



Aqua Regia in Metal Processing: A Critical Review of Reaction Mechanisms, Selectivity, and Industrial Applicability

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ABSTRACT

Original Research Article

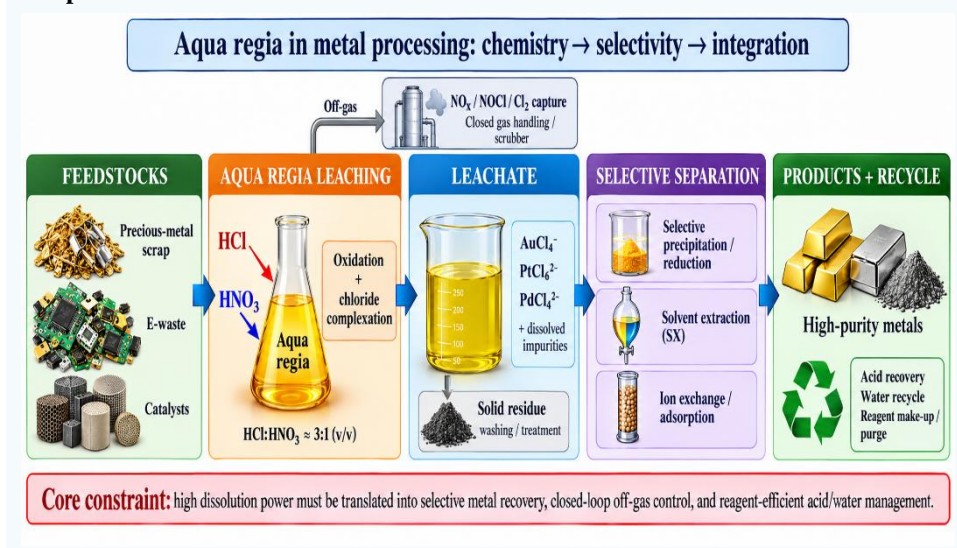
Aqua regia remains one of the most chemically powerful liquid-phase systems for dissolving gold and platinum-group metals, yet its industrial value is frequently overstated when dissolution yield is considered separately from selectivity, off-gas management, corrosion, and downstream purification. This critical review integrates fundamental chemistry, thermodynamics, kinetics, feedstock-specific performance, separations, safety, environmental burden, and process integration for metal processing from 1980 through September 2026. The central argument is that aqua regia should be treated not as a universal leachant but as a high-intensity reaction module whose usefulness depends on how effectively oxidation couples to chloride complexation and how quickly the resulting mixed-metal liquor can be converted into selective product streams. Evidence from electronic waste, high-grade gold scrap, spent catalysts, and complex primary materials shows that high precious-metal dissolution can coexist with excessive base-metal dissolution, reagent consumption, and difficult liquor purification. Temperature and redox potential accelerate dissolution, but they also intensify gas evolution and co-dissolution, creating an operating-window problem rather than a simple maximization problem. Downstream precipitation, solvent extraction, ion exchange, sorption, cementation, and electrowinning can recover value, although each transfers selectivity requirements to a later unit operation. Closed gas handling, acid and oxidant recovery, corrosion-resistant materials, staged pre-leaching, and hybrid flowsheets therefore determine whether aqua regia is technically and environmentally defensible. The review proposes a decision framework that limits aqua regia to high-value, low-mass fractions or final refining duties unless integrated evidence demonstrates favorable whole-flowsheet performance.

Keywords: Aqua Regia, Noble Metals, Chloride Leaching, Selectivity, Electronic Waste, Process Integration.

Highlights

- Aqua regia combines strong oxidation with chloride complexation but is intrinsically non-selective.
- Feed composition, redox potential, chloride activity, and gas evolution jointly define the useful leaching window.
- Industrial viability depends on downstream selectivity, closed gas handling, corrosion control, and reagent recovery.
- Hybrid flowsheets can retain aqua regia for high-value fractions while shifting bulk dissolution to milder routes.

Graphical Abstract



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Introduction

Aqua regia (AR), conventionally prepared by mixing concentrated hydrochloric acid and nitric acid at approximately 3:1 by volume, has long been used for dissolving and refining noble metals. Its unusual strength arises from the simultaneous presence of a strong oxidizing environment and a high chloride activity that stabilizes oxidized noble metals as soluble chloro-complexes. Historical refining practice established AR as a reliable route for high-grade gold-bearing materials, while modern work has extended its use to electronic waste, spent catalysts, analytical digestion, and hybrid recycling circuits (Embleton, 1981; Gowing & Potts, 1991; Rocky et al., 2024).

The modern context is more demanding than simple dissolution. Electronic waste contains copper, nickel, tin, iron, polymers, ceramics, and trace precious metals; spent catalysts combine chemically resistant platinum-group metals (PGMs) with refractory oxide supports; and primary ores can contain sulfides, silicates, carbonaceous matter, and gangue minerals that consume reagents without generating equivalent value. Reviews of e-waste and PGM recycling therefore show that leaching must be evaluated together with pretreatment, separation, product purification, residue management, and scale-up (Do et al., 2023; Jha et al., 2013; Rao et al., 2020; Saguru et al., 2018).

A persistent weakness in the literature is the tendency to report extraction percentage without fully resolving the

leachant's chemical state, the evolving redox potential, chloride complexation, volatile-species losses, or competition between target and non-target metals. Equilibrium calculations demonstrate that HCl–HNO₃ mixtures can generate chlorine-containing volatile species, and experimental studies confirm that temperature and redox state materially affect Au, Cu, and Fe dissolution. Gold dissolution in chloride media also depends on coupled electrochemical and complexation phenomena; therefore, a high initial rate does not guarantee sustained recovery when the oxidant inventory is depleted or reduced species accumulate (Elomaa et al., 2017; Massucci et al., 1999; Nicol, 2023).

This article is a narrative review, not a meta-analysis, synthesizing evidence from 1980 to September 2026 across chemistry, kinetics, feedstock performance, separations, safety, environment, and process integration. Since studies vary in feed composition, reagent excess, pulp density, reactor design, and reporting, extraction values are interpreted contextually. The key question is: when does aqua regia offer an industrial advantage based on feed value, chemistry, kinetics, selectivity, separations, gas handling, and recycling? Table 1 summarizes the chemical functions. Tables 2–6 organize kinetic controls, feedstock evidence, downstream options, alternative systems, and scale-up risks. Figures 1–4 link reactive species, selectivity, flowsheets, and decision logic.

Table 1. Chemical functions of aqua regia and their process consequences

Function	Principal chemical role	Useful effect	Process penalty / diagnostic
Oxidation	HNO ₃ -derived oxidizing capacity and reactive chlorine species	Raises noble metals to soluble oxidation states	Excess oxidizing strength increases NO _x evolution and may intensify base-metal attack
Chloride complexation	High Cl ⁻ activity stabilizes Au, Pt, and Pd chloro-complexes	Pulls dissolution equilibria toward soluble products	High chloride complicates materials selection, downstream extraction, and wastewater treatment
Acidity	Maintains low pH and suppresses hydrolysis of many metal ions	Preserves soluble chloride species	Free acidity is consumed by reactive feed components and changes during operation
Gas-forming chemistry	Generation and loss of NO _x , Cl ₂ , NOCl, and related species	Maintains strong reaction environment when controlled	Requires closed reactors, scrubbing, ventilation, and corrosion management

Note. Concept synthesized from Massucci et al. (1999), Elomaa et al. (2017), Nicol (2023), and Rocky et al. (2024).

Fundamental Chemistry and Reaction Mechanism

Reactive-Species Generation

The familiar shorthand reaction $\text{HNO}_3 + 3\text{HCl} \rightarrow \text{NOCl} + \text{Cl}_2 + 2\text{H}_2\text{O}$ is useful for communicating why freshly mixed aqua regia is more reactive than either acid alone, but it should not be interpreted as a complete molecular mechanism. The liquid and gas phases contain interconverting nitrogen- and chlorine-bearing species whose relative abundances depend on acid concentration, water content, temperature, gas–liquid mass transfer, and time after mixing. Thermodynamic treatment of HCl–HNO₃ mixtures demonstrates that chlorine production and vapor-phase speciation change systematically with composition, which explains why open vessels can progressively lose effective oxidizing capacity even when substantial total acidity remains (Massucci et al., 1999).

From a process perspective, AR is therefore a transient reagent system rather than a fixed-composition acid. Mixing sequence, residence time before contact with the feed, reactor headspace, agitation, and off-gas withdrawal can alter the effective oxidant inventory. A plant that specifies only an HCl:HNO₃ ratio, but does not control redox potential,

temperature, or gas handling, may reproduce the nominal recipe without reproducing the same leaching chemistry.

Coupled Oxidation and Chloride Complexation

Noble-metal dissolution requires an anodic metal-oxidation step and a cathodic reduction step supplied by an oxidant. Chloride then stabilizes oxidized metal species and lowers the effective activity of free metal ions, shifting the overall reaction toward dissolution. Gold chloride systems illustrate the general principle: dissolution kinetics depend not only on oxidant concentration but also on chloride concentration, and different oxidants can generate different dominant gold oxidation states and rate laws (Nicol, 2023; Seisko et al., 2018, 2019; Pereira et al., 2025).

This coupling is the reason oxidation and complexation cannot be optimized independently. Increasing nitrate-derived oxidizing power without enough chloride can favor passivation or unstable products, while increasing chloride without sufficient oxidizing capacity cannot sustain electron transfer from the metal. The operational target is a moving chemical window in which both functions remain adequate while controlling non-target metal dissolution and gas losses. Figure 1 summarizes the coupled sequence.

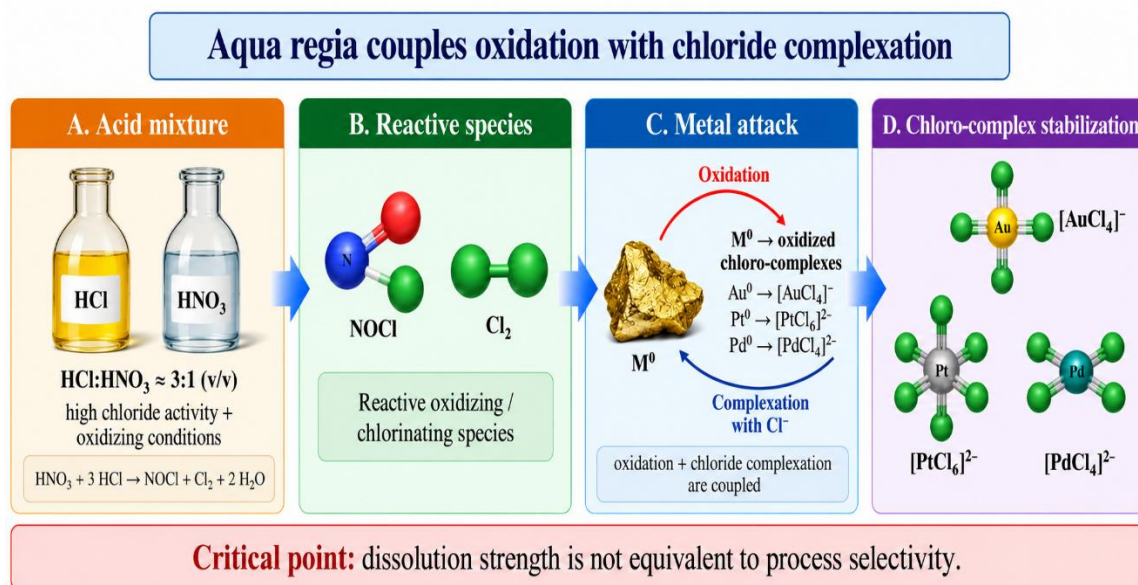


Figure 1. Coupled chemistry of aqua regia from acid mixing to soluble noble-metal chloro-complexes.

Note. Author's synthesis adapted conceptually from Massucci et al. (1999), Elomaa et al. (2017), Nicol (2023), and Rocky et al. (2024).

Figure 1 emphasizes that leachate results from two inseparable chemical operations: oxidation creates soluble oxidation states, and chloride complexation stabilizes them. The same logic also explains why AR is intrinsically vulnerable to non-selective dissolution: many base metals oxidize more easily than Au or PGMs and are present at much higher concentrations in secondary feeds.

Thermodynamics, Redox Control, and Speciation

Redox Potential Is Necessary but Not Sufficient

Experiments on waste printed circuit boards show that the redox potential of aqua regia and temperature affect the dissolution behavior of Au, Cu, and Fe, demonstrating that ORP is an important operating variable rather than merely an analytical descriptor (Elomaa et al., 2017). In a heterogeneous feed, however, ORP reflects the combined response of multiple oxidation and reduction couples, dissolved metals, residual nitrate, reactive chlorine species, and gas exchange. A single potential value therefore cannot uniquely identify active-oxidant concentrations.

Practically, interpret ORP alongside chloride concentration, free acidity, dissolved-metal loading, temperature, and gas

evolution (Pereira, 2026b). A rising or sustained ORP can help diagnose oxidant availability, but the same apparent potential may correspond to different chemical inventories in fresh acid, partially spent liquor, or recycled chloride solution.

Chloro-Complex Stability and Competitive Chemistry

Once noble metals are oxidized, chloride coordination produces anionic complexes that also underpin downstream solvent extraction, ion exchange, and ionic-liquid separations. The speciation that is favorable for leaching can therefore be deliberately exploited in purification, particularly for Pd and other PGMs whose chloride complexes interact selectively with extractants and ion-exchange functionalities (Nguyen et al., 2020; Wang et al., 2021; Wongsawa et al., 2020).

The challenge is that chloride-rich liquors may also contain Fe, Cu, Sn, Zn, Ni, Al, and other dissolved species at concentrations orders of magnitude higher than the precious metals. These species consume acid and oxidant, modify ionic strength, compete for extractants and sorbents, form precipitates during neutralization, and can alter the valence state of target metals. Thermodynamic selectivity at the leach stage is thus often weak even when downstream speciation offers a route to chemical discrimination. Figure 2 summarizes these competing chemical domains as a conceptual operating window.

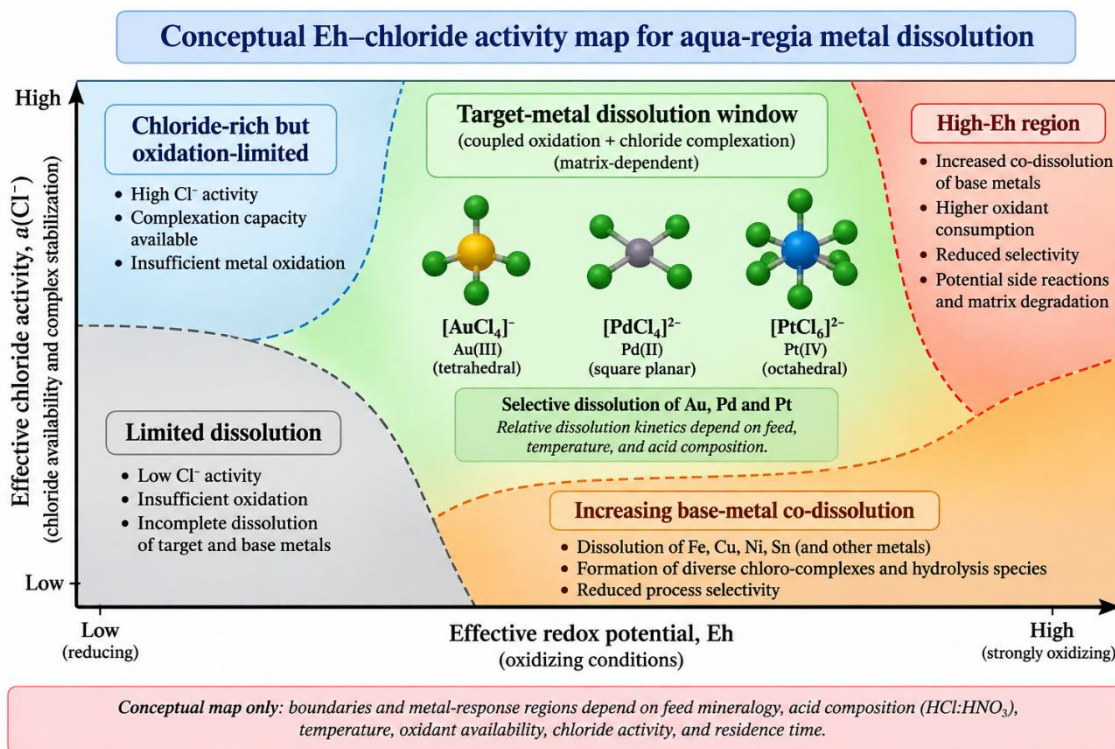


Figure 2. Conceptual operating window linking oxidizing strength, chloride activity, target-metal dissolution, and base-metal co-dissolution.

Note. Author's conceptual synthesis based on Elomaa et al. (2017), Nicol (2023), Seisko et al. (2018, 2019), and the broader chloride-leaching literature.

Figure 2 should be read as a process map rather than a quantitative Eh–pH diagram. It illustrates the central optimization problem: the operating window that delivers useful noble-metal kinetics is bounded on one side by oxidant limitation and on the other by non-selective dissolution, gas evolution, and materials-of-construction penalties.

Kinetics, Mass Transfer, and Passivation

Temperature, Concentration, and Surface Area

Kinetic studies of platinum-bearing catalysts and mixed electronic feeds consistently show strong effects of temperature, reagent concentration, and exposed surface area. Higher temperature usually accelerates chemical reaction and diffusion, but it also increases evaporation and gas release. In spent catalyst systems, particle accessibility, support porosity, and the distribution of PGMs within washcoat phases can become rate-limiting even when solution chemistry is sufficiently aggressive (Baghalha et al., 2009; Elomaa et al., 2017; Tyson & Bautista, 1987; Pereira, 2026a).

Particle-size reduction can shorten diffusion paths and increase reactive area, yet excessively fine grinding may

create filtration problems, increase entrainment losses, and expose additional base-metal or gangue surface. For e-waste, liberation by shredding, physical sorting, or thermal pretreatment can improve precious-metal accessibility, but the optimal degree of comminution is a flowsheet variable rather than a universal leaching prescription.

Mixed Kinetic Regimes and Passivation

Gold dissolution in chloride media illustrates why apparent kinetic constants should be interpreted cautiously. Electrochemical dissolution rates can fall as oxidants are consumed, reduced species accumulate, or equilibrium constraints become important. Ferric- and cupric-chloride studies also show that rate control can shift among interfacial electron transfer, oxidant transport, chloride-dependent surface chemistry, and solution regeneration (Nicol, 2023; Seisko et al., 2018).

Passivation may arise from insoluble salts, silica-rich layers, carbonaceous films, elemental sulfur, or residual polymeric coatings, depending on the feed. Consequently, a higher nominal acid concentration may not restore the dissolution rate if the true resistance is a solid film or an inaccessible PGM particle. Diagnostic leaching should therefore distinguish chemical depletion from physical isolation. Table 2 summarizes the resulting kinetic and scale-up variables.

Table 2. Kinetic variables that govern aqua regia leaching performance

Variable	Primary kinetic effect	Secondary process effect	Scale-up concern
Temperature	Accelerates reaction and diffusion	Increases NO _x /Cl ₂ release and corrosion	Heat removal, vapor containment, and materials compatibility
Particle size/liberation	Increases accessible surface area	May increase fines and gangue attack	Slurry rheology, filtration, dust, and entrainment
Acid and nitrate inventory	Controls acidity and oxidant capacity	Changes gas generation and reagent consumption	Feed variability and dosing strategy
Chloride activity	Stabilizes dissolved chloro-complexes	Affects extraction/sorption selectivity downstream	Recycle impurity buildup and corrosion
Agitation/gas–liquid transfer	Reduces boundary-layer resistance	Can accelerate loss of volatile reactive species	Reactor geometry and scrubber load
Solid loading	Controls reagent-to-feed ratio	Raises dissolved-metal concentration and heat release	Mixing, local depletion, and downstream liquor loading

Note. Synthesis from Baghalha et al. (2009), Tyson and Bautista (1987), Elomaa et al. (2017), Nicol (2023), and Seisko et al. (2018).

Performance across feedstocks

High-Grade Gold Scrap and Refining Intermediates

Aqua regia is most defensible when precious-metal value is concentrated into a small mass of feed. Historical gold-refining practice and modern life-cycle data for high-value scrap show the logic clearly: reagent-intensive chemistry can be acceptable when the feed has a high gold content, and the refinery has established acid handling, gas scrubbing, and purification infrastructure (Bae et al., 2020; Embleton, 1981; Fritz et al., 2020).

Recovering nitric acid and gold from gold-bearing aqua regia solutions using tributyl phosphate is especially important conceptually because it treats the leach liquor as a recyclable chemical inventory rather than a waste stream. Such approaches can reduce fresh reagent demand, but recycling is limited by impurity buildup and by the need to maintain consistent acid and chloride composition (Bae et al., 2020).

Electronic Waste and Printed Circuit Boards

Electronic waste demonstrates both the strengths and weaknesses of AR. Gold can be dissolved efficiently from appropriately prepared circuit-board fractions, but the same reagent can attack Cu, Ni, Fe, Sn, and other abundant metals. Early recovery studies established the feasibility of AR treatment for circuit-board scrap, while recent reviews emphasize that feed complexity, low gold concentration relative to base metals, and downstream selectivity remain dominant challenges (Do et al., 2023; Huang et al., 2022; Park & Fray, 2009; Rao et al., 2020; Sheng & Etsell, 2007).

A more promising direction is to reserve AR for a final enriched fraction or to combine it with selective recovery. Hybrid studies have paired prior base-metal removal with gold recovery, selective precipitation, biosorption, or redox-active sorbents, shifting the design objective from complete

dissolution to integrated selectivity (Abbas et al., 2025; Adam et al., 2024; Kancharla, 2025; Nag et al., 2023).

Spent Catalysts and PGM-Bearing Materials

Spent automotive and industrial catalysts are attractive secondary PGM resources, but refractory supports, encapsulated PGM particles, and the chemical inertness of Pt and Rh complicate leaching. Chloride-rich oxidative leaching, including aqua regia, can achieve substantial dissolution, especially after pretreatment, yet reviews show that commercial practice has historically favored pyrometallurgical concentration before hydrometallurgical refining. This gap between laboratory leaching and industrial adoption reflects kinetics, solids handling, reagent cost, and scale-up rather than an absence of chemical feasibility (Jha et al., 2013; Saguru et al., 2018; Suoranta et al., 2015). Experimental studies by Hasani, Khodadadi, Koleini, Saeedi, and Meléndez (2017) and by Hasani, Khodadadi, Koleini, Saeedi, Pérez-Pacheco, and Meléndez (2017) further document direct chloride and aqua regia leaching of spent automotive catalysts.

Alternative chloride strategies attempt to preserve strong chlorination while changing the delivery mechanism. Iron-chloride vapor treatment and so-called dry aqua regia concepts seek to improve PGM accessibility or reduce liquid-acid burdens. Their relevance is not that they simply replace conventional AR, but that they illustrate a broader design principle: decouple oxidation, chlorination, and mass transfer so that each can be intensified or controlled separately (Taninouchi et al., 2024; Yoshimura & Matsuno, 2019; Yoshimura et al., 2021).

Primary Ores, Concentrates, and Analytical Digestion

Direct AR treatment of primary ores is generally difficult to justify when the valuable metal content is low, and gangue or sulfide minerals impose large acid and oxidant demand. In PGM ores and concentrates, direct chloride leaching is technically possible but must compete with concentration and

smelting-based flowsheets. By contrast, selective or partial AR digestion remains useful analytically because the objective is reproducible mobilization of target elements

rather than economic bulk processing (Gowing & Potts, 1991; Mpinga et al., 2015). Table 3 summarizes where aqua regia is most plausibly positioned for each feed class.

Table 3. Feedstock-specific role of aqua regia

Feedstock	Typical role of AR	Main advantage	Dominant limitation	Preferred process position
High-grade Au scrap	Primary refining leach	High dissolution rate and mature chemistry	Gas handling and acid consumption	Central refining step with recycle
WPCBs / e-waste	Leach of precious-metal-enriched fraction	Strong Au dissolution	Severe Cu/Fe/Ni/Sn co-dissolution	After physical or chemical base-metal removal
Spent autocatalysts	PGM dissolution after pretreatment	Strong chloride chemistry for Pt/Pd	Refractory support and slow Pt/Rh kinetics	After thermal, alloying, or other activation
Primary ores / concentrates	Selective test or specialized direct leach	Chemical power	Low value-to-reagent ratio and gangue demand	Restricted to high-value or preconcentrated material
Analytical digestion	Sample preparation	Rapid broad-spectrum dissolution	Not representative of industrial selectivity	Laboratory analytical use

Note. Adapted from Embleton (1981), Gowing and Potts (1991), Jha et al. (2013), Mpinga et al. (2015), Rao et al. (2020), and Rocky et al. (2024).

Selectivity as the Central Process Limitation

Aqua regia is frequently described as a selective reagent for noble metals because it dissolves metals that resist individual mineral acids. At the flowsheet level, however, this wording can be misleading. In mixed feeds, many base metals dissolve readily and may dominate reagent consumption and dissolved-solids loading. The critical distinction is therefore between capability selectivity—what AR can dissolve that milder acids cannot—and compositional selectivity—how strongly it discriminates the valuable metal from the actual feed matrix. For e-waste, the second form of selectivity is often poor (Elomaa et al., 2017; Rao et al., 2020; Rocky et al., 2024).

The most effective strategy is often to create selectivity before AR is introduced. Physical upgrading, staged acid leaching, thermal removal of organics, magnetic or density separation, and selective base-metal dissolution can reduce the mass and chemical complexity presented to the AR circuit. This changes the reagent from a bulk dissolver into a final high-value extraction tool.

The same principle is visible in integrated e-waste studies: when bulk metals are removed or partitioned first, the precious-metal step becomes smaller and easier to control. Conversely, applying AR directly to a heterogeneous board fraction transfers a large purification burden to downstream operations (Adam et al., 2024; Park & Fray, 2009).

A second form of selectivity can be created after leaching by exploiting charge, coordination, reduction potential, or molecular recognition. This is technically viable, but it does not erase the upstream penalties of dissolving unwanted

metals. An industrial process should therefore compare the cost and environmental burden of avoiding co-dissolution with the cost of separating the resulting mixed chloride solution.

Downstream Recovery and Purification

Precipitation and Reduction

Selective precipitation is attractive because it can convert a complex chloride solution directly into a recoverable solid without a large organic-solvent inventory. Molecularly designed precipitating agents have demonstrated selective Au capture from acidic, mixed-metal solutions, while sequential precipitation has been used to separate Au and Cu from e-waste-derived liquors. Classical PGM refining likewise relies on carefully controlled precipitation and thermal conversion steps. These approaches demonstrate that selectivity can be engineered through speciation and reagent recognition, although robustness to variable industrial liquors remains essential (Kancharla, 2025; Kinsman et al., 2021; Nag et al., 2023; Schreier & Edtmaier, 2003).

Solvent Extraction and Ionic-Liquid Systems

Solvent extraction is well established for separating metal chloro-complexes, and PGM separation from chloride media has generated a large body of extractant-development work. Conventional extractants can provide high selectivity, but phase disengagement, entrainment, solvent loss, fire risk, and extractant degradation must be considered. Ionic-liquid systems offer tunable selectivity and low volatility, although viscosity, cost, water sensitivity, and complete solvent recovery can become practical constraints (Marinho et al., 2010; Nguyen et al., 2020; Wang et al., 2021; Wongsawa et al., 2020).

Ion Exchange, Sorption, and Electrochemical Recovery

Ion-exchange resins and functional sorbents are particularly compatible with chloride liquors because anionic noble-metal complexes can be captured selectively from dilute solutions. Core-shell resins, printed scavengers, polymeric sorbents, and redox-active materials illustrate rapid innovation in this area. Electrodeposition can also recover gold from suitable liquors, but current efficiency and deposit quality deteriorate when competing reducible species are abundant (Abbas et al., 2025; Cyganowski et al., 2017; Lahtinen et al., 2017; Lekka et al., 2015; Zabielska-Konopka et al., 2026).

Recovery Sequence Matters

The order in which metals are separated can be as important as the individual separation method. Cementation, extraction, reduction, and precipitation can be sequenced to exploit differences in redox potential and chloride-complex stability. A route that first removes a dominant interferent may enable a simpler high-selectivity step later, whereas attempting to isolate trace Au or Pd directly from a highly loaded mixed-metal liquor may consume disproportionate reagent and generate lower-purity products (Nguyen & Lee, 2023). Table 4 compares the principal downstream recovery options for these chloride-rich leachates.

Table 4. Downstream options for aqua regia leachates

Method	Selectivity basis	Strength	Key limitation	Best fit
Selective precipitation	Specific ion pairing, solubility, or redox chemistry	Simple solid-liquid separation	Reagent sensitivity to acidity and interferents	High-value target in well-characterized liquor
Solvent extraction	Partitioning of chloro-complexes	High stagewise selectivity	Solvent inventory, entrainment, and degradation	Concentrated continuous refinery circuits
Ion exchange/sorption	Electrostatic and functional-group affinity	Good for dilute streams and polishing	Capacity loss and fouling	Polishing or selective capture
Cementation / chemical reduction	Difference in reduction potential	Low-cost recovery for selected metals	Co-precipitation and impurity carryover	Intermediate recovery before final refining
Electrowinning/electrodeposition	Electrochemical reduction	Direct metal product	Competing cathodic reactions and current efficiency	Relatively clean, conductive liquors

Note. Adapted from Marinho et al. (2010), Cyganowski et al. (2017), Lekka et al. (2015), Kinsman et al. (2021), Wang et al. (2021), and Nguyen and Lee (2023).

Process Integration and Flowsheet Design

Aqua regia processing should be designed backward from the product rather than forward from the leach. The required metal purity defines the acceptable impurity loading of the leachate; the selected downstream method defines the chloride, acidity, and redox window; and these constraints determine whether the feed requires physical upgrading, staged leaching, or thermal pretreatment. Broader reviews of precious-metal recovery and intensified selective separations increasingly emphasize such system-level coupling rather than isolated extraction maxima (Rocky et al., 2024; Wang et al., 2022; Wen et al., 2025).

A robust flowsheet therefore separates four inventories that are often conflated in laboratory studies: valuable metal, base-metal impurities, reactive acid and oxidant, and water and dissolved salts. Assess each recycle loop independently. Acid recovery is beneficial only if impurity accumulation does not destabilize upstream leaching or downstream separation. Water reuse can reduce discharge, but it increases ionic strength and may concentrate nitrate, chloride, and dissolved metals. Purges are unavoidable in most closed circuits and should be sized from impurity balances rather than an arbitrary recycle percentage. Figure 3 integrates these inventories into a feed-to-product flowsheet.

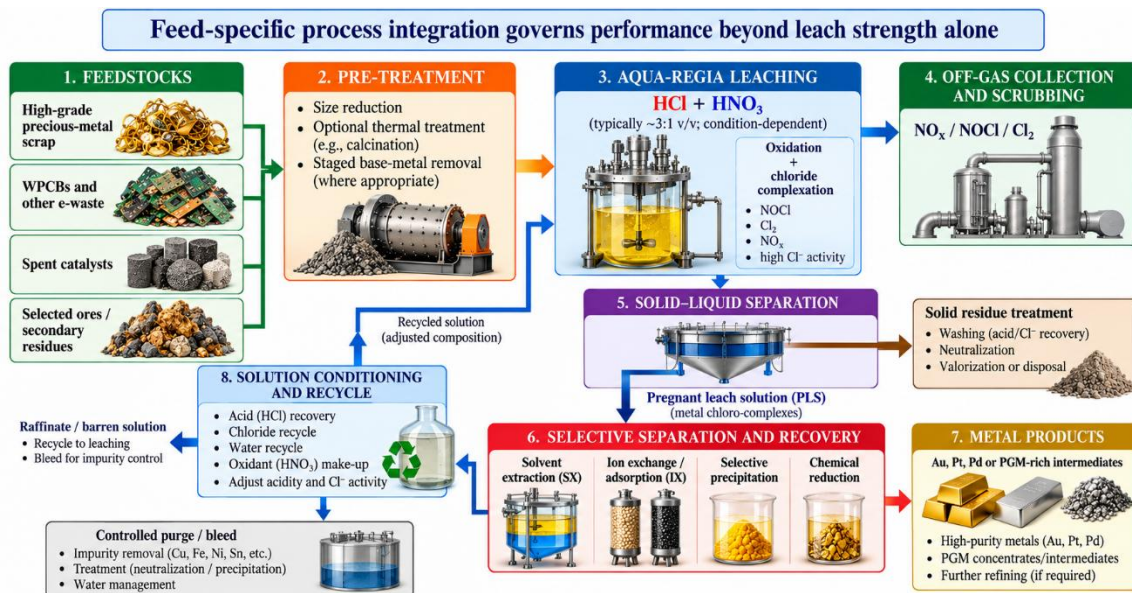


Figure 3. Integrated feed-to-product flowsheet for aqua regia processing.

Note. Author's synthesis adapted from Rocky et al. (2024), Do et al. (2023), Jha et al. (2013), Saguru et al. (2018), and Wang et al. (2022).

Figure 3 highlights a major conclusion of this review: AR should often be placed after value concentration and before high-selectivity recovery, not at the front of a bulk-treatment circuit. This positioning lowers total acid demand, reduces off-gas load, and converts a difficult dilute precious-metal problem into a smaller but richer refining stream.

Environmental, Safety, Corrosion, and Materials Constraints

Off-Gas and Occupational Exposure

The formation of chlorine- and nitrogen-containing volatile species is intrinsic to concentrated HCl – HNO_3 chemistry. Industrial use therefore requires closed or well-contained reactors, negative-pressure ventilation where appropriate, efficient scrubbing, and operating procedures that prevent uncontrolled acid mixing and gas release. The gas load is dynamic because it depends on acid composition, temperature, metal dissolution, headspace behavior, and residence time (Massucci et al., 1999).

Scrubber design should not be treated as a secondary environmental attachment. It is part of the reaction system because removal of volatile species changes reactor chemistry. Multi-stage scrubbing may be needed when acidic mist, NO_x , and chlorine-bearing species coexist, and corrosion-resistant ducting and fans are necessary throughout the gas train.

Corrosion and Containment

Aqua regia combines low pH, chloride, nitrate-derived oxidants, elevated temperature, and potentially high dissolved-metal concentrations. This combination is aggressive toward many common alloys, especially at welds,

crevices, and gas–liquid interfaces. Materials selection must therefore be based on the actual temperature and composition envelope—including startup, cleaning, upset, and recycled-liquor conditions—rather than on nominal fresh-acid composition alone.

Environmental Burden Must Be Assessed at Flowsheet Level

The environmental profile of AR cannot be judged from hazard labels alone. Life-cycle assessment of high-value gold scrap recycling indicates that well-controlled recycling can have substantially lower environmental impacts than primary gold production, despite the use of aqua regia. Conversely, environmental comparisons of gold-recovery technologies show that reagent manufacture, energy demand, waste treatment, and emissions can shift the ranking among routes. The relevant question is therefore whether the complete AR-based recycling system performs better than the realistic alternative for the same feed and product (Fritz et al., 2020; Wang et al., 2019).

Comparison with Alternative Leaching Systems

Alternatives to aqua regia include cyanide, thiosulfate, glycine, ferric chloride, cupric chloride, halide systems, deep eutectic solvents (DESS), and related media. No alternative is universally superior. Cyanide remains highly selective for gold under controlled alkaline conditions but carries toxicity and permitting burdens. Glycine offers a milder alkaline chemistry that can be selective under suitable oxidizing conditions. Ferric and cupric chloride avoid nitrate and can be regenerated electrochemically or by oxidation, but their kinetics and equilibrium constraints require careful control. DES-based systems offer low volatility and tunable chemistry but remain challenged by viscosity, mass transfer, water sensitivity, reagent cost, and scale-up (Birich et al., 2019; Cen

et al., 2020; Oraby et al., 2020; Seisko et al., 2018, 2019; Pereira, 2026c).

The most useful comparison is duty-based. AR is strongest when rapid dissolution of a small, high-value, chemically resistant fraction is required. Milder systems are favored

when selectivity, reagent regeneration, low gas evolution, or bulk treatment dominates the economics. A hybrid circuit can therefore be more rational than selecting a single lixiviant for the entire feed. Table 5 compares these systems by process duty rather than by dissolution strength alone.

Table 5. Comparison of aqua regia with selected alternative leaching systems

System	Typical strength	Typical weakness	Most plausible duty
Aqua regia	Very high dissolution power for Au and PGMs	Low compositional selectivity; NO _x /Cl ₂ ; corrosion	Final refining of high-value fractions
Cyanide	High Au selectivity and mature practice	Acute toxicity; sensitivity to Cu and preg-robbing	Large-scale Au extraction where permitted
Thiosulfate	Non-cyanide Au complexation	Reagent instability and complex solution control	Specialized Au ores and selected secondary feeds
Glycine + oxidant	Mild alkaline system with potential selectivity	Slower kinetics and oxidant management	Cu–Au systems and selective staged leaching
Ferric/cupric chloride	Regenerable chloride oxidation chemistry	Redox regeneration and equilibrium limitations	Closed chloride circuits and selected Au feeds
DES / ionic-liquid media	Tunable solvation and extraction chemistry	Viscosity, cost, water sensitivity, and scale-up	Selective niche separations and emerging processes

Note. Comparative synthesis of Birich et al. (2019), Oraby et al. (2020), Seisko et al. (2018, 2019), Cen et al. (2020), and Wongsawa et al. (2020).

Emerging Developments

Hybrid AR–Separation Systems

The most important recent development is not a new form of aqua regia itself but the tighter integration of AR with selective separation. Hybrid approaches pair strong leaching with sorption, precipitation, extraction, or biological recovery to prevent mixed-metal liquors from becoming the terminal bottleneck. Recent work on redox-active sorbents and selective precipitation illustrates the move toward molecular recognition and direct recovery from acidic chloride media (Abbas et al., 2025; Kinsman et al., 2021; Rocky et al., 2024).

Dry or Low-Liquid Chlorination Concepts

Dry-aqua regia and chloride-vapor treatments seek to reduce bulk liquid handling while retaining highly reactive chlorination chemistry. They may be useful for refractory PGM-bearing solids where liquid diffusion through the support is limiting. Their scale-up challenge is different from conventional AR: gas–solid contact, chlorine-containing vapor control, reactor materials, temperature uniformity, and recovery of volatilized or mobilized metal species become central (Taninouchi et al., 2024; Yoshimura & Matsuno, 2019; Yoshimura et al., 2021).

Data-Rich Control and Selective Intensification

A future industrial AR circuit should be controlled by a small set of chemically meaningful variables, not acid ratio alone. Online ORP, temperature, density, conductivity, free-acid estimation, chloride analysis, and off-gas monitoring can be combined with mass-balance models to infer oxidant depletion and impurity loading. The broader trend in

intensified metal recovery is toward coupling selective chemistry with system-level sensing, staged contact, and controlled regeneration (Wen et al., 2025).

Scale-Up, Techno-Economic Logic, and Critical Knowledge Gaps

Why High Extraction Is Not a Scale-Up Criterion

Laboratory studies can achieve high extraction by using large reagent excesses, low pulp density, long residence times, and open or loosely controlled gas release. Those conditions can conceal industrial penalties. Economic analyses of e-waste recovery and reviews of PGM hydrometallurgy show that scale-up must account for reagent-to-feed ratio, feed grade, throughput, gas control, solid–liquid separation, corrosion, downstream reagent consumption, and final product purity (Karamanoğlu & Aydın, 2016; Saguru et al., 2018).

A useful scale-up metric is value recovered per unit of reactive acid and per unit of gas-handling duty, not extraction percentage alone. This immediately favors high-grade fractions and penalizes bulk low-grade feeds. A second metric is impurity amplification: kilograms of non-target metal dissolved per kilogram of target metal recovered. The ratio connects feed mineralogy to downstream separation cost and should be reported routinely.

Reagent Regeneration, Recycle, and Impurity Bleed

Recovering nitric acid from AR liquors shows that reagent regeneration is chemically possible and potentially valuable,

but the recycle loop must be closed with a complete impurity balance. Each recycle concentrates species that are not removed with the product. Without a controlled purge or selective impurity-removal step, the solution chemistry gradually diverges from fresh AR and may compromise both leaching and downstream separation (Bae et al., 2020).

Critical Research Needs

Four gaps are especially important. First, mechanistic kinetic models should couple oxidant inventory, chloride activity, gas loss, and changing surface area rather than fitting

extraction-time curves empirically. Second, selectivity studies should report full dissolved-metal inventories and impurity-to-target ratios. Third, integrated pilot work should include off-gas scrubbing, corrosion monitoring, reagent recycle, and realistic solid–liquid separation. Fourth, techno-economic and life-cycle assessments should compare complete flowsheets at a common feed grade and product specification, with sensitivity to reagent recovery and purge requirements. Table 6 translates these gaps into practical failure modes, diagnostics, and mitigation measures.

Table 6. Scale-up failure modes, diagnostic variables, and mitigation

Failure mode	Early diagnostic	Underlying cause	Mitigation
Rapid loss of leaching rate	ORP decay; residual metal surface remains	Oxidant depletion or gas loss	Controlled oxidant dosing, closed reactor, redox monitoring
Excess base-metal dissolution	High Cu/Fe/Ni/Sn in liquor	Insufficient upgrading or over-aggressive conditions	Staged pre-leach, feed sorting, narrower redox window
Poor downstream selectivity	High reagent consumption or low product purity	Competitive complexes and acidity variability	Conditioning, selective impurity removal, staged recovery
Corrosion / leakage	Metal contamination, wall loss, gasket failure	Inappropriate materials for real operating envelope	Materials testing, lined equipment, conservative thermal design
Scrubber overload	Rising NO _x /Cl ₂ outlet concentration	Temperature or acid addition exceeds design basis	Feedforward dosing, gas-flow control, redundant scrubbing capacity
Recycle instability	Increasing dissolved salts and slower separation	Accumulation of non-recovered species	Mass-balance-based purge and selective bleed treatment

Note. Author's synthesis of Massucci et al. (1999), Elomaa et al. (2017), Bae et al. (2020), Rocky et al. (2024), and Saguru et al. (2018). The resulting screening logic is presented in Figure 4.

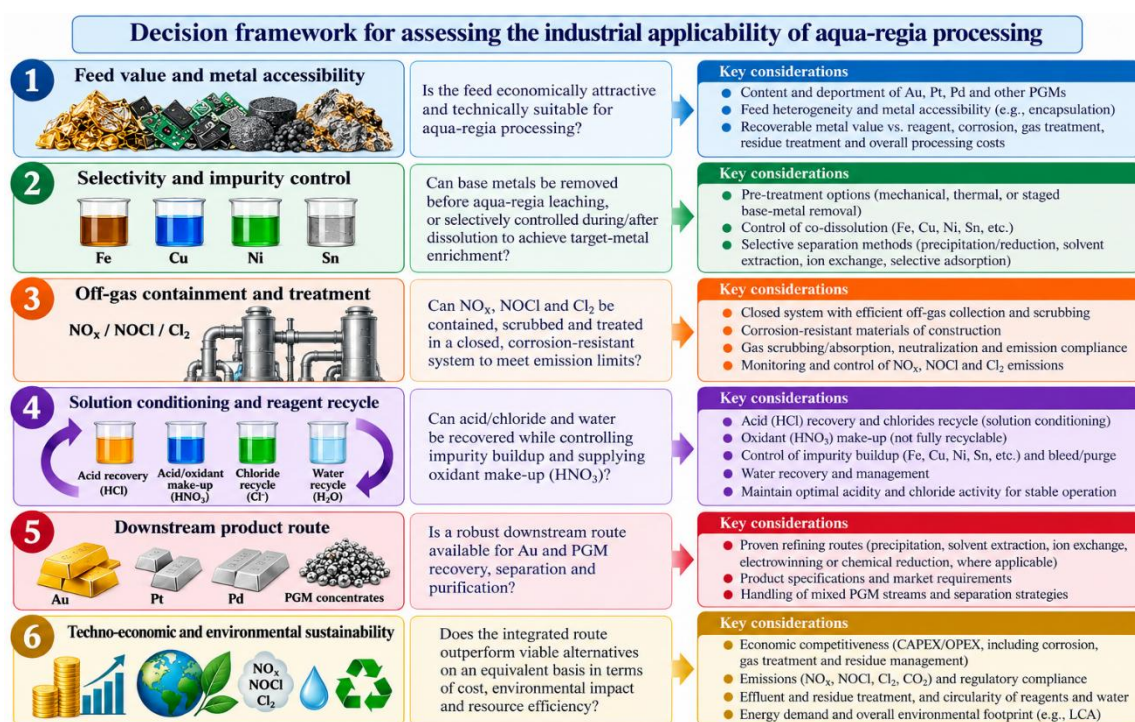


Figure 4. Decision framework for judging industrial applicability of aqua regia.

Note. Author's synthesis based on the integrated evidence reviewed in Sections 5–12.

Figure 4 converts the literature into a practical screening sequence. Aqua regia becomes progressively more defensible as feed value rises, pretreatment reduces non-target mass, gas handling is closed, reagents can be recovered, and a selective downstream product route is demonstrated. Failure at any one step does not automatically rule out AR, but it identifies the unit operation that must be improved before scale-up can be justified.

Conclusions

Aqua regia remains an exceptionally powerful leaching system for gold and platinum-group metals because it combines oxidation with strong chloride complexation. That same chemical intensity, however, creates its principal process liabilities: non-selective dissolution of base metals, volatile NO_x and chlorine-bearing species, severe corrosion, high reagent demand, and complex downstream liquors. The decisive industrial question is therefore not whether aqua regia can dissolve a target metal, but whether the complete flowsheet can convert that dissolution into a selective product while controlling reagents, emissions, residues, and recycle chemistry.

Across the reviewed feedstocks, the strongest use case is a high-value, low-mass fraction such as refined gold scrap, a physically upgraded electronic fraction, or a pretreated PGM concentrate. Applying aqua regia directly to bulk heterogeneous material generally magnifies impurity dissolution and transfers the burden to downstream separation. Staged pretreatment, closed gas handling, redox-based control, acid and oxidant recovery, and selective precipitation, extraction, ion exchange, sorption, or electrochemical recovery can improve viability, but they must be demonstrated together rather than as isolated unit operations.

Future progress should focus on coupled reaction–speciation–mass-transfer models, complete metal inventories, realistic pilot campaigns, and flowsheet-level techno-economic and life-cycle comparisons. The most credible long-term role for aqua regia is therefore as a controlled high-intensity refining module within hybrid circuits, not as a universal bulk lixiviant.

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

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation by the author.

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