride dissolution rate. Iridium (Ir) may be constrained by refractory host phases and slow interfacial dissolution or subsequent ligand substitution of Ir chloride complexes; this is a distinct limitation and does not justify assigning Os-type volatile-oxide behavior to Ir. Osmium (Os) requires a dedicated hazard boundary because sufficiently oxidizing conditions can generate volatile and highly toxic OsO_4. The available source descriptions do not quantify OsO_4 generation for any specific aqua-regia feed. For all three metals, relevant conclusions remain conditional on phase identification, time-dependent dissolved and residue assays,

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specific species measurements, and (where relevant) validated gas capture. The evidence depth is substantially lower than for Pt and Pd, so the present discussion identifies uncertainties rather than asserting comparable mechanistic resolution.

Figure 3 compares the dissolution pathways and process constraints of Pt, Pd, Rh, Ru, Ir, and Os in oxidizing chloride media. The rankings are qualitative and must not be treated as measured, feed-independent recovery sequences.

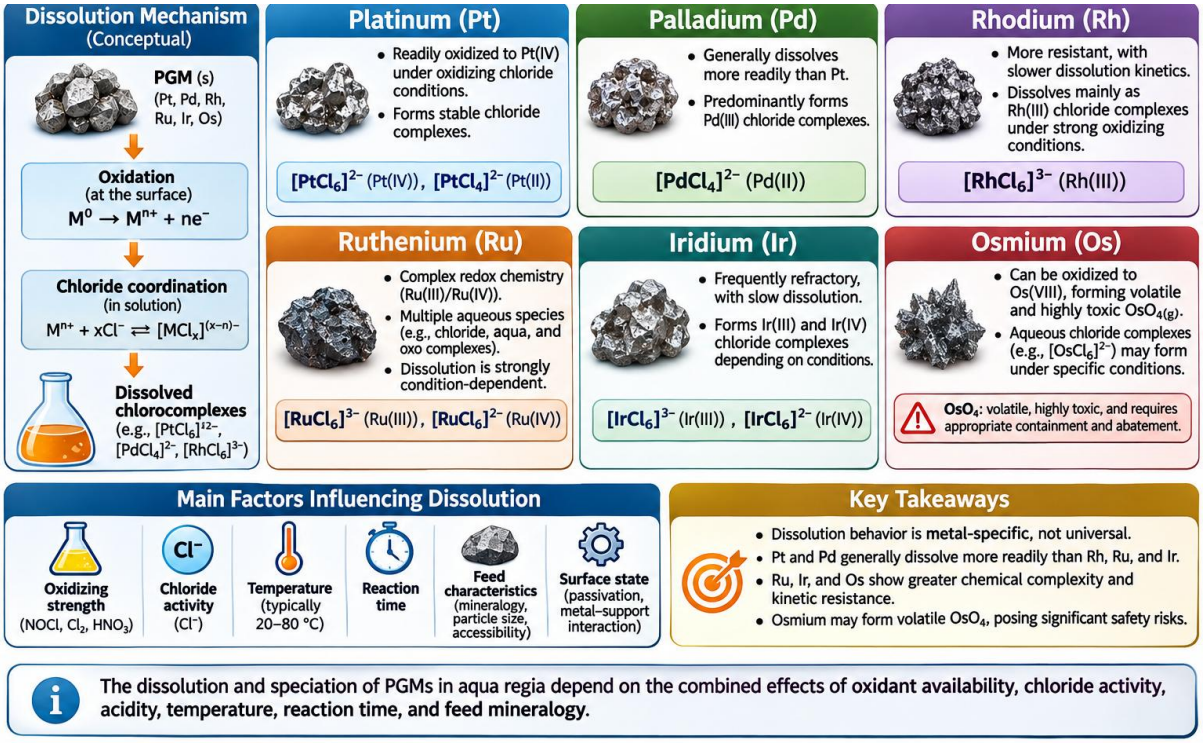

Figure 3. Metal-specific dissolution behavior and representative species of Pt, Pd, Rh, Ru, Ir, and Os. *Note.* Original conceptual illustration generated with AI assistance. Its chemical species and graphical relationships are illustrative, not quantified speciation or kinetic results; the accompanying text governs interpretation. Independent validation of species and source-level mechanistic details remains required before publication.

Figure 3 differentiates comparatively accessible Pt/Pd dissolution from the refractory or more complex behavior often encountered for Rh, Ru, and Ir, while recognizing the particular volatility and toxicity concerns associated with oxidized Os species. Chloride speciation and observed recovery remain conditional on feed and operating conditions.

Table 2 contrasts metal-specific considerations in oxidative chloride leaching. The entries are interpretive rather than experimentally determined universal constants; cross-study comparisons require the original operating conditions.

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Table 2. Metal-specific considerations in oxidative chloride leaching

Metal group	Primary comparison	Experimental reporting priority
Pt	Accessible Pt phase and oxidation/chloride exposure	Pt-specific feed–liquor–residue inventory and measurement time
Pd	Pd(II) species, competing dissolution	Pd-specific mass balance and liquor conditions
Rh	Refractory associations and slow ligand exchange	Rh mineralogy, time history and conditioned-liquor species
Ru	Phase-specific chloro/oxo redox chemistry	Ru-specific solution/residue assays; off-gas only when chemically justified
Ir	Refractory host and complex-exchange kinetics	Ir phase ID, residence time and speciation
Os	Possible volatile OsO_4 in strong oxidants	Os-specific gas capture/analysis and explicit safety controls
Total chloride	Analytically determined total chloride (mol L^{-1})	State method, aliquot/sample time, uncertainty; not free-ion activity
Free chloride/activity	$c(Cl^-,free)$ and $a(Cl^-)=\gamma Cl \times c(Cl^-,free)/c^\circ$	Specify activity model, ionic strength, temperature and uncertainty; proxy if unavailable.
Oxidant exposure	Initial/residual oxidants, dosing, ORP and gas loss vs time	Report measured and estimated variables separately; ORP is not a unique oxidant inventory
Extraction / refined recovery	Target metal in liquor vs target metal in saleable product	Define dry feed, residues, wash streams, stages, time and uncertainty
Impurity loading/selectivity	Co-dissolved impurity mass and target/impurity ratio	State impurity subset, detection limits and leach boundary
Reagent efficiency	Refined or dissolved target mass per net reagent consumed	State acid/oxidant species, make-up/recycle and product boundary

Note. Comparative critical framework; no universal recovery percentages are asserted.

Table 2 separates the distinct risks associated with each minor PGM: ruthenium's oxidation-state-sensitive chemistry, iridium's refractory or slow-exchanging species, and osmium's possible high-valence volatile oxide. These are risk categories, not an experimentally derived ranking of dissolution rates.

The metal-by-metal discussion is most strongly grounded in Pt/Pd catalyst leaching and weaker for minor PGMs. In particular, no single joint parameter should be assigned to Ru, Ir, and Os without feed- and species-resolved evidence. The proposed comparisons are hypotheses for targeted validation, not quantified kinetic orderings.

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Ceramic encapsulation changes the physical contact between lixiviant and PGM. Grinding or washcoat disruption can improve exposure, but changes in extraction alone do not distinguish chemical acceleration from liberation. The cited work spans different pretreatment and leaching approaches and should not be treated as a common kinetic dataset. (Abo Atia & Spooren, 2021; Abo Atia et al., 2021; Demarco et al., 2020)

For automotive catalyst leaching, two separately listed Hasani studies from 2017 must be distinguished by their full author sets: Hasani, Khodadadi, Koleini, Saeedi, and Meléndez (2017) discuss Pt/Pd/Rh in chloride-containing solutions, whereas Hasani, Khodadadi, Koleini, Saeedi, Pérez-Pacheco, and Meléndez (2017) address platinum leaching with aqua regia. The reference titles support these study identities; the precise kinetics and experimental conditions still require checking against the original articles. Extraction requires paired feed, solution, wash, and residue measurements (H'ng et al., 2025; Ilyas & Kim, 2022).

Feed pretreatment changes accessibility and may increase recovered Pt/Pd, but its impact on observed rates is not diagnostic of the intrinsic surface-oxidation mechanism without comparison of particle exposure and residual inventory (Jha et al., 2013; Karim & Ting, 2022; Kim et al., 2016).

A fitted rate constant from a changing acid mixture combines chemistry and transport under that experiment's conditions. Without controlled oxidant-exposure and accessibility measurements, it cannot be transferred as an intrinsic kinetic parameter. (Kukurugya et al., 2025; Murray et al., 2017; Mwase et al., 2012)

The trade-off in comminuting a supported catalyst is both practical and kinetic: exposing PGM surfaces may improve contact while producing fines that complicate solid–liquid separation. No common basis for comparing these effects across the cited studies is established. (Nguyen et al., 2022; Palanisamy et al., 2022; Pereira, 2026c)

A liquor-only metal balance misses retained metal in residues and uncollected washes. Consequently, reassess the apparent extraction advantage against feed and residue assays and the amount of fresh acid consumed. (Prasetyo & Anderson, 2020; Sasaki & Maeda, 2014; Seisko et al., 2019)

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A key experimental contrast is between supported catalyst particles and exposed metal powders: the former require documenting washcoat removal and pore accessibility, whereas the latter more directly probe solution chemistry. The cited sources provide context, but a standardized cross-study rate comparison is not available (Spathariotis et al., 2026; Spooren & Abo Atia, 2020; Sun & Lee, 2015).

When residue mineralogy and oxidant consumption are unavailable, the relative contributions of inaccessible particles, refractory PGM phases, and reagent depletion remain unresolved. Such uncertainty should be reported rather than absorbed into a mechanistic fit. (Suoranta et al., 2015; Taninouchi et al., 2024; Van den Bossche et al., 2021)

In sintered or encapsulated catalyst particles, the leachant may reach the PGM only after penetrating or partially disrupting the surrounding phase. The resulting apparent kinetics are thus specific to the particle architecture and should not be transferred to exposed-metal powders. (Wiecka et al., 2022)

7. Effect of Aqua Regia Composition and Operating Variables

The frequently quoted 3:1 HCl: HNO_3 formulation is a preparation convention, not an optimum established for all PGMs. Identical volume ratios prepared from acids of different strengths yield different initial molar inventories. Temperature, agitation, residence time, particle size, mode of reagent addition, and solid-to-liquid ratio change both useful metal oxidation and parasitic consumption.

Appropriate experimental comparisons should report initial and residual free acid, chloride concentration where measurable, oxidant-related gas evolution, metal-specific dissolution, and complete feed and residue assays. Staged addition may reduce instantaneous oxidant depletion in one process but raise local concentration and safety concerns in another. An optimum must be defined jointly against recovery, selectivity, reagent consumption, and final separation burden.

Figure 4 presents a conceptual operating window in which acid composition and concentration interact with temperature, reagent depletion, matrix demand, and gas losses. Its boundaries are schematic, not experimentally fitted phase or kinetic boundaries.

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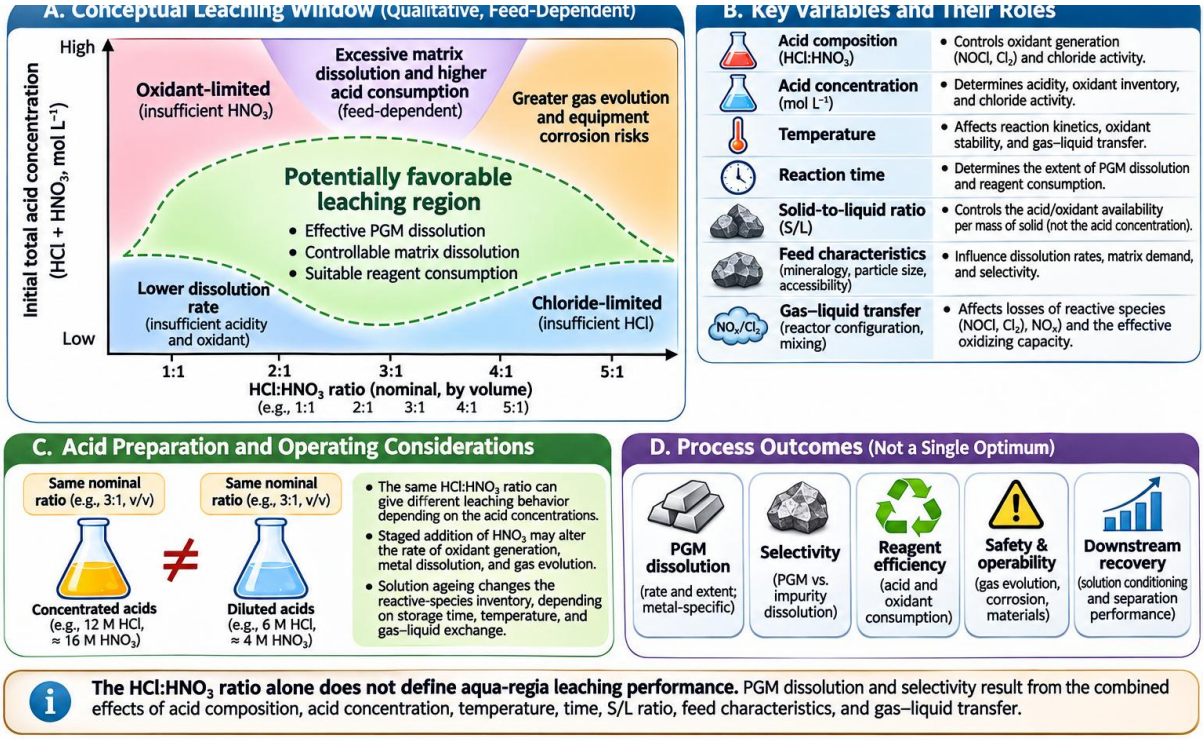

Figure 4. Conceptual effects of acid composition, concentration, and operating conditions on PGM leaching.
Note. Original conceptual illustration generated with AI assistance. Its chemical species and graphical relationships are illustrative, not quantified speciation or kinetic results; the accompanying text governs interpretation. Independent validation of species and source-level mechanistic details remains required before publication.

Figure 4 is a schematic map of interacting operating variables. Its shaded region is not a fitted optimum; the useful acid composition depends on feed oxidation demand, gas containment, metal-specific target recovery, and allowable impurity dissolution.

Figure-verification status. Figures 1–4 and the graphical abstract are present in the working manuscript. They are conceptual illustrations, not measured species distributions or a fitted operating window. Chemical formula, charge, arrow, and source-level validation should be documented in a separate final figure audit before the pending-validation wording can be removed; the revised text does not assert an audit that has not been completed.

The shaded "potentially favorable" zone in Figure 4 is not a fitted operating window and must not be read as proof that an HCl: HNO_3 ratio around 3:1 is preferable. Axes and arrows are schematic, and all process claims require feed-specific experimental confirmation.

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Table 3 defines the minimum reporting variables needed to interpret two nominally similar aqua-regia tests. Composition measurements taken during the run are particularly important because the reagent changes as dissolution proceeds.

Table 3. Minimum variables required for comparison of aqua-regia experiments

Descriptor	Required record	Reason
Starting acid basis	Stock solution concentrations and volumes; initial molar HCl/HNO_3, mixture age; timestamp; uncertainty	Volume ratio is not acid molar inventory.
Reaction/solid basis	T, duration, reactor open/closed, S/L, agitation, particle size, host phase; sampling time and precision	Distinguishes surface accessibility and transfer
Total and free chloride	Total chloride assay (mol L^{-1}); free Cl^- measured or estimated; $a(Cl^-)$ model, γ, T, ionic strength, sample time and uncertainty	Never substitute total chloride for free ion or activity.
Oxidant availability	Initial/residual nitrate or acid if measured; additions; ORP with reference and T; $NO_x/NOCl/Cl_2$ off-gas by species and time; state missing data	ORP is a proxy; no single transferable oxidant activity
Per-metal balances	Feed, liquor, wash, residue, saleable metal; per-metal X and refined R, sampling time, detection limits and uncertainty.	Separates leach extraction from refined recovery
Selectivity and load	For each target/impurity pair, solution ratio and impurity mg L^{-1} or kg/kg dissolved PGM; impurity set and sampling point	Avoids confusing selectivity with chemical consumption
Reagent-use efficiency	Net fresh acid/oxidant moles consumed per kg dissolved or refined target; boundary, recycling, timestamp and uncertainty.	Avoids attributing low reagent use to chemical selectivity
Evidence status	Measured/modeled/calculated proxy / not available for each variable	Prevents unsupported inferred measurements

Note. Suggested reporting checklist developed for this review, not a standardized regulatory requirement.

Table 3 shows why initial acid ratio, without molarity, reactor conditions, and reagent consumption, is an incomplete experimental descriptor.

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Reactor temperature and pretreatment should be recorded separately from acid formulation. Otherwise, differences in exposed metal area or volatilization can be misattributed to the nominal HCl: HNO_3 ratio.

Shorter residence time may arise from improved contact, higher initial oxidant exposure, or different gas retention. Distinguishing these cases requires time-resolved reagent and residue measurements rather than endpoint extraction.

8. Feed Matrix Effects

Spent automotive catalysts contain dispersed PGMs on ceramic supports with constituents such as Al_2O_3, CeO_2, and ZrO_2. The support can shield or expose precious-metal particles, dissolve partially, or modify effective acidity without being a targeted metal product. Metallurgical intermediates, fuel-cell catalysts, petroleum catalysts, and electronic scrap differ strongly in carbon content, base metals, support chemistry, and particle morphology.

In an uncharacterized feed, a high nominal PGM extraction fraction may coexist with substantial dissolution of Cu, Fe, Ni, Al, or other constituents. Ore mineralogy and feed pre-treatment therefore must be reported together with leaching conditions. Extrapolating an extraction result from purified metal powder to catalyst monoliths or concentrates is a frequent source of unsupported process optimism.

A ceramic support and a base-metal-rich matrix impose different reagent demands: limited access to PGM surfaces is not equivalent to consumption of oxidizing species by dissolved impurities. A route comparison should identify which constraint predominates in each feed. (Baloyi et al., 2024; Duclos et al., 2016; Junior & Afonso, 2010)

Bulk PGM grade alone is an insufficient descriptor of feed behavior. The same assay may correspond to dissimilar particle architectures, mineral hosts, and dissolution pathways. (Kamisono et al., 2024; Kim et al., 2013; Kuzuhara et al., 2021)

A ceramic washcoat and a base-metal-rich matrix have different leach impacts: the former may restrict access while the latter can consume oxidants and contaminate the liquor. (Leon-Fernandez et al., 2026; Liu et al., 2023; Morcali, 2020)

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An actionable feed classification would identify the host phases of each PGM, the condition of the washcoat, the accessible surface fraction where measurable, and the inventory of potential oxidant-consuming impurities. (Nguyen et al., 2021; Reddy et al., 2010; Shin et al., 2015)

The support contribution cannot be assigned a universal acid-consumption factor. Alumina-rich washcoats, ceria–zirconia components, and co-present base metals have different dissolution behavior; their separate mass balances are necessary to identify the principal reagent sinks. (Tang et al., 2022; Taninouchi et al., 2017; Wei et al., 2019)

Two feeds with equivalent bulk Pt–Pd–Rh grades can require different conditioning sequences if one contains readily exposed metal crystallites while the other retains refractory inclusions. Feed classification by host phase is therefore essential for a meaningful comparison. (Wen et al., 2023; Xu et al., 2025; Zheng et al., 2022)

9. Dissolution Kinetics and Rate Control

Observed rates can reflect surface electron transfer, oxidant transport, product-film resistance, diffusion through support pores, or depletion of reactive dissolved species. In an evolving HCl–HNO_3 mixture, time-dependent changes in the reagent pool may be mistaken for kinetic phase transitions if acid and gas chemistry are not monitored.

Apparent Arrhenius energies and shrinking-core coefficients are useful descriptors only under the assumptions of the underlying models. A fitted activation energy does not independently establish surface-reaction control, and conversion fractions require accurate residual-metal assays. For process design, mechanistic credibility improves when kinetic tests vary mixing, particle size, acid history, and gas containment independently.

Apparent kinetic constants obtained during reagent depletion may incorporate the evolving solution chemistry; goodness of fit alone cannot uniquely identify surface or diffusion control. (Chen et al., 2022; Dorfling et al., 2011; Hu et al., 2026)

Independent information on particle-size response, agitation, residue morphology, redox evolution, and acid consumption is needed to separate external transport, intraparticle diffusion, and surface reaction. (Kim et al., 2010; Nicol, 2023; Nogueira et al., 2020)

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Regression against a shrinking-core equation is not a mechanistic test when oxidant availability and gas escape change over the experimental period. (Seisko et al., 2018; Zhang et al., 2020)

10. Selectivity, Co-Dissolution, and Solution Complexity

Maximizing dissolved PGM fraction does not necessarily maximize refined product yield or minimize impurity loading. These performance dimensions require distinct indicators. For metal i: leach extraction Xi = m(i, dissolved in clarified pregnant liquor)/m(i, initial feed); refined recovery Ri = m(i, saleable refined product)/m(i, initial feed). Define dissolution selectivity against impurity j as Sij, leach = m(i, dissolved)/m(j, dissolved) for the same sampled liquor and time, with zero-denominator cases reported as undefined. Downstream separation selectivity must instead identify the separated/retained phases and compare distribution or recovered masses for the same stage. Impurity loading can be reported as mass of specified co-dissolved elements per unit solution volume or per mass of dissolved target PGM; declare the impurity set. Net reagent-use efficiency is m(i, dissolved or refined)/moles of net fresh acid or oxidant consumed, specifying which reagent, regeneration/recycle credit, and process boundary. These are proposed accounting definitions, not validated universal optimization scores.

The relevant comparison must separate dissolution selectivity, purification selectivity, and final refined-metal recovery. A high-extraction route can be economically inferior if nitrate destruction, chloride adjustment, iron control, or repeated extraction stages impose excessive loss and operating expense.

All comparisons should specify dry-feed metal inventory; point of liquor sampling; reagent and water additions; treatment of entrained and wash solutions; metal deportment through separation stages; and the refined-product specification. Absent material balances or blank/control data should be reported as missing rather than used to calculate a selectivity or consumption ratio. Ratios involving a near-zero impurity denominator require detection-limit treatment.

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Greater PGM extraction may be offset by increased impurity loading and more demanding purification; a selectivity metric must therefore compare recovered PGM mass with co-dissolved species. (Chen et al., 2021; Ge et al., 2023; Granados-Fernández et al., 2021)

Route comparisons need to distinguish metal dissolution, transfer to a separator, and final metal yield. Purification losses and reagent conditioning can reverse an apparent advantage at the leach stage. (Marinho et al., 2010; Moon et al., 2018; Murai & Kubo, 2026)

Leach optimization cannot be reduced to maximizing PGM extraction if a higher acid dose also increases Fe, Cu, Ni, or support dissolution. (Nicol et al., 2021; Pereira, 2026b; Wang et al., 2022)

The apparent ranking of two leaching routes can reverse when assessed after stripping and metal refining. Process comparisons should specify the recovery denominator and track where each PGM leaves the flowsheet. (Ye et al., 2025; Yu et al., 2024)

11. Downstream Separation after Aqua Regia Leaching

Post-leach treatment is not independent of leaching chemistry. Residual nitric acid and nitrate can influence redox conditions, while chloride activity determines the charge and extractability of many PGM complexes. Solvent extraction, ion exchange, membranes, selective adsorption, precipitation, and reduction each impose different requirements on speciation and competing ions.

An integrated Pt–Pd–Rh strategy should specify whether individual metals are initially isolated, co-extracted, selectively stripped, or recovered through a sequence of chemical conversions. Separation behavior reported for synthetic single-metal chloride salts is useful for mechanistic interpretation but cannot substitute for multimetal leachate testing with realistic impurity inventories.

Table 4 distinguishes separation principles and the compatibility questions that arise for mixed PGM chloride liquors. Reported selectivity is meaningful only alongside solution composition and regeneration performance.

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Table 4. Downstream recovery alternatives for chloride-bearing PGM liquors

Operation	Useful basis	Potential constraint
Solvent extraction	Metal-dependent chloro-complex distribution	Acid, nitrate, and co-extraction effects
Ion exchange/chelation	Charge and ligand-dependent affinity	Regeneration and competing ions
Membranes/adsorbents	Phase-specific or ligand-specific binding	Fouling and performance in mixed feeds
Selective precipitation/reduction	Controlled conversion to isolated solids	Coprecipitation, purity, and losses
Extraction vs refined recovery	Xi and Ri by element; feed-to-liquor and feed-to-product boundaries	Confusing intermediate concentration with final yield
Dissolution/separation selectivity	Define PGM-to-impurity dissolved mass ratio and stage-specific separation distribution.	Unstated impurity set or incomparable process boundary
Impurity loading	Measured co-dissolved mass per liquor volume or target metal mass, with sampling time	Purification burden understated
Reagent-use efficiency	Net fresh reagent moles per kg dissolved or refined PGM; recycling credit specified	Acid savings mislabeled as selectivity.

Note. Qualitative synthesis of published technology classes; selectivity must be verified for the actual leachate.

Use Table 4 as a compatibility screen: a separation method becomes an industrial candidate only when its performance has been tested in liquor containing the residual oxidants, chloride species, and impurities arising from the actual leach.

Evidence from purified gold or single-metal chloride liquors can reveal sorption or extraction behavior, but does not establish Pt–Pd–Rh separation factors in a nitrate-bearing multimetal solution. The cited studies therefore provide methodological context rather than a pooled performance benchmark. (Cyganowski et al., 2017; Firmansyah et al., 2019; Gupta & Singh, 2013)

For solvent extraction or resin processing, uptake is one stage of a cycle. Reliable route comparisons also need stripping yield, impurity deportment, reagent regeneration, and cumulative losses to waste streams. (He et al., 2026; Hosseinzadeh & Petersen, 2024; Kononova et al., 2010)

The transfer step requiring specific validation is contact with the actual pregnant liquor after any nitrate-destruction or conditioning treatment. An idealized synthetic salt solution

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cannot reproduce every competing ion or residual oxidant. (Lee et al., 2010; Lee et al., 2020; MacDonald et al., 2024)

Recovery media differ in their tolerance of nitrate, chloride concentration, and impurities. Comparative evaluation should report both loading and complete regeneration losses. (Marinho et al., 2011; Matsumiya et al., 2019; Nguyen & Lee, 2023)

Single-solute distribution coefficients are useful for screening affinity, but multimetal systems additionally require tests for competition, displacement, co-loading, and stripping losses. These cannot be derived by simply combining independent uptake values. (Nguyen et al., 2023; Nguyen et al., 2020; Nikoloski et al., 2015)

High initial sorption is not equivalent to high refined recovery. Relevant evidence includes repeated-cycle behavior, stripping completeness, and final impurity levels. (Paiva, 2023; Paiva et al., 2017; Paiva et al., 2022)

Residual nitrate and oxidizing species may change the chemistry an extraction reagent encounters after the initial leach. Compatibility testing should therefore employ an appropriately conditioned, compositionally representative liquor. (Radzyminska-Lenarcik et al., 2021; Shen et al., 2011; Shen et al., 2010a)

Both chloro-complex distributions and separation-medium competition vary with the solution matrix. Any comparison should therefore identify chloride-activity assumptions, interfering ions, regenerated-reagent inventory, and metal losses in the aqueous raffinate. (Song et al., 2026; Sun & Lee, 2011; Sun et al., 2012)

An apparently selective sorbent tested on a simple PGM salt solution remains a laboratory screening result until its behavior has been established in a multicomponent process liquor. (Zabielska-Konopka et al., 2026)

12. Reagent Efficiency, Safety, Environmental Burden, and Alternatives

Aqua-regia processing must address generation and containment of NO_x, NOCl, and potentially Cl_2, materials compatibility, acid losses, and chloride- and nitrate-bearing effluents. Evaluate alternative routes based on electro-generated oxidants, chloride salts, ionic liquids,

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eutectic solvents, or biological pretreatments using complete process boundaries, not the absence of nitric acid alone.

Industrial comparison requires net metal recovery, utilities, emissions abatement, reagent regeneration, occupational controls, and residue management. Life-cycle assessment and techno-economic analysis cannot simply transfer assumptions from automotive catalysts to mineral concentrates or fuel-cell materials, because feed grade and process integration differ substantially.

Table 5 identifies the boundaries required for a fair process comparison, from reagent preparation and emissions control to final metal quality and waste management.

Table 5. Integrated evaluation criteria for aqua regia and competing PGM processes

Domain	Minimum outcome	Typical bias if omitted
Metallurgical performance	Per-element feed-to-liquor extraction X and feed-to-saleable-metal refined recovery R; sampling boundary	Liquor assay mistaken for final product recovery
Selectivity and impurity loading	For specified target i/impurity j: dissolved mass i/mass j; impurity mg L^{-1} and per kg dissolved target; separation stage split factors	Unreported impurity set/near-zero denominator obscures selectivity.
Reagent-use efficiency	Net consumed moles of each fresh acid/oxidant per kg dissolved or refined target; explicit recycle boundary.	Lower reagent demand incorrectly described as higher selectivity.
Energy and utilities	Electricity, heat and water per kg refined target, at specified scale	Energy burden omitted
Safety and emissions	NO_x, NOCl, Cl_2, possible OsO_4 where applicable; corrosion/effluent and abatement	Unpriced environmental and occupational risk
Technology readiness	Demonstrated scale, reactor closure, gas capture and downstream product specification	Lab-scale dissolution overgeneralized

Note. Original assessment framework; specific numerical values require feed- and site-dependent measurements.

The process boundaries in Table 5 prevent a leaching-only comparison from being mistaken for a whole-route assessment. The choice of alternative must account for reagent preparation, gas abatement, separation performance, treatment of residual liquor, and refined-product quality.

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A lower-toxicity label for an alternative lixiviant does not establish a lower life-cycle burden without accounting for regeneration, energy, off-gas treatment, and final waste handling. (Duclos et al., 2020; Fajar et al., 2021; Ghodrat et al., 2017)

Industrial readiness must be argued from integrated balances, corrosion and emission control, and refined product specifications—not laboratory dissolution values alone. (Karim et al., 2024; Kuralay et al., 2026; Lanaridi et al., 2022)

Environmental route selection requires a consistent system boundary from reagent supply through off-gas abatement, separation, water treatment, and residue disposition. (Lanaridi et al., 2021; C. Liu et al., 2024; Lord et al., 2025)

Bench-scale recovery is only a component of process feasibility; reagent closure, materials compatibility, effluent treatment, and saleable-metal quality remain necessary evidence. (Pereira, 2026e; Rezvanian et al., 2026; Wongsawa et al., 2020)

13. Conclusions and Future Research Priorities

Aqua regia is best treated as a time-dependent oxidative chloride system rather than a fixed 3:1 HCl: HNO_3 reagent. Interpreting it requires an initial and evolving chemical inventory, gas exchange, support or mineral-host accessibility, and explicit dissolved-metal and refined-product boundaries. In the evidence reviewed, Pt and Pd have more directly relevant catalyst-leaching descriptions than Ru, Ir, or Os; the latter require separate assessment and should not be assigned a shared kinetic or volatility behavior. Total chloride, estimated free chloride activity, redox-potential proxies, and oxidant inventory are not interchangeable measurement quantities. The proposed reporting framework distinguishes extraction, dissolved-metal selectivity, downstream separation, impurity loading, reagent consumption, and refined recovery, but is not a validated industrial protocol.

Metal-specific dissolution, particularly for rhodium and refractory Ru–Ir–Os associations, cannot be inferred from Pt or Pd extraction alone. The distinction between dissolution selectivity and refined recovery is equally important: a high PGM extraction percentage can coexist with severe impurity loading and expensive leachate conditioning.

Priorities include in situ monitoring of redox and chlorine/nitrogen species; complete acid and off-gas balances; residue-based kinetic tests; experimentally supported Rh and minor-

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PGM pathways; and integrated separation trials on actual multimetal liquors. Future route assessments should report per-metal refined yield, reagent regeneration, occupational and environmental controls, and feed-specific process economics.

Declarations

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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

Abbas, Y., Ali, S., Basharat, M., Sharif, H. M. A., Iqbal, M. A., Bououdina, M., Wang, H., & Khan, N. A. (2025). Rapid and selective e-waste gold extraction from aqua regia by dual redox active sites of skeleton-modulated poly(organo)phosphazenes. *Chemical Engineering Journal*, *513*, 163037. https://doi.org/10.1016/j.cej.2025.163037

Abo Atia, T., & Spooren, J. (2021). Fast microwave leaching of platinum, rhodium, and cerium from spent non-milled autocatalyst monolith. *Chemical Engineering and Processing—Process Intensification*, *164*, 108378. https://doi.org/10.1016/j.cep.2021.108378

Abo Atia, T., Wouters, W., Monforte, G., & Spooren, J. (2021). Microwave chloride leaching of valuable elements from spent automotive catalysts: Understanding the role of hydrogen peroxide. *Resources, Conservation and Recycling*, *166*, 105349. https://doi.org/10.1016/j.resconrec.2020.105349

Bae, M., Lee, J.-C., Lee, H., & Kim, S. (2020). Recovery of nitric acid and gold from gold-bearing aqua regia by tributyl phosphate. *Separation and Purification Technology*, *235*, 116154. https://doi.org/10.1016/j.seppur.2019.116154

Baloyi, N. P., Nheta, W., Sibanda, V., & Safari, M. (2024). Mineralogical insights into PGM recovery from Middle Group (1–4) chromite tailings. *Minerals*, *14*(9), 924. https://doi.org/10.3390/min14090924

Chen, Y., Guan, S., Ge, H., Chen, X., Xu, Z., Yue, Y., Yamashita, H., Yu, H., Li, H., & Bian, Z. (2022). Photocatalytic dissolution of precious metals by TiO2 through photogenerated free radicals. *Angewandte Chemie International Edition*, *61*, e202213640. https://doi.org/10.1002/anie.202213640

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Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Chen, Y., Xu, M., Wen, J., Wan, Y., Zhao, Q., Cao, X., Ding, Y., Wang, Z. L., Li, H., & Bian, Z. (2021). Selective recovery of precious metals through photocatalysis. *Nature Sustainability*, *4*, 618–626. https://doi.org/10.1038/s41893-021-00697-4

Cyganowski, P., Garbera, K., Leśniewicz, A., Wolska, J., Pohl, P., & Jermakowicz-Bartkowiak, D. (2017). The recovery of gold from the aqua regia leachate of electronic parts using a core–shell type anion exchange resin. *Journal of Saudi Chemical Society*, *21*(6), 741–750. https://doi.org/10.1016/j.jscs.2017.03.007

Demarco, J. O., Cadore, J. S., Veit, H. M., Madalosso, H. B., Tanabe, E. H., & Bertuol, D. A. (2020). Leaching of platinum group metals from spent automotive catalysts using organic acids. *Minerals Engineering*, *159*, 106634. https://doi.org/10.1016/j.mineng.2020.106634

Ding, Y., Zhang, S., & Liu, B. (2019). Recovery of precious metals from electronic waste and spent catalysts: A review. *Resources, Conservation and Recycling*, *141*, 284–298. https://doi.org/10.1016/j.resconrec.2018.10.041

Ding, Y., Zheng, H., Zhang, S., Liu, B., Wu, B., & Jian, Z. (2020). Highly efficient recovery of platinum, palladium, and rhodium from spent automotive catalysts via iron melting collection. *Resources, Conservation and Recycling*, *155*, 104644. https://doi.org/10.1016/j.resconrec.2019.104644

Dong, H., Zhao, J., Chen, J., Wu, Y., & Li, B. (2015). Recovery of platinum group metals from spent catalysts: A review. *International Journal of Mineral Processing*, *145*, 108–113. https://doi.org/10.1016/j.minpro.2015.06.009

Dorfling, C., Akdogan, G., Bradshaw, S. M., & Eksteen, J. J. (2011). Determination of the relative leaching kinetics of Cu, Rh, Ru and Ir during the sulphuric acid pressure leaching of leach residue derived from Ni-Cu converter matte enriched in platinum group metals. *Minerals Engineering*, *24*(6), 583–589. https://doi.org/10.1016/j.mineng.2010.08.021

Duclos, L., Chattot, R., Dubau, L., Thivel, P., Mandil, G., Laforest, V., Bolloli, M., Vincent, R., & Svecova, L. (2020). Closing the loop: Life cycle assessment and optimization of a PEMFC platinum-based catalyst recycling process. *Green Chemistry*, *22*, 1919–1933. https://doi.org/10.1039/C9GC03630J

Duclos, L., Svecova, L., Laforest, V., Mandil, G., & Thivel, P.-X. (2016). Process development and optimization for platinum recovery from PEM fuel cell catalyst. *Hydrometallurgy*, *160*, 79–89. https://doi.org/10.1016/j.hydromet.2015.12.013

Elomaa, H., Seisko, S., Junnila, T., Sirviö, T., Wilson, B. P., Aromaa, J., & Lundström, M. (2017). The effect of the redox potential of aqua regia and temperature on the Au, Cu, and Fe dissolution from WPCBs. *Recycling*, *2*(3), 14. https://doi.org/10.3390/recycling2030014

Fajar, A. T. N., Hanada, T., & Goto, M. (2021). Recovery of platinum group metals from a spent automotive catalyst using polymer inclusion membranes containing an ionic liquid carrier. *Journal of Membrane Science*, *629*, 119296. https://doi.org/10.1016/j.memsci.2021.119296

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Firmansyah, M. L., Kubota, F., & Goto, M. (2019). Selective recovery of platinum group metals from spent automotive catalysts by leaching and solvent extraction. *Journal of Chemical Engineering of Japan*, *52*(11), 835–842. https://doi.org/10.1252/jcej.19we093

Ge, T., He, J.-D., Xu, L., Xiong, Y.-H., Wang, L., Zhou, X.-W., Tian, Y.-P., & Zhao, Z. (2023). Recovery of platinum from spent automotive catalyst based on hydrometallurgy. *Rare Metals*, *42*, 1118–1137. https://doi.org/10.1007/s12598-022-02236-2

Ghodrat, M., Rhamdhani, M. A., Sharafi, P., & Samali, B. (2017). A comparative life cycle assessment of recycling the platinum group metals from automobile catalytic converters: An Australian perspective. *Metallurgical and Materials Transactions E*, *4*, 77–88. https://doi.org/10.1007/s40553-017-0109-1

Granados-Fernández, R., Montiel, M. A., Díaz-Abad, S., Rodrigo, M. A., & Lobato, J. (2021). Platinum recovery techniques for a circular economy. *Catalysts*, *11*(8), 937. https://doi.org/10.3390/catal11080937

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

Gupta, B., & Singh, I. (2013). Extraction and separation of platinum, palladium, and rhodium using Cyanex 923 and their recovery from real samples. Hydrometallurgy, 134–135, 11–18. https://doi.org/10.1016/j.hydromet.2013.01.001

Hasani, M., Khodadadi, A., Koleini, S. M. J., Saeedi, A. H., & Meléndez, A. M. (2017). Simultaneous leaching of Pt, Pd, and Rh from automotive catalytic converters in chloride-containing solutions. *Journal of Physics: Conference Series*, *786*, 012042. https://doi.org/10.1088/1742-6596/786/1/012042

Hasani, M., Khodadadi, A., Koleini, S. M. J., Saeedi, A. H., Pérez-Pacheco, Y., & Meléndez, A. M. (2017). Platinum leaching from automotive catalytic converters with aqua regia. *Journal of Physics: Conference Series*, *786*, 012043. https://doi.org/10.1088/1742-6596/786/1/012043

He, X., Lu, Y., Kang, X., Liu, K., Wang, G., Yang, H., Liu, L., Dong, H., Zhao, J., Wang, Y., Wang, C., & Han, J. (2026). Solvent extraction of rhodium from chloride media: Speciation, activation, and separation mechanisms. *Metals*, *16*(6), 567. https://doi.org/10.3390/met16060567

Hedrich, S., Kraemer, D., Junge, M., Marbler, H., Bau, M., & Schippers, A. (2020). Bioprocessing of oxidized platinum group element ores as pre-treatment for efficient chemical extraction of PGE. *Hydrometallurgy*, *196*, 105419. https://doi.org/10.1016/j.hydromet.2020.105419

H'ng, Y. N., Almeida, M. I. G. S., Lamb, R. N., & Kolev, S. D. (2025). A comparative evaluation of leaching reagents of platinum group metals from spent catalytic

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
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DOI: 10.66104/0g04vq90
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converters using microwave heating. *Chemistry—An Asian Journal*, *20*(5), e202400895. https://doi.org/10.1002/asia.202400895

Hosseinzadeh, M., & Petersen, J. (2024). Recovery of Pt, Pd, and Rh from spent automotive catalysts through combined chloride leaching and ion exchange: A review. *Hydrometallurgy*, *228*, 106360. https://doi.org/10.1016/j.hydromet.2024.106360

Hosseinzadeh, M., & Petersen, J. (2025). Platinum(IV), palladium(II), and rhodium(III) recovery from mixed acidic chloride solutions using chelating ion exchange resin Puromet MTS9600. *Solvent Extraction and Ion Exchange*, *42*(6–7), 609–635. https://doi.org/10.1080/07366299.2024.2446472

Hu, Y., Xu, J., Zhang, F., Tian, Y., & Ren, Y. (2026). Leaching kinetics of precious metals from platinum–palladium concentrate using H_2O_2 in an acidic chloride system. *Minerals Engineering*, *237*, 110031. https://doi.org/10.1016/j.mineng.2025.110031

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), 93. https://doi.org/10.3390/resources10090093

Ilyas, S., & Kim, H. (2022). Recovery of platinum-group metals from an unconventional source of catalytic converter using pressure cyanide leaching and ionic liquid extraction. *JOM*, *74*, 1020–1026. https://doi.org/10.1007/s11837-021-05119-6

Ilyas, S., Srivastava, R. R., Kim, H., Ilyas, N., & Sattar, R. (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

Jha, M. K., Lee, J.-C., Kim, M.-S., Jeong, J., Kim, B.-S., & Kumar, V. (2013). Hydrometallurgical recovery/recycling of platinum by the leaching of spent catalysts: A review. *Hydrometallurgy*, *133*, 23–32. https://doi.org/10.1016/j.hydromet.2012.11.012

Junior, S. G. B., & Afonso, J. C. (2010). Processing of spent platinum-based catalysts via fusion with potassium hydrogenosulfate. *Journal of Hazardous Materials*, *184*, 717–723. https://doi.org/10.1016/j.jhazmat.2010.08.098

Kamisono, M., Hanada, T., & Goto, M. (2024). Platinum group metal recycling from spent automotive catalysts using reusable hydrophobic deep eutectic solvent. *ACS Sustainable Resource Management*, *1*(5), 1021–1028. https://doi.org/10.1021/acssusresmgt.4c00100

Karamanoğlu, P., & Aydın, S. (2016). An economic analysis of the recovery of gold from CPU, boards, and connectors using aqua regia. *Desalination and Water Treatment*, *57*(6), 2570–2575. https://doi.org/10.1080/19443994.2015.1063086

Karim, S., & Ting, Y.-P. (2020). Ultrasound-assisted nitric acid pretreatment for enhanced biorecovery of platinum group metals from spent automotive catalyst. *Journal of Cleaner Production*, *255*, 120199. https://doi.org/10.1016/j.jclepro.2020.120199

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Karim, S., & Ting, Y.-P. (2022). Bioleaching of platinum, palladium, and rhodium from spent automotive catalyst using bacterial cyanogenesis. *Bioresource Technology Reports*, *18*, 101069. https://doi.org/10.1016/j.biteb.2022.101069

Karim, S., Saw, H. M., & Ting, Y.-P. (2024). Evaluation of green chemistry metrics for sustainable recycling of platinum group metals from spent automotive catalysts via bioleaching. *Green Chemistry*, *26*, 4112–4126. https://doi.org/10.1039/D3GC03918H

Kim, B.-S., Lee, J.-C., Jeong, J., Kim, M.-S., & Kim, W. (2013). A novel process for extracting precious metals from spent mobile phone PCBs and automobile catalysts. *Materials Transactions*, *54*(6), 1045–1048. https://doi.org/10.2320/matertrans.M2013051

Kim, C., & Hong, H.-J. (2024). Recovery and isolation strategies of platinum, palladium, and rhodium from spent automotive catalyst leachate using a polyethylene-imine-grafted cellulose nanofibril aerogel. *Industrial & Engineering Chemistry Research*, *63*(10), 4547–4556. https://doi.org/10.1021/acs.iecr.3c04137

Kim, M.-S., Kim, E.-Y., Jeong, J., Lee, J.-C., & Kim, W. (2010). Recovery of platinum and palladium from the spent petroleum catalysts by substrate dissolution in sulfuric acid. *Materials Transactions*, *51*(10), 1927–1933. https://doi.org/10.2320/matertrans.M2010218

Kim, M.-S., Park, S.-W., Lee, J.-C., & Choubey, P. K. (2016). A novel zero-emission concept for electrogenerated chlorine leaching and its application to extraction of platinum group metals from spent automotive catalyst. *Hydrometallurgy*, *159*, 19–27. https://doi.org/10.1016/j.hydromet.2015.10.030

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

Kononova, O. N., Leyman, T. A., Melnikov, A. M., Kashirin, D. M., & Tselukovskaya, M. M. (2010). Ion exchange recovery of platinum from chloride solutions. *Hydrometallurgy*, *100*, 161–167. https://doi.org/10.1016/j.hydromet.2009.11.011

Kononova, O. N., Melnikov, A. M., Borisova, T. V., & Krylov, A. S. (2011). Simultaneous ion exchange recovery of platinum and rhodium from chloride solutions. *Hydrometallurgy*, *105*, 341–349. https://doi.org/10.1016/j.hydromet.2010.11.009

Kukurugya, F., Wouters, W., & Spooren, J. (2025). Microwave-assisted chloride leaching for efficient recovery of platinum group metals from spent automotive catalysts: An approach for chemical reagent reduction. *Cleaner Engineering and Technology*, *24*, 100868. https://doi.org/10.1016/j.clet.2024.100868

Kuralay, Y., Ilkhani, Z., Hardy, J., Capozzi, L., & Aiouache, F. (2026). Towards sustainable bioleaching of platinum group metals from spent automotive catalysts. *Materials*, *19*(16), 3495. https://doi.org/10.3390/ma19163495

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Kuzuhara, S., Ota, M., & Kasuya, R. (2021). Recovery of platinum group metals from spent automotive catalysts using lithium salts and hydrochloric acid. *Materials*, *14*(22), 6843. https://doi.org/10.3390/ma14226843

Lanaridi, O., Platzer, S., Nischkauer, W., Hidalgo Betanzos, J., Unzurrunzaga Iturbe, A., Del Rio Gaztelurrutia, C., Sanchez-Cupido, L., Siriwardana, A., Schnürch, M., Limbeck, A., Konegger, T., & Bica-Schröder, K. (2022). Benign recovery of platinum group metals from spent automotive catalysts using choline-based deep eutectic solvents. *Green Chemistry Letters and Reviews*, *15*(2), 405–415. https://doi.org/10.1080/17518253.2022.2068973

Lanaridi, O., Sahoo, A. R., Limbeck, A., Naghdi, S., & Binnemans, K. (2021). Toward the recovery of platinum group metals from a spent automotive catalyst with supported ionic liquid phases. *ACS Sustainable Chemistry & Engineering*, *9*(1), 375–386. https://doi.org/10.1021/acssuschemeng.0c07384

Lee, J. Y., Raju, B., Kumar, B. N., Kumar, J. R., Park, H. K., & Reddy, B. R. (2010). Solvent extraction separation and recovery of palladium and platinum from chloride leach liquors of spent automobile catalyst. *Separation and Purification Technology*, *73*(2), 213–218. https://doi.org/10.1016/j.seppur.2010.04.003

Lee, J.-C., Kurniawan, N., Hong, H., Chung, K.-W., & Kim, S. (2020). Separation of platinum, palladium, and rhodium from aqueous solutions using ion exchange resin: A review. *Separation and Purification Technology*, *246*, 116896. https://doi.org/10.1016/j.seppur.2020.116896

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

Liu, C., Sun, S., Tu, G., & Xiao, F. (2023). A novel method for extraction of platinum from spent automotive catalyst: Utilization of spent fluid catalytic cracking catalyst as flux. *Environmental Technology*, *44*(2), 139–149. https://doi.org/10.1080/09593330.2021.1965662

Liu, C., Sun, S., Zhu, X., & Tu, G. (2024). Comprehensive review on recovery of platinum group metals from spent automotive catalysts by metal capture technology: Present progress and outlook. *Journal of Environmental Chemical Engineering*, *12*(5), 114017. https://doi.org/10.1016/j.jece.2024.114017

Liu, M., Yang, C., Tian, M., Zhao, Y., Liu, X., Zhan, C., Li, Z., Xue, T., He, F., Wang, H., & 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, M., Zhao, Y., Tian, M., Liu, K., Hu, G., Zhang, J., Xue, T., Qi, T., & Zhang, H. (2024). Extraction of PGMs from insoluble Fe–Si–PGMs alloy by combined thermochemical and mechanochemical leaching: Sustainable, efficient, and scalable. *Separation and Purification Technology*, *333*, 125925. https://doi.org/10.1016/j.seppur.2023.125925

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Lord, J., White, R., Murphy, R., & Sadhukhan, J. (2025). Aligning platinum recycling with hydrogen economy growth: A comparative LCA of hydrometallurgical and pyrometallurgical methods. *Green Chemistry*, *27*, 14577–14588. https://doi.org/10.1039/D5GC02447A

MacDonald, L., Zhang, D., & Karamalidis, A. (2024). Platinum group metals: Key solid phase adsorption technologies for separation from primary and secondary sources. *Resources, Conservation and Recycling*, *205*, 107590. https://doi.org/10.1016/j.resconrec.2024.107590

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

Marinho, R. S., da Silva, C. N., Afonso, J. C., & da Cunha, J. W. S. D. (2011). Recovery of platinum, tin, and indium from spent catalysts in chloride medium using strong basic anion exchange resins. *Journal of Hazardous Materials*, *192*(3), 1155–1160. https://doi.org/10.1016/j.jhazmat.2011.06.021

Matsumiya, M., Song, Y., Tsuchida, Y., Ota, H., & Tsunashima, K. (2019). Recovery of platinum by solvent extraction and direct electrodeposition using ionic liquid. *Separation and Purification Technology*, *214*, 162–167. https://doi.org/10.1016/j.seppur.2018.06.018

Moon, J.-Y., Nishihama, S., & Yoshizuka, K. (2018). Recovery of platinum and palladium from spent automobile catalyst by solvent-impregnated resins. *Solvent Extraction and Ion Exchange*, *36*, 470–479. https://doi.org/10.1080/07366299.2018.1527806

Morcali, M. H. (2020). A new approach to recover platinum-group metals from spent catalytic converters via iron matte. *Resources, Conservation and Recycling*, *159*, 104891. https://doi.org/10.1016/j.resconrec.2020.104891

Mpinga, C. N., Eksteen, J. J., Aldrich, C., & Dyer, L. (2015). Direct leach approaches to platinum group metal (PGM) ores and concentrates: A review. *Minerals Engineering*, *78*, 93–113. https://doi.org/10.1016/j.mineng.2015.04.015

Murai, T., & Kubo, H. (2026). High-efficiency recovery of platinum-group metals from spent automotive catalysts using ammonium hydrogen sulfate. *Materials Transactions*, *67*(5), 871–880. https://doi.org/10.2320/matertrans.M-M2026803

Murray, A. J., Zhu, J., Wood, J., & Macaskie, L. E. (2017). A novel biorefinery: Biorecovery of precious metals from spent automotive catalyst leachates into new catalysts. *Minerals Engineering*, *113*, 102–108. https://doi.org/10.1016/j.mineng.2017.08.011

Mvokwe, S. A., Oyedeji, O. O., Agoro, M. A., Meyer, E. L., & Rono, N. (2025). A critical review of the hydrometallurgical and pyrometallurgical recovery processes of platinum group metals from end-of-life fuel cells. *Membranes*, *15*(1), 13. https://doi.org/10.3390/membranes15010013

Mwase, J. M., Petersen, J., & Eksteen, J. J. (2012). A conceptual flowsheet for heap leaching of platinum group metals (PGMs) from a low-grade ore concentrate. Hydrometallurgy, 111–112, 129–135. https://doi.org/10.1016/j.hydromet.2011.11.012

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Nguyen, T. N. H., & Lee, M. S. (2023). Recovery of Au and Pd from the etching solution of printed circuit boards by cementation, solvent extraction, reduction, and precipitation. *Journal of Industrial and Engineering Chemistry*, *126*, 214–223. https://doi.org/10.1016/j.jiec.2023.06.011

Nguyen, V. N. H., Song, S. J., & Lee, M. S. (2022). Separation of palladium and platinum metals by selective and simultaneous leaching and extraction with aqueous/non-aqueous solutions. *Hydrometallurgy*, *208*, 105814. https://doi.org/10.1016/j.hydromet.2021.105814

Nguyen, V. T., Binnemans, K., & Riaño, S. (2023). Refining of palladium, platinum, and rhodium from a pregnant leach solution of spent automotive catalysts by continuous counter-current solvent extraction with ionic liquids in mixer-settlers. *Industrial & Engineering Chemistry Research*, *62*(24), 9549–9562. https://doi.org/10.1021/acs.iecr.3c00851

Nguyen, V. T., Riaño, S., & Binnemans, K. (2020). Separation of precious metals by split-anion extraction using water-saturated ionic liquids. *Green Chemistry*, *22*, 8375–8388. https://doi.org/10.1039/D0GC02356F

Nguyen, V. T., Riaño, S., & Binnemans, K. (2021). Solvometallurgical recovery of platinum group metals from spent automotive catalysts. *ACS Sustainable Chemistry & Engineering*, *9*(1), 337–350. https://doi.org/10.1021/acssuschemeng.0c07355

Nicol, G., Goosey, E., Şanlı Yıldız, D., Loving, E., Nguyen, V. T., Riaño, S., Yakoumis, I., Martinez, A. M., Siriwardana, A., Unzurrunzaga, A., Spooren, J., Abo Atia, T., Michielsen, B., Dominguez-Benetton, X., & Lanaridi, O. (2021). Platinum group metals recovery using secondary raw materials (PLATIRUS): Project overview with a focus on processing spent autocatalyst. *Johnson Matthey Technology Review*, *65*(1), 127–147. https://doi.org/10.1595/205651321X16057842276133

Nicol, M. J. (2023). The dissolution of gold in chloride media under ambient conditions—A re-assessment of mechanisms. *Hydrometallurgy*, *222*, 106175. https://doi.org/10.1016/j.hydromet.2023.106175

Niemelä, M., Pitkäaho, S., Ojala, S., Keiski, R. L., & Perämäki, P. (2012). Microwave-assisted aqua regia digestion for determining platinum, palladium, rhodium, and lead in catalyst materials. *Microchemical Journal*, *101*, 75–79. https://doi.org/10.1016/j.microc.2011.11.001

Nikoloski, A. N., Ang, K.-L., & Li, D. (2015). Recovery of platinum, palladium, and rhodium from acidic chloride leach solution using ion exchange resins. *Hydrometallurgy*, *152*, 20–32. https://doi.org/10.1016/j.hydromet.2014.12.006

Nogueira, C. A., Paiva, A. P., Costa, M. C., & Rosa da Costa, A. M. (2020). Leaching efficiency and kinetics of the recovery of palladium and rhodium from a spent auto-catalyst in HCl/$CuCl_2$ media. *Environmental Technology*, *41*(18), 2293–2304. https://doi.org/10.1080/09593330.2018.1563635 tandfonline.com

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Paiva, A. P. (2023). Recent advances in platinum and palladium solvent extraction from real leaching solutions of spent catalysts. *Catalysts*, *13*, 1146. https://doi.org/10.3390/catal13071146

Paiva, A. P., Ortet, O., Carvalho, G. I., & Nogueira, C. A. (2017). Recovery of palladium from a spent industrial catalyst through leaching and solvent extraction. *Hydrometallurgy*, *171*, 394–401. https://doi.org/10.1016/j.hydromet.2017.06.014

Paiva, A. P., Piedras, F. V., Rodrigues, P. G., & Nogueira, C. A. (2022). Hydrometallurgical recovery of platinum-group metals from spent auto-catalysts—Focus on leaching and solvent extraction. *Separation and Purification Technology*, *286*, 120474. https://doi.org/10.1016/j.seppur.2022.120474

Palanisamy, M. M., Kandasamy, K., & Myneni, V. R. (2022). Two-phase leaching for metal recovery from waste printed circuit boards: Statistical optimization. *Chemical Industry & Chemical Engineering Quarterly*, *28*(2), 103–113. https://doi.org/10.2298/CICEQ210115022M

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/10.5281/zenodo.22658215

Pereira, A. C. (2026c). Electro-assisted leaching of platinum-group metals: Interfacial electron transfer, in situ oxidant generation, redox-mediator regeneration, and process integration—A critical review. *Nexus Science Review*, *1*(6). https://doi.org/10.66104/3t0rav54

Pereira, A. C. (2026d). Iridium extraction and recovery from primary ores and secondary materials: Process chemistry, metallurgical routes, selectivity, and industrial scale-up—A critical review. *Journal International Review of Research Studies*, *1*(11). https://doi.org/10.66104/weke5g87

Pereira, A. C. (2026e). 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

Pietrantonio, M., Pucciarmati, S., Forte, F., De Angelis, D., & Fontana, D. (2025). Recovery of metallic gold, silver, and copper from end-of-life mobile phones by hydrometallurgy. *Journal of Material Cycles and Waste Management*, *27*, 2395–2403. https://doi.org/10.1007/s10163-025-02240-5

Prasetyo, E., & Anderson, C. (2020). Platinum group elements recovery from used catalytic converters by acidic fusion and leaching. *Metals*, *10*(4), 485. https://doi.org/10.3390/met10040485

Radzyminska-Lenarcik, E., Pyszka, I., & Kosciuszko, A. (2021). Separation and recovery of gold(III), palladium(II), and platinum(IV) by solvent extraction using a new β-

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

diketone derivative from acidic solutions. *Materials*, *14*(16), 4436. https://doi.org/10.3390/ma14164436

Raju, B., Kumar, J. R., Lee, J.-Y., Kwon, H.-S., Kantam, M. L., & Reddy, B. R. (2012). Separation of platinum and rhodium from chloride solutions containing aluminum, magnesium, and iron using solvent extraction and precipitation methods. Journal of Hazardous Materials, 227–228, 142–147. https://doi.org/10.1016/j.jhazmat.2012.05.025

Rao, M. D., Singh, K. K., Morrison, C. A., & Love, J. B. (2020). Challenges and opportunities in the recovery of gold from electronic waste. *RSC Advances*, *10*, 4300–4309. https://doi.org/10.1039/C9RA07607G

Reddy, B. R., Raju, B., Lee, J. Y., & Park, H. K. (2010). Process for the separation and recovery of palladium and platinum from spent automobile catalyst leach liquor using LIX 84I and Alamine 336. *Journal of Hazardous Materials*, *180*(1–3), 253–258. https://doi.org/10.1016/j.jhazmat.2010.04.022

Rezvanian, S. M. R., Karimi-Jashni, A., & Zerafat, M. M. (2026). Sustainable hydrothermal leaching for platinum recovery from petrochemical spent catalysts: Experimental study and process optimization. *Scientific Reports*, *16*, 18147. https://doi.org/10.1038/s41598-026-43945-3

Rocky, M. M. H., Rahman, I. M. M., Endo, M., & Hasegawa, H. (2024). Comprehensive insights into aqua regia-based hybrid methods for efficient recovery of precious metals from secondary raw materials. *Chemical Engineering Journal*, *495*, 153537. https://doi.org/10.1016/j.cej.2024.153537

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

Sasaki, H., & Maeda, M. (2014). Zn-vapor pretreatment for acid leaching of platinum group metals from automotive catalytic converters. Hydrometallurgy, 147–148, 59–67. https://doi.org/10.1016/j.hydromet.2014.04.019

Seisko, S., Aromaa, J., & Lundström, M. (2019). Features affecting the cupric chloride leaching of gold. *Minerals Engineering*, *137*, 94–101. https://doi.org/10.1016/j.mineng.2019.03.030

Seisko, S., Lampinen, M., Aromaa, J., Laari, A., Koiranen, T., & Lundström, M. (2018). Kinetics and mechanisms of gold dissolution by ferric chloride leaching. *Minerals Engineering*, *115*, 131–141. https://doi.org/10.1016/j.mineng.2017.10.017

Shen, S., Guishen, L., Pan, T., He, J., & Guo, Z. (2011). Selective adsorption of platinum ions from chloride solutions obtained by leaching chlorinated spent automotive catalysts on ion exchange resin Diaion WA21J. *Journal of Colloid and Interface Science*, *364*(2), 482–489. https://doi.org/10.1016/j.jcis.2011.08.043

Shen, S., Pan, T., Liu, X., Yuan, L., Wang, J., Zhang, Y., & Guo, Z. (2010a). Adsorption of palladium(II) complexes from chloride solutions obtained by leaching chlorinated

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

spent automotive catalysts on ion exchange resin Diaion WA21J. *Journal of Colloid and Interface Science*, *345*(1), 12–18. https://doi.org/10.1016/j.jcis.2010.01.049

Shen, S., Pan, T., Liu, X., Yuan, L., Wang, J., Zhang, Y., & Guo, Z. (2010b). Adsorption of rhodium(III) complexes from chloride solutions obtained by leaching chlorinated spent automotive catalysts on ion-exchange resin Diaion WA21J. *Journal of Hazardous Materials*, *179*(1–3), 104–112. https://doi.org/10.1016/j.jhazmat.2010.02.064

Shin, D., Park, J., Jeong, J., & Kim, B.-S. (2015). A biological cyanide production and accumulation system and the recovery of platinum-group metals from spent automotive catalysts by biogenic cyanide. *Hydrometallurgy*, *158*, 10–18. https://doi.org/10.1016/j.hydromet.2015.09.021

Song, S. G., Shi, Y. B., & Lee, M. S. (2026). Sequential separation of Pd(II), Pt(IV), and Rh(III) from synthetic hydrochloric acid leaching solution of spent automotive catalyst containing Al(III) and Ce(III) by chemical reduction, precipitation, and solvent extraction. Mineral Processing and Extractive Metallurgy Review. https://doi.org/10.1080/08827508.2026.2724559

Song, S. J., Nguyen, V. N. H., & Lee, M. S. (2024). Separation of palladium, platinum, and rhodium from metallic mixture by selective dissolution with hydrochloric acid solutions containing oxidizing agents. *Mineral Processing and Extractive Metallurgy Review*, *45*(4), 356–367. https://doi.org/10.1080/08827508.2023.2176852

Spathariotis, S., Zagoraiou, E., Moschovi, A.-M., Polyzou, E., & Yakoumis, I. (2026). Leaching of platinum group metals from spent automotive catalytic converters using deep eutectic solvents: A review. *Purification*, *2*(2), 5. https://doi.org/10.3390/purification2020005

Spooren, J., & Abo Atia, T. (2020). Combined microwave-assisted roasting and leaching to recover platinum group metals from spent automotive catalysts. *Minerals Engineering*, *146*, 106153. https://doi.org/10.1016/j.mineng.2019.106153

Sun, P. P., & Lee, M. S. (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

Sun, P. P., & Lee, M. S. (2015). Mixer-settler operation for the recovery of platinum, iron, and hydrochloric acid from the leaching solution of spent petroleum reforming catalysts. *Journal of Industrial and Engineering Chemistry*, *21*, 134–137. https://doi.org/10.1016/j.jiec.2014.02.049

Sun, P. P., Lee, J. Y., & Lee, M. S. (2012). Separation of platinum(IV) and rhodium(III) from acidic chloride solution by ion exchange with anion resins. Hydrometallurgy, 113–114, 200–204. https://doi.org/10.1016/j.hydromet.2011.12.009

Sun, S., Jin, C., He, W., Li, G., Zhu, H., & Huang, J. (2022). A review on management of waste three-way catalysts and strategies for recovery of platinum group metals from them. *Journal of Environmental Management*, *305*, 114383. https://doi.org/10.1016/j.jenvman.2021.114383

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

Suoranta, T., Zugazua, O., Niemelä, M., & Perämäki, P. (2015). Recovery of palladium, platinum, rhodium and ruthenium from catalyst materials using microwave-assisted leaching and cloud point extraction. *Hydrometallurgy*, *154*, 56–62. https://doi.org/10.1016/j.hydromet.2015.03.014

Tang, H., Peng, Z., Li, Z., Ma, Y., Zhang, J., Ye, L., Wang, L., Rao, M., Li, G., & Jiang, T. (2021). Recovery of platinum-group metals from spent catalysts by microwave smelting. *Journal of Cleaner Production*, *318*, 128266. https://doi.org/10.1016/j.jclepro.2021.128266

Tang, H., Peng, Z., Tian, R., Ye, L., Zhang, J., Rao, M., & Li, G. (2022). Recycling of platinum-group metals from spent automotive catalysts by smelting. *Journal of Environmental Chemical Engineering*, *10*(6), 108709. https://doi.org/10.1016/j.jece.2022.108709

Taninouchi, Y., Watanabe, T., & Okabe, T. H. (2017). Recovery of platinum group metals from spent catalysts using electroless nickel plating and magnetic separation. *Materials Transactions*, *58*(3), 410–419. https://doi.org/10.2320/matertrans.M-M2017801

Taninouchi, Y.-K., Sunagawa, K., Okabe, T. H., & Nakano, H. (2024). Iron chloride vapor treatment for leaching platinum group metals from spent catalysts. *Journal of Sustainable Metallurgy*, *10*, 2227–2240. https://doi.org/10.1007/s40831-024-00910-6

Van den Bossche, A., Rodriguez Rodriguez, N., Riaño, S., Dehaen, W., & Binnemans, K. (2021). Dissolution behavior of precious metals and selective palladium leaching from spent automotive catalysts by trihalide ionic liquids. *RSC Advances*, *11*(17), 10110–10120. https://doi.org/10.1039/D1RA00695A

Wang, J., Xu, W., Liu, H., Yu, F., & Wang, H. (2021). Extractant structures and their performance for palladium extraction and separation from chloride media: A review. *Minerals Engineering*, *163*, 106798. https://doi.org/10.1016/j.mineng.2021.106798

Wang, M., Tan, Q., Chiang, J. F., & Li, J. (2022). Precious metal recovery. *Joule*, *6*, 1798–1832. https://doi.org/10.1016/j.joule.2021.11.002

Wei, X., Liu, C., Cao, H., Ning, P., Jin, W., Yang, Z., Wang, H., & Sun, Z. (2019). Understanding the features of PGMs in spent ternary automobile catalysts for development of cleaner recovery technology. *Journal of Cleaner Production*, *239*, 118031. https://doi.org/10.1016/j.jclepro.2019.118031

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

Wen, Y., Tribby, E. L., & Tang, Y. (2025). Intensified and selective recovery of critical metals from aqueous extracts: Fundamentals and system design. *Chemical Engineering Journal*, *512*, 162661. https://doi.org/10.1016/j.cej.2025.162661

Wiecka, Z., Cota, I., Tylkowski, B., & Regel-Rosocka, M. (2023). Recovery of platinum group metals from spent automotive converters and their conversion into efficient

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

recyclable nanocatalysts. *Environmental Science and Pollution Research*, *30*, 90168–90179. https://doi.org/10.1007/s11356-022-24593-2

Wiecka, Z., Rzelewska-Piekut, M., & Regel-Rosocka, M. (2022). Recovery of platinum group metals from spent automotive converters by leaching with organic and inorganic acids and extraction with quaternary phosphonium salts. *Separation and Purification Technology*, *280*, 119933. https://doi.org/10.1016/j.seppur.2021.119933

Wongsawa, T., Traiwongsa, N., Pancharoen, U., & Nootong, K. (2020). A review of the recovery of precious metals using ionic liquid extractants in hydrometallurgical processes. *Hydrometallurgy*, *198*, 105488. https://doi.org/10.1016/j.hydromet.2020.105488

Wu, W., & Zha, G. (2025). Vacuum distillation-assisted hydrometallurgical route for industrial production of 99.999% pure gold from Au–Ag alloy feedstocks. *Metals*, *15*(11), 1271. https://doi.org/10.3390/met15111271

Xu, B., Chen, Y., Zhou, Y., Zhang, B., Liu, G., Li, Q., Yang, Y., & Jiang, T. (2022). A review of recovery of palladium from spent automobile catalysts. *Metals*, *12*(4), 533. https://doi.org/10.3390/met12040533

Xu, J., Ma, Y., Zhang, F., Tian, Y., Hu, Y., Ren, Y., & Cheng, Z. (2025). Efficient enrichment of platinum group metals from spent automotive catalyst via copper matte capture followed by roasting and leaching. *Separation and Purification Technology*, *377*, 134424. https://doi.org/10.1016/j.seppur.2025.134424

Xv, B., Li, Z., Zha, G., Liu, D., Yang, B., & Jiang, W. (2025). Recovery of platinum group metals from spent automotive catalysts: Review of conventional techniques and vacuum metallurgy. *Resources, Conservation and Recycling*, *215*, 108103. https://doi.org/10.1016/j.resconrec.2024.108103

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. https://doi.org/10.1016/j.hydromet.2025.106537

Yoshimura, A., & Matsuno, Y. (2019). The improvement of platinum recovery ratio in the recycling process using “dry aqua regia.” Materials Transactions, 60(10), 2223–2228. https://doi.org/10.2320/matertrans.M2019142

Yoshimura, A., Tochigi, S., & Matsuno, Y. (2021). Fundamental study of palladium recycling using “dry aqua regia” considering the recovery from spent auto-catalyst. *Journal of Sustainable Metallurgy*, *7*, 266–276. https://doi.org/10.1007/s40831-020-00335-x

Yu, F., Tian, M., Wang, X., Zhang, W., Wang, C., Wen, J., Wang, J., Guo, Y., & Huang, G. (2024). Selective recovery of platinum from spent catalysts to fabricate platinum/amorphous manganese oxide/corrugated silica carrier for formaldehyde

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/11/2026
Vol: 1.11
DOI: 10.66104/0g04vq90
Pages: 1-39

removal. *Journal of Environmental Chemical Engineering*, *12*(6), 114637. https://doi.org/10.1016/j.jece.2024.114637

Zabielska-Konopka, M., Zambrzycka-Szelewa, E., Bobrowska, D. M., & Godlewska-Żyłkiewicz, B. (2026). Selective separation of platinum, palladium, and rhodium from spent automotive catalysts using a polymeric sorbent. *Hydrometallurgy*, *244*, 106769. https://doi.org/10.1016/j.hydromet.2026.106769

Zhang, L., Song, Q., Liu, Y., & Xu, Z. (2020). An integrated capture of copper scrap and electrodeposition process to enrich and prepare pure palladium for recycling of spent catalyst from automobiles. *Waste Management*, *108*, 172–182. https://doi.org/10.1016/j.wasman.2020.04.013

Zhang, Q., Sang, Z., Li, Q., Gong, J., Shi, R., Zhang, B., Zhang, Z., Li, S., & Yang, X. (2023). Palladium(II) extraction from acidic chloride media using an ionic liquid-based aqueous two-phase system and reductive stripping with hydrazine hydrate to recover palladium metal. *Hydrometallurgy*, *216*, 106017. https://doi.org/10.1016/j.hydromet.2022.106017

Zheng, H., Ding, Y., Wen, Q., Liu, B., & Zhang, S. (2021). Separation and purification of platinum group metals from aqueous solution: Recent developments and industrial applications. *Resources, Conservation and Recycling*, *167*, 105417. https://doi.org/10.1016/j.resconrec.2021.105417

Zheng, H., Ding, Y., Wen, Q., Zhao, S., He, X., Zhang, S., & Dong, C. (2022). Slag design and iron capture mechanism for recovering low-grade Pt, Pd, and Rh from leaching residue of spent auto-exhaust catalysts. *Science of the Total Environment*, *802*, 149830. https://doi.org/10.1016/j.scitotenv.2021.149830

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

Zhu, J., & Huang, K. (2022). Selective recovery of gold from dilute aqua regia leachate of waste printed circuit board by thiol-modified garlic peel. *Environmental Science and Pollution Research*, *29*, 55990–56003. https://doi.org/10.1007/s11356-022-19584-2