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Processing of Platinum Group Metals: From Primary Ores to Secondary Resources and Sustainable Recovery Strategies

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ABSTRACT

Original Research Article

Platinum group metals (PGMs), including Pt, Pd, Rh, Ir, Ru, and Os, are essential materials used in catalysis, electronics, and energy technologies. Their extraction from both primary ores and secondary sources faces challenges due to complex mineralogy, low grades, and high chemical stability. This critical review explores current processing methods for PGMs, such as pyrometallurgical concentration, hydrometallurgical extraction, and advanced separation techniques. Special focus is placed on leaching mechanisms, solvent extraction, ion exchange, and innovative technologies like bioleaching and deep eutectic solvents. The integration of primary and secondary processing, particularly from spent catalysts and electronic waste, is evaluated in terms of efficiency, selectivity, and environmental impact. Key research gaps are identified in multi-metal separation, reagent selectivity, and process improvements, offering a roadmap for sustainable and efficient PGM recovery.

Keywords: PGM processing, Platinum group metals, Hydrometallurgy, Solvent extraction, Catalyst recycling, Precious metals, Leaching, Circular economy.

Highlights

- PGM processing is constrained by complex mineralogy and low metal grades.
- Hydrometallurgical routes dominate refining and separation stages.
- Secondary resources (spent catalysts, e-waste) are increasingly important.
- Selective separation of Pt, Pd, Rh remains a major challenge.
- Sustainable processing requires integration of advanced separation technologies.

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Introduction

Platinum group metals (PGMs)—Pt, Pd, Rh, Ir, Ru, and Os—are vital due to their catalytic activity, corrosion resistance, thermal stability, and electrochemical performance. They are used in automotive emission control, petroleum refining, chemical production, electronics, and low-carbon energy tech (Hughes et al., 2021; Nose & Okabe, 2024). Pt, Pd, and Rh dominate automotive catalysts, while Pt and Ir are key in PEM systems and hydrogen production (Mvokwe et al., 2025; Osmieri & Meyer, 2022).

Despite their technological importance, PGM supply is constrained by geographically concentrated production and capital-intensive extraction routes (Mettler et al., 2023). At the same time, increasing demand—especially driven by energy transition technologies—has intensified pressure on supply chains, resulting in a structural imbalance rather than a temporary market fluctuation (Zhang et al., 2024).

Primary PGM resources are inherently difficult to process. Most deposits occur in Ni–Cu sulfide systems or layered mafic intrusions, where PGMs are present at low concentrations within complex mineral assemblages (Aleksandrova & O'Connor, 2020). Typical head grades are only a few grams per tonne, which limits overall recovery efficiency. From a mineralogical perspective, PGMs are often finely disseminated, associated with sulfides and chromite phases, and incompletely liberated during comminution (Alexandrova & O'Connor, 2021; Sahu et al., 2021). The presence of fine particles and heterogeneous phase distributions further reduces flotation efficiency and contributes to significant metal losses (Corin et al., 2021).

Primary processing, therefore, requires large-scale infrastructure, high energy input, and multi-stage flowsheets involving comminution, flotation, smelting, and refining. These operations are strongly influenced by ore variability, leading to increased capital expenditure (CAPEX), operational complexity, and process risk (Mettler et al., 2023).

From a chemical standpoint, PGMs exhibit high thermodynamic stability and slow reaction kinetics under mild conditions, which significantly limit dissolution rates and complicate hydrometallurgical recovery (Chidunchi et al., 2024). Even in chloride systems, where stable metal complexes can form, dissolution is often hindered by kinetic limitations and surface passivation phenomena (Fan et al., 2023). In addition, the presence of base metals such as Fe, Cu, and Ni promotes competing reactions and reduces selectivity during the leaching and separation stages (Paiva et al., 2022; Nguyen et al., 2026). As a result, the same properties that make PGMs technologically valuable also make their extraction particularly challenging.

Process evaluation must therefore consider not only recovery efficiency but also reagent consumption, residence time, selectivity, and impurity control, as these factors directly impact process economics and operational stability (Paiva, 2023).

These constraints have driven increasing interest in secondary PGM resources, including spent automotive catalysts, fuel cell components, refinery catalysts, and electronic waste. These materials often contain PGM concentrations in the order of $kg \cdot t^{-1}$, several orders of magnitude higher than those found in primary ores (Grilli et al., 2023; Radojević et al., 2025). Recycling of secondary resources offers clear advantages in terms of metal concentration, reduced material throughput, and lower energy demand, while also contributing to waste minimization and circular economy strategies (Generowicz, 2022; Lord et al., 2025).

However, secondary resources introduce a different set of challenges. These materials are highly heterogeneous, consisting of complex substrates, porous washcoats, and variable contaminant levels, including sulfur, lead, and phosphorus. This compositional variability complicates both pyrometallurgical and hydrometallurgical processing and reduces reproducibility at scale (Yakoumis et al., 2021; Yang et al., 2023).

Recent research has expanded beyond conventional processing routes, incorporating hybrid pyrometallurgical–hydrometallurgical systems, solvent extraction, ion exchange, bioleaching, ionic liquids, and deep eutectic solvents (Banerjee et al., 2024; Mokhodoeva et al., 2023). While these approaches show promise, the field remains fragmented, with many studies focusing on individual metals, simplified systems, or isolated process steps.

This fragmentation limits industrial applicability, as few studies integrate mineralogical constraints, reaction mechanisms, separation performance, and economic considerations into a unified framework. In practice, process selection depends on the combined evaluation of CAPEX, OPEX, feed variability, and waste management requirements (Bediako & Repo, 2025; Wan et al., 2025).

This review critically evaluates current processing strategies for PGMs from both primary and secondary sources, covering pyrometallurgical concentration, hydrometallurgical extraction, separation and purification techniques, and emerging low-impact technologies. Particular emphasis is placed on kinetic limitations, selectivity challenges, and multi-metal interactions that constrain industrial performance.

The following section presents the methodology adopted in this study, including the literature search strategy, selection criteria, and analytical framework used to assess recent advances in PGM processing.

Methodology

The literature search covered PGM processing from primary ores and secondary sources, using keywords related to feed types and extraction methods like PGMs, ores, automotive catalysts, fuel cells, hydrometallurgy, pyrometallurgy, solvent extraction, ion exchange, bioleaching, ionic liquids, deep eutectic solvents, urban mining, and metals recycling (Paiva & Nogueira, 2021).

The time frame was limited to 2020–2026 to focus on recent advances in process intensification, green solvents, and circular economy strategies. Earlier studies were included only for context regarding established routes. Priority was given to peer-reviewed journals, review articles, and key conference proceedings, with theses included only if they provided unique data. Studies were excluded if they focused solely on catalyst performance, lacked operational detail, or did not address the extraction, separation, or recovery of PGMs.

The dataset contains 96 references that cover the entire processing chain, with no orphan citations. It is organized into six sections: sources of PGMs, pyrometallurgical processing, hydrometallurgical processing, separation and purification, secondary-resource processing, and emerging technologies. This structure avoids a descriptive list and enables direct comparison across feed types, processing methods, and maturity levels.

From an engineering perspective, quantitative indicators like metal grades, yields, reagent use, temperature, and selectivity are prioritized. Typical feedstocks vary: primary ores contain 1–10 $g\bullet t^{-1}$ PGMs, whereas spent catalysts contain 1000–3000 $g\cdot t^{-1}$ PGMs. Recoveries range from 80% to 98%, depending on conditions.

The impact of energy intensity on CAPEX and OPEX is key to industrial relevance. Many studies report performance qualitatively, limiting comparability and weakening process evaluation.

The study selection process, covering identification, screening, eligibility, and final inclusion of references, is summarized in Figure 1.

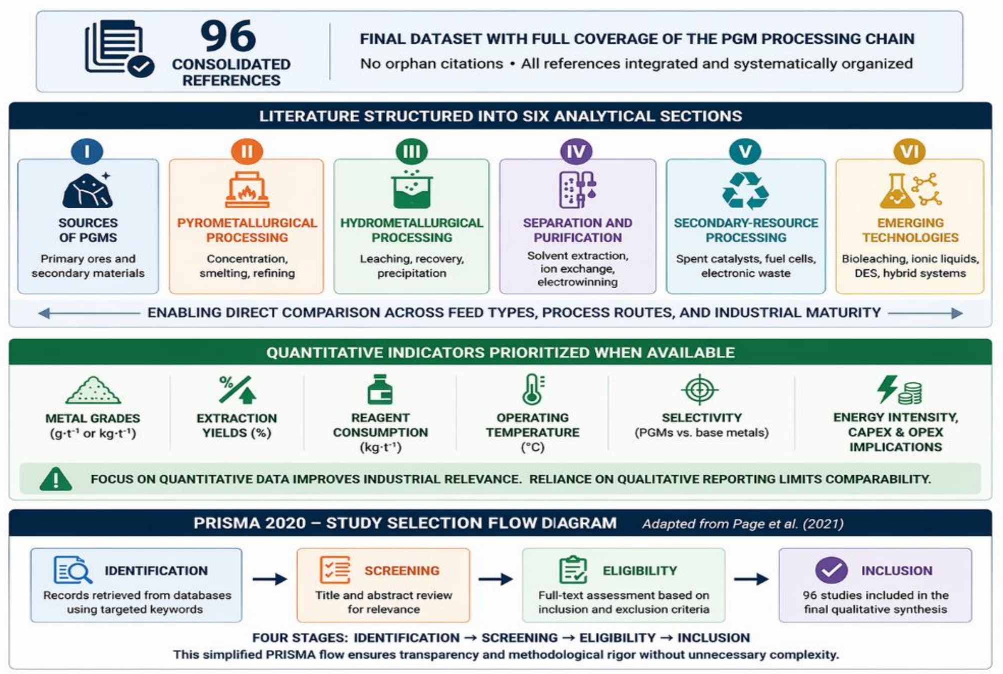


Figure 1. PRISMA-based flow diagram used to organize literature identification, screening, eligibility assessment, and final inclusion for the present review. Adapted from Page et al. (2021).

Figure 1 summarizes the study selection process, which follows four stages: identification, screening, eligibility, and inclusion. This simple structure suffices for an engineering review, ensuring transparency without added complexity.

The diagram depicts the literature filtering process, beginning with broad studies on PGM extraction, recycling, and separation, and screening excluded irrelevant or non-quantitative works. Eligibility focused on studies with operational data, recovery performance, or mechanistic insights. The final set comprised relevant studies on metallurgical processing and evaluation.

This structured selection is critical. PGM processing involves heterogeneous systems with low-grade ores, high-value secondary materials, and complex multi-metal feeds. Without rigorous filtering, technology comparisons are unreliable. The methodology ensures subsequent sections are based on comparable, industrially relevant data.

This section analyzes PGMs' sources, distinguishing between primary mineral deposits and secondary resources such as spent catalysts and electronic waste.

Sources of PGMs

The origin of platinum group metals (PGMs) influences processing, costs, and environmental impact. Primary ores require extensive mining, while secondary resources have higher grades but more variability. This affects the entire process, from crushing to refining.

Primary ores

Primary PGMs primarily originate from magmatic sulfide deposits and layered mafic intrusions, occurring as discrete minerals or as inclusions within base-metal sulfides such as pentlandite and chalcopyrite (Aleksandrova & O'Connor, 2020; Alexandrova & O'Connor, 2021). Production targets key provinces such as the Bushveld Complex and Norilsk–Talnakh, which dominate the global market (Hughes et al., 2021; Nose & Okabe, 2024). Their importance is heightened by supply concentration and long development timelines (Mettler et al., 2023).

Ore grade limits extraction with 2-10 $g\cdot t^{-1}$ concentrations, much lower than secondary resources. PGMs are associated with Fe, Cu, Ni, and gangue, complicating processing (Sahu et al., 2021). Minerals are finely disseminated, often smaller than 50 μm, limiting liberation and recovery (Corin et al., 2021).

The impact is evident in flotation, with fine particles (30–40% of PGM inventory) showing low recovery in conventional circuits (Corin et al., 2021). Plant performance depends on mineral associations, grain size, and matrices like chromite or silicate (Alexandrova & O'Connor, 2021).

Tailings reprocessing reveals unrecovered PGMs are often trapped in ultrafine or complex mineral phases (Baloyi et al., 2024).

The industrial route involves crushing, grinding, and flotation to produce a sulfide-rich concentrate, which is then treated by pyrometallurgy (Aleksandrova & O'Connor, 2020). Although robust, it's not optimized for fine or complex ores and suffers significant flotation losses under variable mineralogy.

Ore variability complicates processing because feed composition fluctuates, affecting reagent requirements, flotation performance, and concentrate quality. Secondary tailings are a resource, but recovery is harder after oxidation and prior processing (McFadzean et al., 2024). Current methods are limited and inconsistent.

Emerging approaches aim to overcome these limitations. Bio-beneficiation and advanced physical separation techniques could improve the recovery of fine and refractory materials. However, most are still at the laboratory or pilot stage with limited industrial validation.

Primary PGM processing uses a multi-stage flowsheet to upgrade low-grade ores for smelting. The steps—comminution, flotation, and thermal treatment—depend on mineralogy and can't be simplified without losing recovery, as summarized in Figure 2.

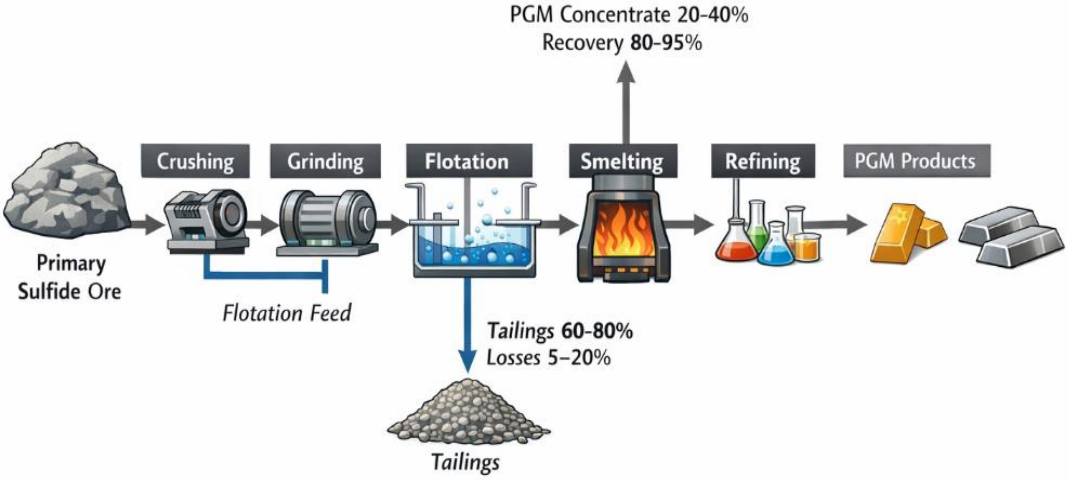


Figure 2. Simplified flowsheet for PGM recovery from primary sulfide ores, including comminution, flotation, smelting, and refining stages. Adapted from Aleksandrova and O'Connor (2020) and Sahu et al. (2021).

Figure 2 illustrates the process flow and mass distribution along the main PGM flowsheet. After crushing and grinding, the material becomes flotation feed with no rejection. Separation occurs during flotation, producing concentrate and tailings.

The concentrate usually accounts for 20–40% of the mass but contains most of the PGMs. Recoveries are 80–95%, depending on mineralogy and conditions. The rest, 60–80%, is tailings, with 5–20% PGM losses.

This stage defines plant performance. Losses mainly occur at flotation due to fine particles and complex mineral associations, limiting recovery. Once PGMs are lost to tailings, recovery becomes harder and more expensive.

The concentrate undergoes smelting and converting, concentrating PGMs into matte while removing Fe and S, and is then refined to produce high-purity metals.

The process is energy-intensive, with comminution, drying, and smelting raising costs. Smelting alone can use over 1–3 MWh per tonne, depending on furnace design and feed (Nose & Okabe, 2024). This high energy use across stages increases CAPEX and OPEX.

Primary PGM production depends on large-scale operations to achieve economies of scale that offset low ore grades and high energy costs, resulting in long payback periods and limited flexibility. In contrast, secondary resources often have higher metal grades and simpler liberation, reducing processing steps and energy use. The next section discusses these feedstocks and their process implications.

Secondary sources

Secondary resources now complement primary PGM supply, mainly from spent catalytic converters, fuel-cell components, refinery catalysts, electronic waste, and industrial residues (Yakoumis et al., 2021; Grilli et al., 2023). Automotive catalysts dominate due to their large base and steady flow (Zhang et al., 2024).

The main advantage is grade. Primary ores have 2–10 $g \cdot t^{-1}$ of PGMs, while spent catalysts can reach 1–3 $kg \cdot t^{-1}$ (Hughes et al., 2021). Higher concentrations vary by formulation and conditions (Chidunchi et al., 2024; Radojević et al., 2025). This reduces metal throughput, energy use, and waste.

This advantage is structural. It changes process economics. However, it does not simplify the system.

Secondary materials are heterogeneous, comprising ceramic or metallic substrates, porous washcoats (usually Al_2O_3-based), and dispersed PGMs, which can alloy or oxidize (Yang et al., 2023). Contaminants like sulfur, lead, and phosphorus complicate processing (Huang et al., 2024). Consequently, feed variability exceeds that of primary ores.

Processing routes involve thermal pre-treatment, smelting, metal collection, and hydrometallurgy (Han et al., 2023; Liu et al., 2021). Matte or metallic collectors concentrate PGMs before separation (Morcali, 2020). Alternatively, direct hydrometallurgical methods with selective leaching are explored (Demarco et al., 2020; Yakoumis et al., 2020).

Recent developments focus on process intensification and integration, like co-processing with electronic waste, electrometallurgical methods, and hybrid pyro–hydro flowsheets (Chen et al., 2024; Ye et al., 2025). Most are still at pilot scale.

The contrast between primary and secondary sources is not only geological but also quantitative and critical for process design, influencing throughput, energy use, and flowsheet complexity. Figure 3 shows typical PGM concentrations in these resources.

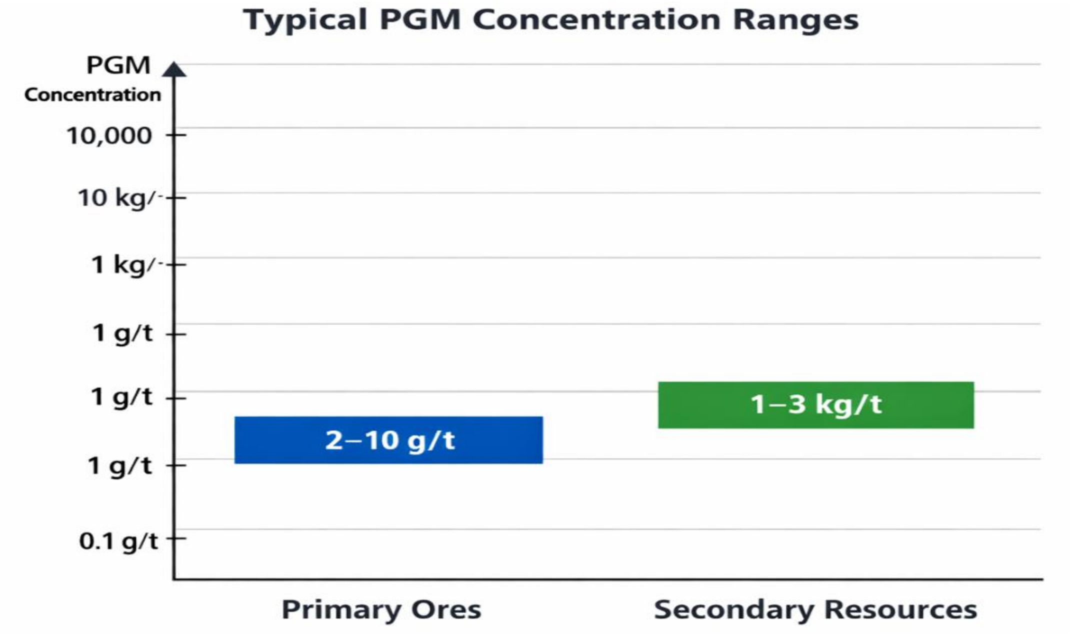


Figure 3. Typical PGM concentration ranges in primary ores (g·t⁻¹) and secondary resources (kg·t⁻¹). Adapted from Hughes et al. (2021), Chidunchi et al. (2024), and Radojević et al. (2025).

Figure 3 shows that secondary resources have PGM levels 100 to 1000 times higher than those in primary ores, thereby reducing mass, energy, and waste. Higher grades improve process economics by lowering CAPEX and OPEX per kilogram of PGM and enabling shorter, less energy-intensive flowsheets.

This advantage is not absolute due to increased complexity. Secondary materials are heterogeneous, with composition varying by catalyst type, service history, and contamination levels. Fluctuating impurities like S, Pb, and P affect stability. Therefore, selectivity often outweighs throughput, especially in multi-metal systems. (Smith et al., 2022)

Secondary processing offers sustainability benefits by reducing land use and mining waste, and improving resource efficiency, thereby supporting circular economy strategies. However, environmental gains depend on emissions, reagent use, and residue management (Lord et al., 2025; Bediako & Repo, 2025; Generowicz et al., 2023; Wang et al., 2026).

These contrasts shape the industrial landscape. Primary processing focuses on scale and energy use. Secondary processing is about selectivity and chemical complexity. Primary and secondary methods complement each other: primary methods provide a large-scale supply, while secondary methods improve efficiency and lessen environmental impact.

The main challenge is integration. Differences in grade, composition, and phase distribution directly affect process selection. In practice, both streams often converge in pyrometallurgical stages for initial concentration.

This section focuses on pyrometallurgical processing, especially smelting and matte production, as the initial step in PGM concentration and recovery.

Pyrometallurgical Processing

Pyrometallurgical processing is the main method for industrial PGM recovery, used mainly for primary ores and high-volume secondary materials. It pre-concentrates PGMs, which are present at low levels, via thermal steps that concentrate them into sulfide or metallic phases prior to hydrometallurgical refining, thereby significantly increasing PGM concentration (Han et al., 2023).

The process is robust and scalable, handling large volumes and complex feeds, remaining key in industrial flowsheets despite new routes (Wan et al., 2025). Recent advances aim at efficiency and secondary resource integration, but core principles stay the same (Wang et al., 2026)

Smelting and matteproduction

Smelting is the initial high-temperature stage for PGM concentration, usually between 1200 and 1600 °C, depending on feed and furnace. It focuses on phase partitioning, transferring PGMs into a collector phase while gangue forms slag. This enriches PGMs before refining.

In primary processing, flotation concentrates containing Ni–Cu–Fe sulfides are smelted into Ni–Cu–Fe matte, which serves as a collector for PGMs (Aleksandrova & O'Connor, 2020; Han et al., 2023). Secondary processing adds collector metals like Fe, Cu, or Ni to form metal–PGM alloys (Ding et al., 2020; Morcali, 2020). This flexibility enables pyrometallurgical routes to handle heterogeneous, variable feeds.

Collection efficiencies are high, with recoveries above 95% for Pt, Pd, and Rh under optimized conditions (Tang et al., 2021; Han et al., 2023). However, recovery varies across the PGM group. Minor elements such as Ir, Ru, and Os often exhibit lower recoveries due to differences in stability and partitioning (Fan et al., 2023; Wan et al., 2025).

Recent developments focus on improving process integration and energy efficiency. Co-smelting of electronic waste uses Cu from printed circuit boards as an in situ collector, thereby reducing the need for external reagents (Chen et al., 2024). Microwave-assisted smelting enhances heat transfer and reduces processing time (Tang et al., 2021), while hybrid routes optimize slag chemistry to improve PGM partitioning and minimize metal losses (Martinez et al., 2021; Wang et al., 2026).

Feed materials like primary concentrates and secondary resources are introduced into a smelting furnace, where fluxes and reductants control slag chemistry and promote metal collection. Gangue transfers to slag, while PGMs concentrate in the matte or alloy for refining.

Despite its industrial maturity, smelting remains energy-intensive, generating off-gas and losing materials through dust, slag, and spillages. Improving control of phase equilibria, furnace operation, and process integration is essential to maximize recovery and reduce environmental impact.

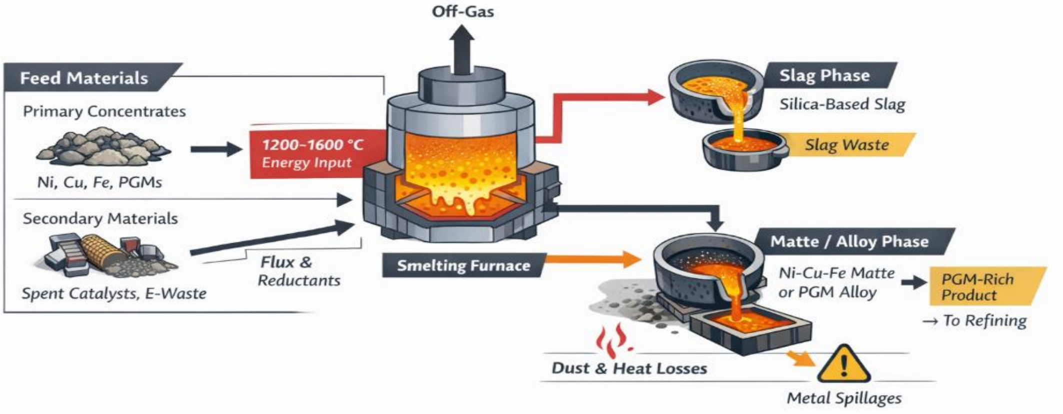


Figure 4. Generalized pyrometallurgical route for PGM recovery, including smelting, slag formation, and matte/alloy collection. Adapted from Han et al. (2023) and Wan et al. (2025).

Smelting involves multiple steps: feed prep, furnace operation, phase separation, and tapping. Precise process control is essential since PGM partitioning depends heavily on temperature, oxygen potential, and slag chemistry. Small changes, like in FeO or SiO_2, can greatly increase PGM losses to slag (Wan et al., 2025). This sensitivity demands strict operational control, especially with variable secondary feeds.

Smelting is robust but energy-heavy, handling large, complex materials at high costs. It pre-concentrates by removing Fe and S, upgrading the matte for hydrometallurgical refining.

Converting

After smelting, the matte or alloy undergoes converting to remove Fe, S, and other base elements, concentrating PGMs. This controlled oxidation converts Fe to FeO, transferring it to slag, and releases sulfur as SO_2. The metallic phase becomes richer in Ni, Cu, and PGMs as the process continues.

Converting typically occurs at 1200-1400 °C like smelting, with precise oxygen control to minimize PGM losses (Wan et al., 2025; Wang et al., 2026). In secondary processing, it can be simplified or replaced by direct alloy refining based on feed. For Fe–PGM systems, refining methods like slag cleaning or electrorefining help reduce impurities and concentrate PGM (Yang et al., 2023; Ye et al., 2025).

Pyrometallurgical processing remains the primary method for PGM-bearing materials. Its success depends on temperature, collector metal choice, and slag chemistry, all of which influence PGM recovery. Understanding these factors is essential for assessing efficiency, energy consumption, and environmental impact. Table 1 shows typical operating conditions and key performance indicators for PGM smelting and converting.

Table 1. Typical operating conditions and performance indicators for PGM smelting and converting processes. Adapted from Jones, R. T. (2014); Ndlovu, S. (2008); and Schlesinger, M. E., King, M. J., Sole, K. C., & Davenport, W. G. (2011).

Parameter	Typical range	Technical implication
Temperature	1200–1600 °C	High energy demand, refractory requirements
Recovery (Pt, Pd, Rh)	90–98%	Efficient collection in matte/alloy
Collector metals	Fe, Cu, Ni	Controls PGM partitioning
Slag losses	1–5%	Depends on slag chemistry
Gas emissions	SO_2, CO_2	Requires gas treatment systems

Table 1 shows that PGM recovery requires high energy at 1200–1600 °C, demanding significant energy and refractory durability. High recoveries (90–98%) depend on effective collection of matte or alloy phases, primarily influenced by collector metals such as Fe, Cu, and Ni. Process efficiency depends on slag behavior, with losses of 1–5% depending on slag chemistry and conditions. Gas emissions such as SO_2 and CO_2 require treatment, raising costs. While effective for bulk PGM, pyrometallurgical routes entail notable energy and environmental trade-offs.

Pyrometallurgy's main limitation is its high energy use, with smelting and converting demanding 1–3 MWh per tonne, depending on furnace design and feed (Nose & Okabe, 2024; Lord et al., 2025). This leads to high costs, capital for furnaces and gas treatments, and vulnerability to energy prices. Emissions of CO_2 and SO_2 require mitigation, raising CAPEX and OPEX (Lord et al., 2025; Zhang et al., 2024).

Despite constraints, pyrometallurgy effectively concentrates PGMs, offering robustness, scalability, and maturity. However, it lacks selectivity, producing a PGM-rich phase that requires further refinement. This links processing routes: pyrometallurgy concentrates PGMs, hydrometallurgy separates and purifies them.

The efficiency of PGM recovery relies on both smelting and downstream chemical processing. The next section explores hydrometallurgical methods, emphasizing leaching systems, reaction mechanisms, and kinetic limits affecting PGM dissolution and recovery from intermediates and secondary resources.

Hydrometallurgical Processing

Hydrometallurgical processing is essential for recovering PGMs from pyrometallurgical residues or for treating secondary materials. Unlike smelting, which concentrates PGMs into metal, hydrometallurgy dissolves, separates, and purifies at the molecular level, despite challenges from PGMs' stability and complex multi-metal matrices.

Hydrometallurgy often dominates OPEX, mainly due to reagent use and long residence times. Acid consumption can exceed 50–200 kg per tonne, depending on process selectivity and impurities (Nguyen et al., 2026; Pianowska et al., 2023). Improving selectivity and kinetics is vital to cut operating costs.

Leaching systems

Leaching is the initial step in hydrometallurgy, transferring PGMs from solids to solution. Its success depends on the leaching system, affecting dissolution, selectivity, reagent use, and downstream compatibility.

Main systems include aqua regia, chloride media, sulfate systems, and alternative solvents. Aqua regia ($HCl + HNO_3$) dissolves PGMs quickly but lacks selectivity for base metals. Chloride systems (e.g., Cl_2/HCl, NaCl with oxidants) are common in industry, forming stable chlorocomplexes for separation. Sulfuric acid systems are less common for direct PGM leaching and are used in pretreatment or selective stages. (Rezaei et al. 2025)

Chloride media dominate because PGMs form stable chloro-complexes, enabling efficient recovery and processing (Nguyen et al., 2026; Paiva et al., 2022). However, these systems require strong oxidants such as Cl_2, H_2O_2, or Fe^{3+} to overcome the inertness of metallic PGMs, thereby increasing complexity and reagent use (Chidunchi et al., 2024; Griffiths, 2025).

Recent research aims to improve selectivity and lower environmental impact. Bio-cyanide systems mobilize Pd and Pt under mild conditions (Ilyas et al., 2022). Deep eutectic solvents (DES) enable selective dissolution with less acid use (Mokhodoeva et al., 2023; Lanaridi et al., 2022). Pressure-assisted leaching boosts reaction speed and extraction (Griffiths, 2025).

No leaching system offers perfect efficiency, selectivity, and sustainability. Selecting a process involves feed features, downstream needs, and environmental factors. Figure 5 summarizes key PGMs leaching systems, showing mechanisms, conditions, and trade-offs.

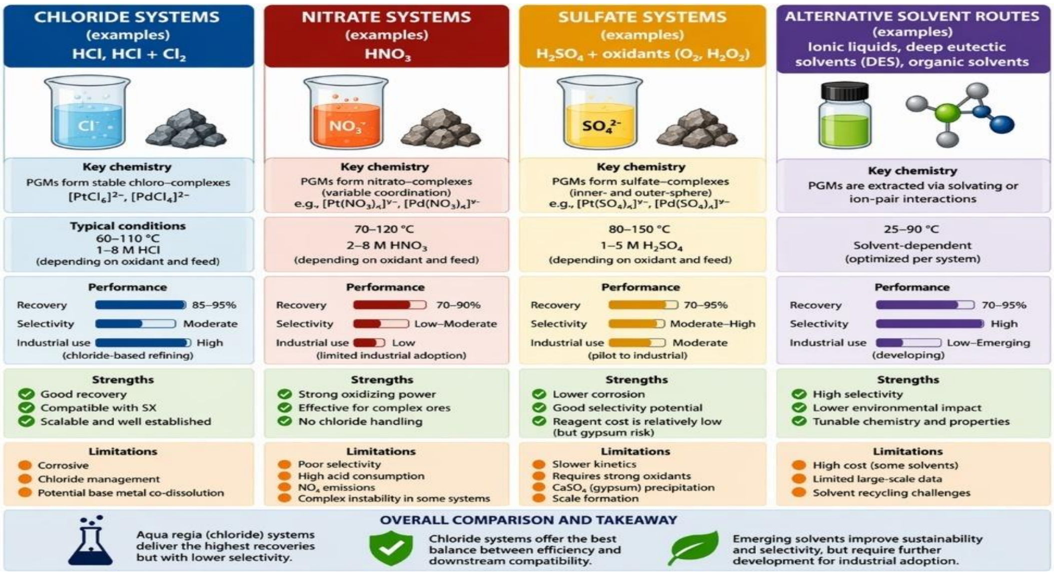


Figure 5. Main leaching systems for PGMs, including chloride, nitrate, sulfate, and alternative solvent routes. Adapted from Nguyen et al. (2026) and Paiva et al. (2022).

Figure 5 shows that no single leaching system is best, as each balances recovery, selectivity, and complexity. Chloride systems, such as aqua regia, achieve high recoveries (85–95%) and remain popular despite limited selectivity and corrosion. Nitrate systems are strong oxidizers but less selective, requiring more reagents and producing NO$_x$ emissions.

Sulfate-based systems balance cost, selectivity, and environmental impact, but require high temperatures and oxidants to achieve good kinetics. New solvent systems like ionic liquids and deep eutectic solvents offer better selectivity and lower environmental impact but are still developing and lack industrial validation. The comparison shows process choice must weigh recovery, selectivity, environmental impact, and integration, not a single metric.

Reaction chemistry

PGMs dissolve via the formation of stable metal complexes, particularly in chloride media. For platinum, a representative dissolution reaction is:

$$\mathrm{Pt} + 2\mathrm{Cl}_2 + 2\mathrm{Cl}^- \rightarrow [\mathrm{PtCl}_6]^{2-}$$

This reaction indicates that strongly oxidizing conditions are required and that chloride complexation stabilizes the dissolved metal species. Similar mechanisms affect Pd, Rh, and Ir, with speciation depending on oxidation state, chloride activity, and ligand environment. These behaviors are fundamentally governed by the formation and stability of anionic chloro-complexes, whose chemistry underpins most industrial separation strategies for PGMs (Bernardis et al., 2005; Fan et al., 2023; Nguyen et al., 2026).

In chloride systems, Pt typically forms $[PtCl_6]^{2-}$, Pd forms $[PdCl_4]^{2-}$, while Rh generally forms kinetically inert Rh(III) chloro-complexes, which significantly limit both dissolution and extraction efficiency.

Speciation plays a central role in downstream separation, since solvent extraction efficiency depends strongly on complex charge, coordination geometry, and ligand-exchange kinetics (Pianowska et al., 2023; Paiva et al., 2022). Alternative media, such as ionic liquids and deep eutectic solvents, can alter coordination environments, potentially improving selectivity by stabilizing intermediate species and reducing water activity, thereby influencing both thermodynamic stability and reaction kinetics (Mokhodoeva et al., 2022; Lanaridi et al., 2021; Cen et al., 2020).

The efficiency of PGM recovery during hydrometallurgical processing depends on the speciation of the metals in solution. In chloride media, PGMs form stable chloro-complexes with various oxidation states and structures, affecting their reactivity, mobility, and separation. Understanding these species is key to designing effective downstream processes. Table 2 summarizes the main PGM species involved in chloride leaching and their implications for separation.

Table 2. Dominant chloro-complex species of PGMs in chloride media and their implications for separation. Adapted from Nguyen, T. A., et al. (2026) and Paiva, A. P., et al. (2022).

Metal	Dominant species	Oxidation state	Separation implication
Pt	$[PtCl_6]^{2-}$	+4	Strongly extractable
Pd	$[PdCl_4]^{2-}$	+2	High mobility
Rh	Complex chloro-species	+3	Slow kinetics
Ir	$[IrCl_6]^{2-}$	+4	Stable but slow dissolution

Table 2 shows that speciation is crucial in downstream processing, affecting both separation and chemistry. Stable chloro-complexes like $[PtCl_6]^{2-}$ and $[PdCl_4]^{2-}$ increase metal mobility and aid separation via solvent extraction and ion exchange. In contrast, elements such as Rh and Ir exhibit complex speciation and slower dissolution, thereby requiring more intensive or multi-stage processing. These differences link separation performance to leaching chemistry, so process design must consider speciation early to optimize extraction, flowsheet complexity, and costs.

A particularly important limitation concerns rhodium. In chloride media, Rh(III) commonly forms kinetically inert chloro-complexes whose ligand substitution rates are significantly slower than those of Pt(IV) and Pd(II). As a result, rhodium is disadvantaged at multiple stages of the flowsheet: it dissolves more slowly, re-equilibrates more slowly during solution conditioning, and is often extracted less efficiently in conventional solvent extraction and ion-exchange systems. This behavior is mechanistically important because poor rhodium recovery is not explained by thermodynamics alone, but by the combined effects of slow ligand exchange, persistent coordination environments, and lower transfer kinetics between aqueous and organic or resin phases. Classical reviews of PGM separation through anionic chloro-complexes emphasize precisely these differences in ligand substitution kinetics and complex behavior

Kinetics

Kinetics limit PGM hydrometallurgy, even when thermodynamically favorable. Reaction rates are often slow, especially for noble and refractory phases. Leaching involves three regimes: surface-reaction control (early or high-oxidant stages), diffusion control (mass transfer through layers), and mixed control (common in practice).

Leaching times vary from hours to days, depending on temperature, particle size, and oxidant strength (Yakoumis et al., 2021; Nguyen et al., 2026). Pt dissolves in chloride systems in 6–24 hours, while Rh is slower due to its inertness. Smaller particles (<50 µm) improve dissolution but raise costs (Sahu et al., 2021; Corin et al., 2021). Temperature influences rates with activation energies of 40–80 $kJ \cdot mol^{-1}$, showing chemical control (Nguyen et al., 2026). Advanced methods such as pressure leaching, microwave processing, mechanochemical activation, and complexing agents may boost rates but are mostly lab-scale and require more industrial testing (Griffiths, 2025; Ye et al., 2025).

Critical perspective

Hydrometallurgical processing offers greater selectivity than pyrometallurgy but faces challenges such as slower kinetics, higher reagent consumption, and greater complexity. It must selectively dissolve PGMs among other metals, especially in heterogeneous secondary resources. Once in solution, the focus shifts to separation and purification using methods such as solvent extraction, ion exchange, and precipitation, highlighting their selectivity, efficiency, and industrial use.

Separation and Purification

After leaching, PGMs form complex ions in chloride solution. The key challenge is separating PGMs from co-extracted metals such as Fe, Cu, Ni, and Al, as well as from impurities, which is vital for high-purity metals (Nguyen et al., 2026; Paiva et al., 2022). Separation and purification impact product quality, recovery, and cost. Industrial methods such as solvent extraction, ion exchange, and precipitation are used in multi-step flowsheets.

Solvent extraction

Solvent extraction (SX) is the dominant industrial technique for the selective separation of PGMs from leach solutions. The process is based on the transfer of metal complexes from an aqueous phase to an organic phase containing specific extractants, enabling stepwise separation in multi-component systems.

In chloride media, SX performance is heavily influenced by metal speciation (e.g., $[PtCl_6]^{2-}$, $[PdCl_4]^{2-}$), type of extractant (amines, phosphine oxides, organophosphorus compounds), and solution chemistry, especially acidity and chloride concentration. This dependence on chloro-complex speciation reflects the classical separation framework of PGMs, in which differences in complex stability and ligand-exchange kinetics control extractability and selectivity (Bernardis et al., 2005)

Selectivity results from differences in the affinity of individual PGMs for organic extractants. For example, Pt(IV) is effectively extracted by tertiary amines and phosphine oxides, whereas Pd(II) exhibits high extractability in chloride systems. Conversely, Rh(III) remains challenging to extract due to its kinetic inertness, often requiring more complex or multi-stage strategies.

Under optimized conditions, Pt and Pd extraction exceeds 90–99%, while Rh recovery is lower and process-dependent (Pianowska et al., 2023; Nguyen et al., 2026). SX is effective but multi-stage, requiring precise control of phase equilibria, mass transfer, and reagent stability, adding complexity and cost. Figure 6 shows a simplified SX flowsheet with extraction, scrubbing, and stripping. Advances enhance selectivity and sustainability through deep eutectic solvents (DES), continuous systems that reduce time and solvent use, and hybrid systems that combine ionic liquids with traditional extractants (Mokhodoeva et al., 2023; Lanaridi et al., 2022; Phakoukaki et al., 2025; Paiva & Nogueira, 2021).

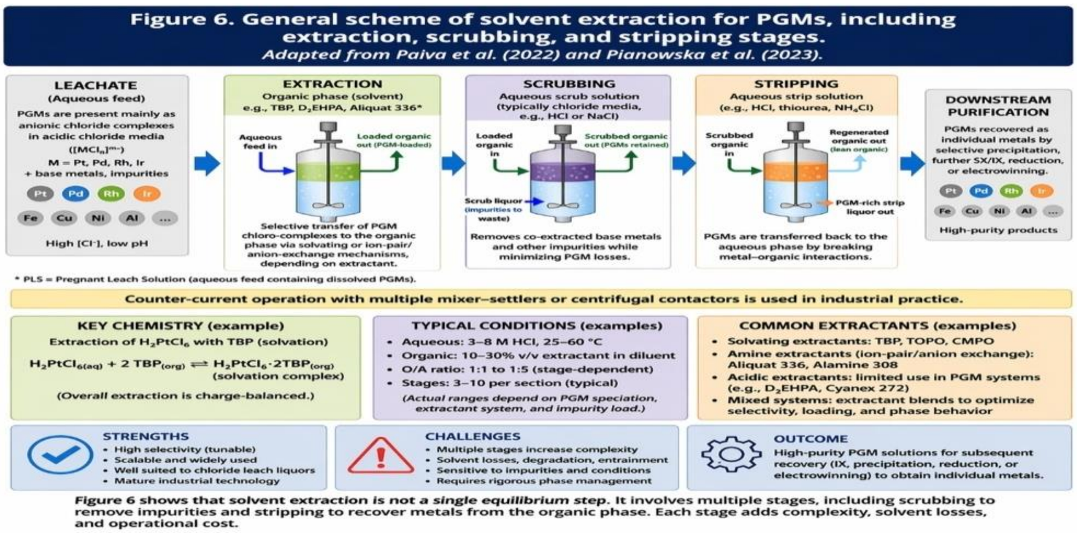


Figure 6. General scheme of solvent extraction for PGMs, including extraction, scrubbing, and stripping stages. Adapted from Paiva et al. (2022) and Pianowska et al. (2023).

Figure 6 shows that solvent extraction involves several stages: extraction, scrubbing, and stripping. During extraction, PGM chloro-complexes move to the organic phase, while impurities stay in the aqueous raffinate. Scrubbing removes co-extracted metals and contaminants, improving selectivity and stabilizing the organic phase. Stripping recovers PGMs into a purified aqueous solution for further processing.

Despite its high selectivity and industrial use, SX is complex due to its multi-stage setup, which increases operational complexity, solvent losses, and costs. Its performance depends on feed variability, phase behavior, and reagent stability, especially in secondary resource processing. Economically, SX adds costs through extractant use, solvent losses, degradation, and energy for mixing and separation. SX design must balance efficiency, simplicity, and cost.

Ion exchange

Ion exchange (IX) complements solvent extraction in PGM separation, especially in chloride media, using functionalized resins to adsorb metal complexes for recovery from dilute solutions. IX depends on resin functional groups, metal species, and solution chemistry, like acidity and ions. Under optimal conditions, recovery of PGMs—particularly Pt and Pd—can surpass 85–95% (Goc et al., 2023; Goc et al., 2024b). It is useful for treating dilute streams, polishing solutions, and PGM recovery from effluents.

Recent advances focus on enhancing selectivity and efficiency through dynamic ion exchange with improved mass transfer, specialized resins for PGM complexes, and the combination of IX with solvent extraction and precipitation in multi-stage flowsheets. Ion exchange is more modular and flexible than solvent extraction, but it is often part of an integrated process. Figure 7 shows the main stages: adsorption, washing, and elution.

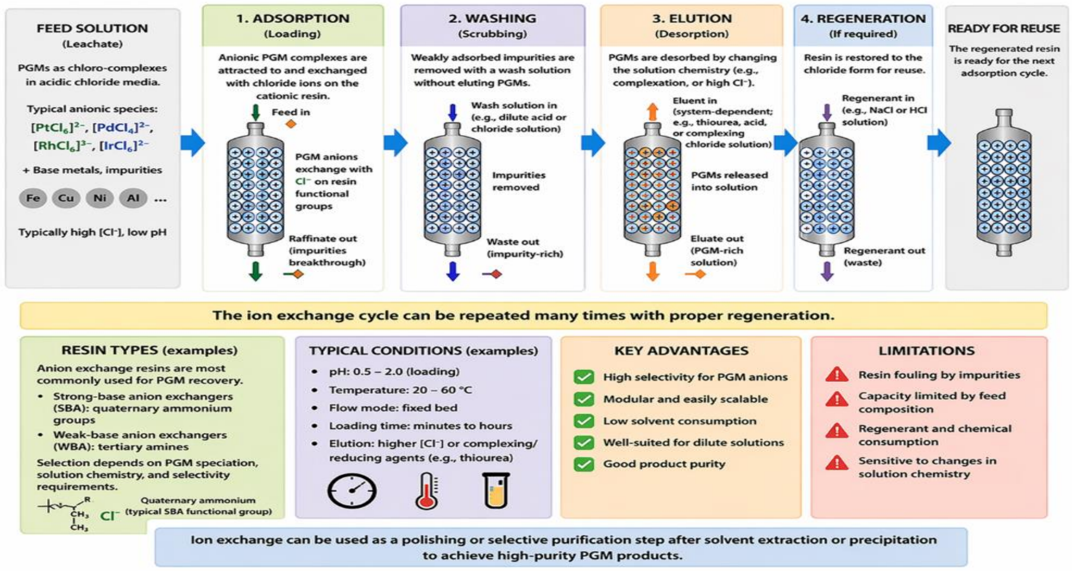


Figure 7. Ion exchange process for PGM recovery, including adsorption, washing, and elution stages. Adapted from Goc et al. (2024a) and Siwela et al. (2024).

Figure 7 shows ion exchange as a cyclic process with adsorption, washing, and elution. During adsorption, PGM chloro-complexes are retained; most base metals stay in the raffinate. Washing removes impurities, improving purity and preventing contamination. Elution desorbs PGMs, yielding a concentrated solution for recovery.

Ion exchange offers high selectivity, low solvent use, and effectiveness in polishing dilute streams. However, its performance is limited by resin factors such as cost, degradation, and lower loading capacity than solvent extraction. IX systems are sensitive to feed composition, especially to competing ions such as Fe^{3+} and Cu^{2+}, which can reduce selectivity and cause fouling. It's rarely used alone and is often integrated into multi-stage flowsheets. Effectiveness depends on controlling feed chemistry, selecting a suitable resin, and integrating efficiently with upstream leaching and downstream purification.

Precipitation

Precipitation in PGM processing turns dissolved metal complexes into insoluble compounds for filtration and refining, using chemical reduction, insoluble salts, or sulfide precipitation. It's cost-effective for bulk recovery but less selective than solvent extraction or ion exchange, with co-precipitated impurities requiring extra refining (Goc et al., 2024b; Radojević et al., 2025). Recovery exceeds 90%, but purity varies based on solution and process control (Goc et al., 2024a; Ye et al., 2025).

The separation and purification of PGMs employ hydrometallurgical methods like solvent extraction, ion exchange, and precipitation, each with trade-offs in selectivity, recovery, and cost. The choice depends on feed properties, purity needs, and operations, as shown in Table 3.

Table 3. Comparison of solvent extraction, ion exchange, and precipitation for PGM separation. Adapted from Pianowska et al. (2023), Goc et al. (2024b), Nguyen et al. (2026), and Wan et al. (2025).

Method	Selectivity	Recovery	Advantages	Limitations
Solvent extraction	High (Pt, Pd)	90–99%	High efficiency, industrially established	Solvent cost, multi-stage complexity
Ion exchange	Moderate–high	85–95%	Good for dilute streams, modular	Resin cost, lower capacity
Precipitation	Low–moderate	>90%	Simple, low cost	Poor selectivity, co-precipitation

Table 3 shows that no single technique optimizes selectivity, recovery, and simplicity. Solvent extraction offers the best selectivity and recovery for Pt and Pd and remains the main industrial method, despite high costs due to its multi-stage setup and solvent requirements.

Ion exchange balances selectivity and flexibility, ideal for dilute solutions and polishing, but has low capacity and impurity sensitivity. Precipitation is simple, cost-effective, and has high recovery, but is less selective due to impurity co-precipitation. Effective PGM recovery requires integrating techniques in multi-stage flowsheets, leveraging each method's strengths to optimize performance, cost, and complexity.

Critical perspective

Separation and purification are among the most complex in PGM processing. The main challenge is not recovery but achieving high selectivity in multi-metal systems. Differences in speciation, kinetics, and complex stability hinder the separation of Pt, Pd, Rh, and Ir.

Rhodium is challenging to assess due to its slow dissolution, complex speciation, and accumulation in streams. Base metals such as Fe, Cu, and Ni interfere with extraction, reducing selectivity and increasing reagent consumption. Multi-stage processing raises costs. Separation technologies are well established but depend on the feed composition, especially for secondary resources, which are more variable and contaminated. The next section discusses secondary resource processing, focusing on catalyst recycling, e-waste treatment, and their integration with hydrometallurgical and separation processes.

Secondary Resource Processing

Secondary PGM resources differ from primary concentrates not only in grade, but also in substrate complexity, contaminant burden, and process variability. These differences strongly influence pre-treatment requirements, collector-phase behavior, leaching selectivity, and downstream purification. In practice, secondary-resource processing is therefore less defined by a single extraction step than by the need to manage heterogeneous feed chemistry across integrated thermal and hydrometallurgical stages.

The following subsections focus on the two most important secondary-resource categories discussed in the literature—spent automotive catalysts and electronic waste—highlighting how feed heterogeneity, impurity load, and metal speciation affect process selection, recovery efficiency, and industrial applicability.

Catalyst recycling

Spent automotive catalysts are the main secondary PGMs source, containing Pt, Pd, and Rh on ceramic supports such as Al_2O_3 and cordierite, along with residual Fe, Ce, Si, Pb, and Zn. PGMs are usually in strongly bonded metallic or oxide phases, making recovery difficult. However, their concentrations—500 to 2000 g/t—are up to 100 times higher than primary ores, making them highly recyclable (Radojević et al., 2025; Cieszyńska, 2023).

Processing spent catalysts involves pre-treatment, metal concentration, and hydrometallurgical refining. The complexity of the feed and the strong association of PGMs with the matrix mean that no single method can achieve both high recovery and purity.

Two main processing strategies are used. The pyrometallurgical route smelts catalysts with collector metals like Fe, Cu, or Ni to produce a PGM-rich alloy or matte (Ding et al., 2020; Morcali, 2020). It is robust, achieving over 95% recoveries, but requires high temperatures (>1200–1500 °C) and consumes significant energy (Han et al., 2023; Wan et al., 2025). Recent advances include co-smelting with waste printed circuit boards, microwave-assisted smelting, and slag engineering to improve phase partitioning (Huang et al., 2024; Tang et al., 2021; Yang et al., 2023).

Hydrometallurgical processing relies on selective leaching systems, including aqua regia, chloride media with oxidants (e.g., Cl_2, Fe^{3+}, H_2O_2), and alternative lixiviants tailored to specific feed characteristics. Reported leaching efficiencies for Pt and Pd can exceed 90–98% under optimized conditions; however, these values are highly dependent on feed type (e.g., primary concentrates vs. spent catalysts), degree of pre-treatment (thermal activation, comminution), oxidant strength, and chloride activity. In contrast, lower and more variable recoveries are typically observed in impurity-rich or heterogeneous secondary materials, where metal accessibility and competing reactions limit performance (Braga et al., 2025; Demarco et al., 2020).

Recent developments aim to improve both process efficiency and sustainability through enhanced reaction kinetics and selectivity. These include electrochemical and mechanochemical activation to overcome passivation and diffusion limitations, bio-derived lixiviant systems (e.g., bio-cyanide) to reduce chemical intensity, and hybrid pyro–hydrometallurgical flowsheets that combine high-temperature concentration with selective downstream leaching. While these approaches show promising improvements in laboratory-scale studies, direct quantitative comparison with conventional chloride-based systems remains limited due to differences in feed composition, operating conditions, and scale of investigation (Ye et al., 2025; Ilyas et al., 2022; Liang & Qu, 2023).

In industry, integrated flowsheets combining mechanical, thermal, and chemical steps are preferred to balance recovery, selectivity, and cost. Figure 8 shows a process scheme that highlights the pre-treatment, concentration, and refining stages for efficient PGM recovery from complex secondary resources.

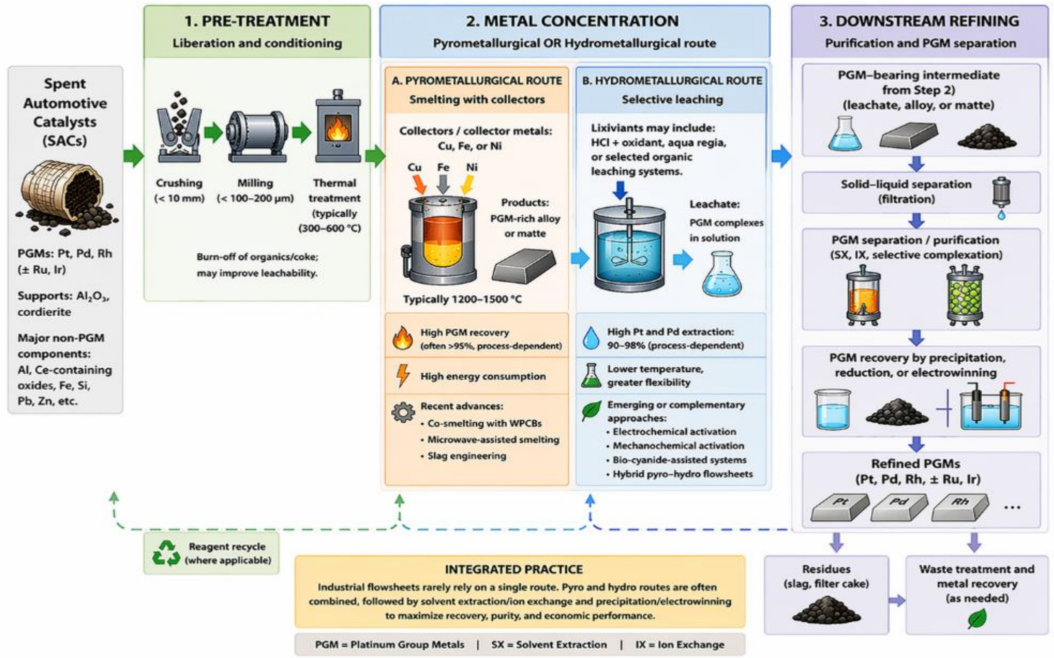


Figure 8. Typical flowsheet for PGM recovery from spent automotive catalysts, including pre-treatment, smelting or leaching, and downstream refining. Adapted from Yakoumis et al. (2021), Nicol et al. (2021), and Mvokwe et al. (2025).

Figure 8 demonstrates that PGM recovery from spent automotive catalysts is inherently a multi-stage process comprising pre-treatment, metal concentration, and downstream refining. Pre-treatment steps such as crushing, milling, and thermal conditioning are essential for liberating PGMs from ceramic supports and removing volatile components, thereby enhancing process efficiency.

Metal concentration can be achieved via pyrometallurgical or hydrometallurgical routes, each with distinct advantages. Pyrometallurgical processing offers robustness and high recovery, but at the cost of elevated energy consumption, whereas hydrometallurgical approaches provide greater selectivity and operational flexibility under milder conditions.

In industrial practice, these routes are frequently combined to maximize overall performance.

Downstream refining involves solid–liquid separation and selective recovery methods like solvent extraction, ion exchange, or precipitation to produce high-purity PGMs. The figure shows that industrial flowsheets use integrated strategies rather than a single process to optimize recovery, selectivity, and cost.

Despite the maturity of catalyst recycling, limitations remain. Feed heterogeneity, metal–support interactions, and high reagent use hinder optimization. Rhodium recovery is especially challenging due to its low solubility and slow dissolution, which often limit efficiency (Fan et al., 2023; Nguyen et al., 2026).026)

E-waste processing

Electronic waste (e-waste) is a vital, secondary source of PGMs, typically at lower concentrations than automotive catalysts, ranging from 10 to 500 g/t depending on the device (Chen et al., 2024; Paiva et al., 2022). PGMs are mainly in circuit boards, connectors, coatings, and components within complex matrices.

Processing routes typically involve mechanical pre-treatment, such as shredding, followed by thermal or chemical treatment, and then hydrometallurgical recovery. Recent advances include co-processing e-waste with spent catalysts, combined pyro–hydro flowsheets for multi-metal extraction, and selective leaching with solvent extraction for targeted recovery (Huang et al., 2024; Chen et al., 2024; Paiva et al., 2022).

Despite lower metal grades, e-waste processing offers benefits over primary mining, such as reduced mining and transportation, lower environmental impact, and support for the circular economy. It can cut CAPEX by 30–60% by removing mining and comminution, with generally lower energy use—especially in hydrometallurgy. Recovery is also faster and more flexible.

Recycling currently accounts for approximately 20–30% of the global PGM supply, a share that is expected to increase as regulatory pressure, resource constraints, and circular economy strategies intensify (Zhang et al., 2024; Hughes et al., 2021). Life cycle assessment (LCA) studies generally indicate that secondary PGM recovery can significantly reduce environmental impacts, with reported CO_2 emission reductions of 40–80% and solid waste reductions exceeding 90% compared to primary production. However, these values are highly dependent on system boundaries, allocation methods, energy mix, feed composition, and pre-treatment requirements and should therefore be interpreted as indicative rather than universally applicable (Lord et al., 2025).

Secondary processing remains challenging due to feed variability, multi-metal interactions, and the limited scalability of emerging tech. Waste stream integration, such as catalysts, e-waste, and fuel cells, remains unresolved (Bediako & Repo, 2025; Nicol et al., 2021). Conventional recycling relies on aggressive reagents and intensive energy use, prompting alternatives such as bioleaching, deep eutectic solvents, and ionic liquids to enhance selectivity, reduce environmental impact, and enable process intensification.

Emerging Technologies

Conventional PGM processing involves aggressive reagents, high temperatures, and multi-step separation, leading to high energy and chemical use. New methods like bioleaching, DES, and ILs seek to improve selectivity and reduce environmental impact but are still in early stages of research with limited industry adoption.

Bioleaching

Bioleaching employs microorganisms or biogenic reagents to extract PGMs from solid matrices, using microbial activity to produce lixiviants such as cyanide and organic acids that oxidize metal phases and facilitate PGM dissolution. It suits low-grade materials and complex waste streams where traditional methods are inefficient or costly (Banerjee et al., 2024; Pathak et al., 2022; Chipise et al., 2022; Hedrich et al., 2020).

Bioleaching usually occurs at ambient conditions, cutting energy use and infrastructure needs. Recovery varies by system, with platinum and palladium typically 40–90%, but rhodium recovery is much lower due to its chemical stability (Ilyas et al., 2022; Compagnone et al., 2023).

The mechanisms, including cyanide complexation, redox dissolution, and surface modification, enhance metal accessibility (Banerjee et al., 2024). They depend on microbial activity, solution chemistry, and substrate traits.

Recent developments enhance performance through process integration. Hybrid systems using bioleaching and ionic liquids aim to improve selectivity, transfer, and recovery with downstream hydrometallurgy (Ilyas et al., 2022; Nguyen et al., 2026). Pre-treatment methods like mineral oxidation and mechanical activation are used to increase metal bioavailability (Ye et al., 2025).

Despite advances, the industrial use of bioleaching remains limited by slow kinetics, sensitivity, and scaling issues (Pathak et al., 2022; Chipise et al., 2022). It is better as a pre-treatment than a standalone method. Table 4 outlines its mechanisms, performance, and limitations for PGM recovery.

Table 4. Bioleaching of platinum group metals: mechanisms, performance, and limitations. Adapted from recent advances in biometallurgical processing.

Aspect	Description	Technical Implication
Principle	Microbial generation of lixiviants (cyanide, organic acids)	Enables metal mobilization under mild conditions
Main mechanisms	Cyanide complexation; redox dissolution; surface modification	Enhances PGM solubility and accessibility
Operating conditions	Ambient temperature and pressure	Low energy consumption
Best applications	Low-grade materials; complex waste streams	Suitable for urban mining and residues
Typical recovery	Pt, Pd: 40–90%; Rh: low	Strong dependence on kinetics and system design
Recent advances	Integration with ionic liquids; coupling with hydrometallurgy; pre-treatment	Improved selectivity and overall recovery
Advantages	Low energy demand; environmentally favorable	Reduced chemical intensity
Limitations	Slow kinetics; scale-up challenges; biological sensitivity	Limited industrial adoption

Bioleaching provides a low-energy method for PGM recovery, ideal for complex, low-grade materials. Operating under ambient conditions with microbially produced lixiviants such as cyanide and organic acids minimizes chemical use and environmental impact (Banerjee et al., 2024; Pathak et al., 2022). Unlike traditional leaching, bioleaching depends on in situ lixiviant production and microbial surface modifications.

The process involves interactions among microorganisms, solution chemistry, and solid substrates, leading to metal mobilization via mechanisms such as biogenic complexation, redox dissolution, and surface alteration of mineral phases, thereby enhancing access to PGM (Banerjee et al., 2024; Hedrich et al., 2020). Understanding these pathways is crucial to optimizing performance and overcoming kinetic limits. Figure 9 shows the main bioleaching mechanisms: lixiviant generation, metal dissolution, and complex formation.

Bioleaching faces challenges such as slow rates, control issues, and sensitivity. Pt and Pd recovery varies (40–90%), Rh recovery is low due to inertness (Ilyas et al., 2022; Compagnone et al., 2023). Scale-up and stability issues hinder industrial use.

Recent advances in bioleaching, like hydrometallurgy, ionic liquids, and pre-treatments, improve selectivity and performance (Ilyas et al., 2022; Nguyen et al., 2026). More work is needed to enhance robustness, accelerate kinetics, and confirm long-term industrial stability.

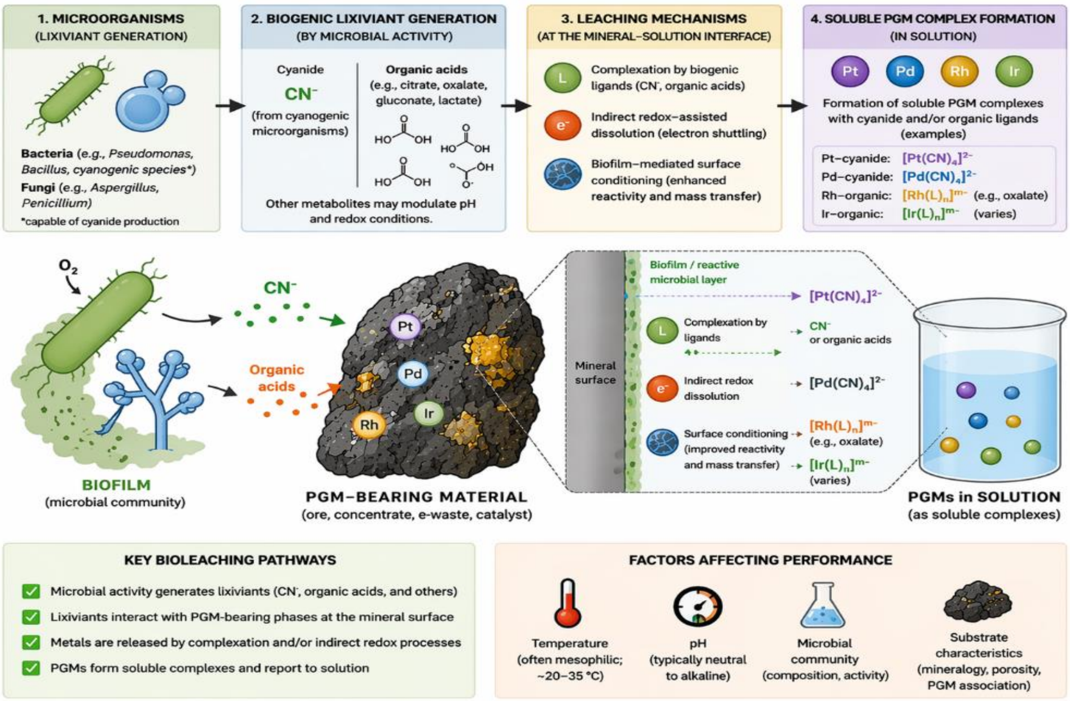


Figure 9. Schematic representation of bioleaching pathways for PGMs, including microbial lixiviant generation and metal complexation. Adapted from Banerjee et al. (2024).

Figure 9 shows bioleaching involves interconnected biochemical and chemical mechanisms. Microorganisms produce lixiviants like cyanide and organic acids that interact with PGM-bearing minerals. Metal mobilization occurs via complexation and redox reactions, while microbial activity and biofilm formation modify surfaces, thereby improving metal access.

Soluble species formation, such as metal–cyanide and organic ligand complexes, enables PGMs to enter solution. Their efficiency varies with temperature, pH, microbial community, and substrate, leading to variability and limited control.

Bioleaching operates under mild conditions with fewer chemicals but faces challenges such as slow kinetics, sensitivity to environmental conditions, and limited effectiveness against tough PGMs, which hinder scale-up and industrial use. It's best seen as part of an integrated process with pre-treatment and recovery to improve efficiency.

Deep eutectic solvents (DES)

Deep eutectic solvents (DES) are promising PGM processing alternatives, made by combining hydrogen bond donors like urea or acids with acceptors such as choline chloride. They are customizable liquids with strong solvating abilities (Mokhodoeva et al., 2023; Yuan et al., 2022).

DES systems offer low volatility, less toxicity, and high selectivity for metal complexation. Their tunability enables targeted interaction with specific PGM species for selective extraction under mild conditions. Applications include leaching spent catalysts, extracting from chloride media, and integrated leaching–separation systems (Paiva et al., 2022; Gholami et al., 2025).

Extraction efficiencies for Pt and Pd reach 90–99%, while Rh and Ir are lower and more variable due to kinetic limitations and complex speciation (Mokhodoeva et al., 2023). Recent advances include hydrophobic DES for better phase separation and selectivity, DES–ionic liquid hybrid systems for multi-metal recovery, and electrochemically assisted leaching to boost kinetics (Kamisono et al., 2024; Lanaridi et al., 2021; Riaz, 2025).

DES-based extraction relies on metal ion and solvent interactions for phase transfer and recovery. Understanding these at the molecular level is essential for improving selectivity and process performance. Figure 10 illustrates key extraction mechanisms of PGMs in DES: coordination, transfer, and recovery.

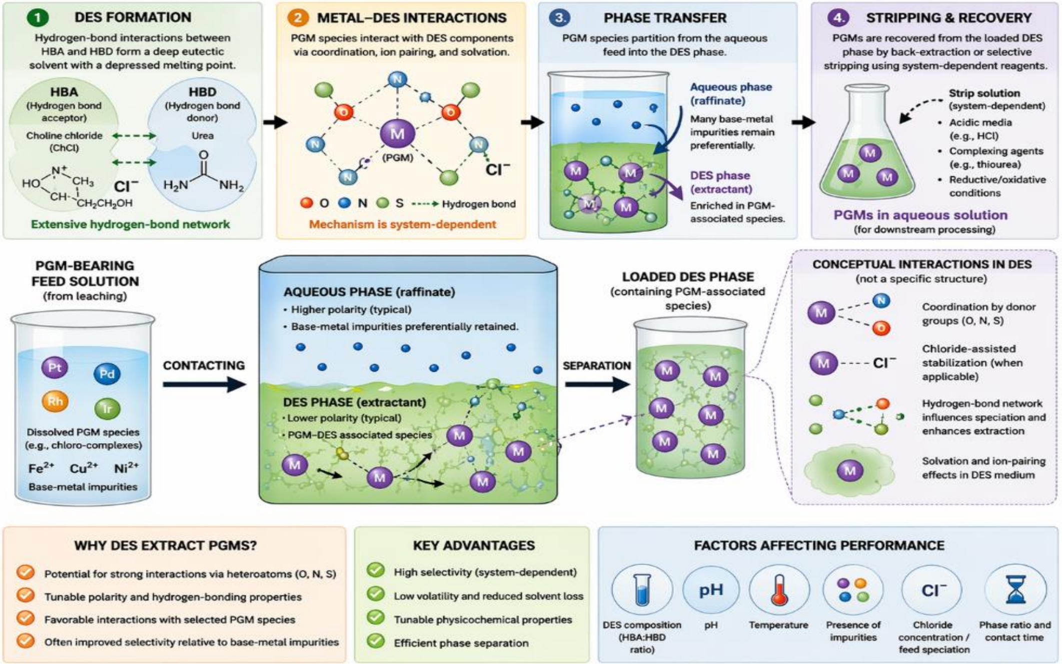


Figure 10. Mechanism of PGM extraction using deep eutectic solvents, showing metal coordination and phase transfer. Adapted from Mokhodoeva et al. (2023) and Gholami et al. (2025).

Figure 10 shows PGM extraction in DES systems depends on coordination between metal ions and solvent components, mainly hydrogen bond donors and acceptors. Metals are stabilized via complexes, often with chloride or ligands, aiding their transfer from water to DES. The process involves dissolution, complexation, phase transfer, and stripping for recovery. Tunable DES composition influences selectivity and efficiency, especially for Pt and Pd, which form stable complexes.

The figure highlights limitations like high viscosity hindering mass transfer and slow phase disengagement, reducing efficiency. Extracting Rh and Ir is challenging due to slow DES systems having advantages in selectivity and sustainability, but limited stability data and scale-up issues hinder industrial use. Further optimization is needed to improve transport, robustness, and enable large-scale applications.

Ionic liquids

Ionic liquids (ILs) are low-melting salts (<100 °C) with high stability, strong solvating ability, and tunable polarity. They selectively interact with metal complexes, useful in platinum group metal (PGM) processing, especially in chloride systems where metal speciation is critical (Paiva & Nogueira, 2021; Mokhodoeva et al., 2023).

ILs in hydrometallurgy enable selective leaching, solvent extraction, and metal transport, with chloride complex stability improving compatibility with traditional leaching media and enhancing selectivity for PGMs (Nguyen et al., 2026; Pianowska et al., 2023). High palladium extraction efficiencies are seen with trihalide IL systems, especially in chloride environments (Van den Bossche et al., 2021). Hybrid approaches, like coupling ILs with bioleaching or IL–DES systems, aim to improve multi-metal separation and reduce reagent use (Ilyas et al., 2022; Lanaridi et al., 2022).

Reported recoveries for Pt and Pd exceed 90%, but Rh and Ir are harder to extract because of slower kinetics and stable complexes (Gholami et al., 2025). Despite the benefits, industrial use is limited by high synthesis costs, potential toxicity of some ILs, and regeneration challenges (Paiva et al., 2022; Yuan et al., 2022).

Research develops sustainable, cost-effective, recyclable IL systems. ILs and related solvents enable more selective, eco-friendly PGM processing. Table 5 summarizes their key properties, uses, and limitations.

Table 5. Ionic liquids in platinum group metal processing: properties, applications, and limitations. Adaptedfrom Paiva, A. P., & Nogueira, C. A. (2021); Mokhodoeva, O., et al. (2023); Yuan, Y., et al. (2022); and Gholami, M., et al. (2025).

Aspect	Description	Technical Implication
Definition	Molten salts with a melting point <100 °C	Operate in liquid phase at mild conditions
Key properties	High thermal stability; strong solvating ability; tunable polarity	Enables selective complexation of PGMs
Main applications	Leaching; solvent extraction; metal transport	Integration with hydrometallurgical flowsheets
Selectivity	High affinity for chloride complexes	Effective for Pt and Pd separation
Typical recovery	Pt, Pd: >90%; Rh, Ir: lower	Kinetic limitations for heavier PGMs
Representative systems	Trihalide ILs; IL–DES hybrids; bioleaching–IL systems	Enhanced multi-metal separation capability
Advantages	Low vapor pressure; high selectivity; compatibility with chloride media	Reduced emissions and improved process control
Limitations	High cost; toxicity (some ILs); regeneration complexity	Barrier to industrial scale-up

Table 5 shows ionic liquids are a versatile platform for PGM extraction due to their affinity for chloride complexes and tunable structure. These enable high selectivity for Pt and Pd and integrate with existing flowsheets (Paiva & Nogueira, 2021; Mokhodoeva et al., 2023).

Pt and Pd recoveries often exceed 90%, but Rh and Ir extraction is limited by kinetics and complex speciation (Gholami et al., 2025). The versatility of IL systems, including IL–DES hybrids and bioleaching, broadens their use in multi-metal separation (Ilyas et al., 2022; Lanaridi et al., 2022).

Despite advantages, challenges such as high cost, potential toxicity, and regeneration issues hinder large-scale use (Paiva et al., 2022; Yuan et al., 2022). IL systems offer better selectivity and lower emissions but require development to enhance economic viability and scalability.

Overall, the data show ionic liquids have superior selectivity and low emissions compared to conventional solvents, but economic and environmental constraints hinder industrial use (Mokhodoeva et al., 2023; Paiva et al., 2022).

Emerging technologies show promise but haven't reached full industrial maturity due to scale-up limits, process stability challenges, integration difficulties, and ongoing economic uncertainty.

These constraints are technology-specific: bioleaching is hindered by slow kinetics, DES systems face mass transfer issues, and high costs and regeneration challenges limit ionic liquids. Consequently, these are more complementary to traditional hydrometallurgy.

Limitations in PGM processing arise from kinetic and mechanistic constraints like slow dissolution, surface passivation, and multi-metal interactions, which hinder efficiency and scalability. The next section examines these challenges, emphasizing reaction mechanisms and rate-controlling steps.

Kinetic and Mechanistic Challenges

Despite decades of technological development, PGM processing remains limited by slow reaction kinetics and complex pathways. These restrictions affect recovery, reagent use, and economics, with reaction rate and mass transfer often more challenging than thermodynamic considerations. PGMs have low dissolution rates, resist chemical attack, and are highly stable and inert.

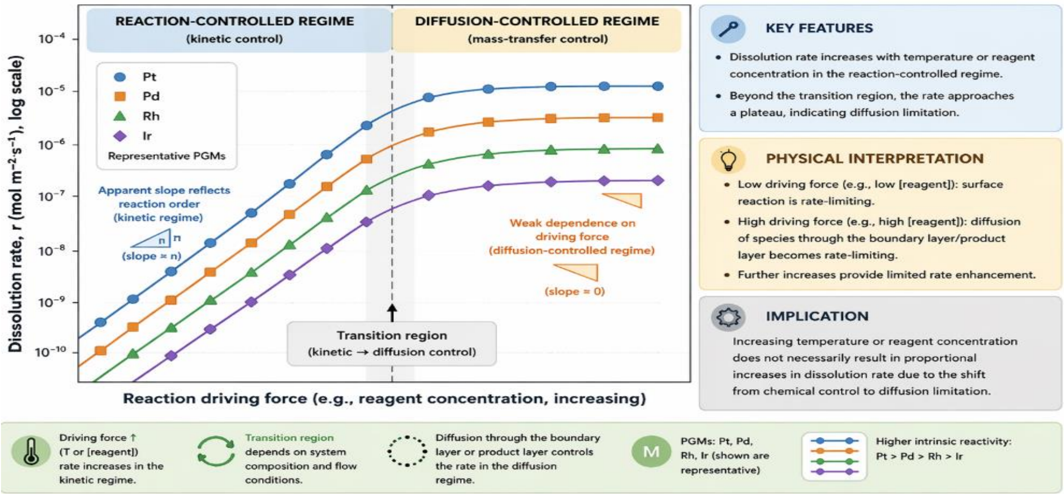
Slow dissolution

Platinum group metals (PGMs) are very stable and require harsh conditions like strong oxidizers, high chloride activity, and high temperatures for dissolution. Even with methods like aqua regia or Cl_2/HCl, leaching can take hours to days depending on particle size and pre-treatment (Demarco et al., 2020; Nguyen et al., 2026).

The dissolution process involves rate-controlling mechanisms like surface reaction kinetics, boundary layer diffusion, and porous layer diffusion. For secondary resources like spent catalysts, challenges increase due to PGM dispersion on supports, limited access to active sites, and encapsulation within oxide matrices.

Reported activation energies for PGM dissolution are usually 40–80 kJ·mol^{-1}, indicating a shift from reaction-controlled to diffusion-controlled regimes, as shown in Figure 11. This highlights the transition between chemical reaction and diffusion control (Braga et al., 2025; Coelho, 2023).

Recent methods to boost dissolution include mechanochemical activation, electrochemical leaching, and alternative solvents like deep eutectic solvents (DES) and ionic liquids (ILs), enhancing mass transfer and metal access (Ye et al., 2025; Riaz, 2025; Mokhodoeva et al., 2023; Yuan et al., 2022).



KEY FEATURES

- Dissolution rate increases with temperature or reagent concentration in the reaction-controlled regime.
- Beyond the transition region, the rate approaches a plateau, indicating diffusion limitation.

PHYSICAL INTERPRETATION

- Low driving force (e.g., low [reagent]): surface reaction is rate-limiting.
- High driving force (e.g., high [reagent]): diffusion of species through the boundary layer/product layer becomes rate-limiting.
- Further increases provide limited rate enhancement.

IMPLICATION

Increasing temperature or reagent concentration does not necessarily result in proportional increases in dissolution rate due to the shift from chemical control to diffusion limitation.

Driving force ↑ (T or [reagent]) rate increases in the kinetic regime.

Transition region depends on system composition and flow conditions.

Diffusion through the boundary layer or product layer controls the rate in the diffusion regime.

PGMs: Pt, Pd, Rh, Ir (shown are representative)

Higher intrinsic reactivity: Pt > Pd > Rh > Ir

Figure 11. Typical dissolution behavior of PGMs showing transition from reaction-controlled to diffusion-controlled regimes. Adapted from Nguyen et al. (2026) and Pianowska et al. (2023).

Figure 11 illustrates that increasing temperature or reagent concentration does not necessarily result in proportional increases in dissolution rate, reflecting the transition from chemical control to diffusion limitation.

At lower temperatures or reagent concentrations, PGM dissolution is reaction-controlled, governed by surface reaction kinetics and rising with chemical driving force. In this region, process performance is sensitive to operating conditions, and increasing reagent strength or temperature can greatly improve dissolution.

Beyond a critical transition, the system becomes diffusion-controlled, with mass transfer limitations—like diffusion through boundary or product layers—dominating the rate. Increasing temperature or reagent concentration yields diminishing returns, and the dissolution rate plateaus.

This explains why aggressive conditions don't always improve PGM recovery and highlights the importance of transport phenomena like particle size, agitation, and hydrodynamics in process optimization. Effective PGM dissolution needs balancing chemical reactivity with mass transfer to overcome kinetic constraints.

Surface passivation

Surface passivation limits PGM processing by forming a layer on the metal surface, inhibiting reactions, reducing reactive site accessibility, and slowing dissolution.

Passivation involves oxide layer formation, silica or alumina deposition, and residues from feed. In spent catalysts, it worsens from sintering, strong metal–support interactions, and refractory oxides. Studies show passivation can cut leaching rates by 50–90%, even in harsh chemicals (Demarco et al., 2020; Yakoumis et al., 2020), underscoring its role as a rate-limiting step in PGM dissolution.

Several mitigation strategies include thermal pre-treatment to remove residues, complexing agents to destabilize surface layers, and mechanical activation to expose reactive surfaces. However, these increase process complexity and costs. Passivation is rarely fully eliminated and is usually managed through process optimization.

Multi-metal systems

PGM processing involves multi-metal systems, including PGMs (Pt, Pd, Rh, Ir, Ru), base metals like Fe, Cu, Ni, rare earths, and contaminants. This complexity affects reaction pathways and process performance. Competition among metals for reagents impacts leaching, separation, and reagent use. Complex speciation complicates processing; PGMs form various aqueous complexes: Pt forms stable hexachloro complexes, Pd tetrachloro species, and Rh shows slower ligand exchange, influencing extraction behavior (Nguyen et al., 2026; Paiva et al., 2022).

Multi-metal systems exhibit coupled transport, where reaction and diffusion influence each other. Precipitation can block access to other species, and alloy formation (e.g., Fe–PGM systems) can alter dissolution behavior and kinetics. These interactions increase mass transfer resistance and reduce process efficiency. Recent studies show recovery efficiency drops by 20–40% in multi-metal systems compared to single-metal ones, due to chemical competition and transport limits (Chen et al., 2024; Yang et al., 2023).

PGM recovery in industrial systems involves complex interactions with base metals affecting selectivity, kinetics, and stability. Understanding these is key to designing efficient separation processes. Figure 12 shows the main reactions and transport phenomena in multi-metal PGM systems.

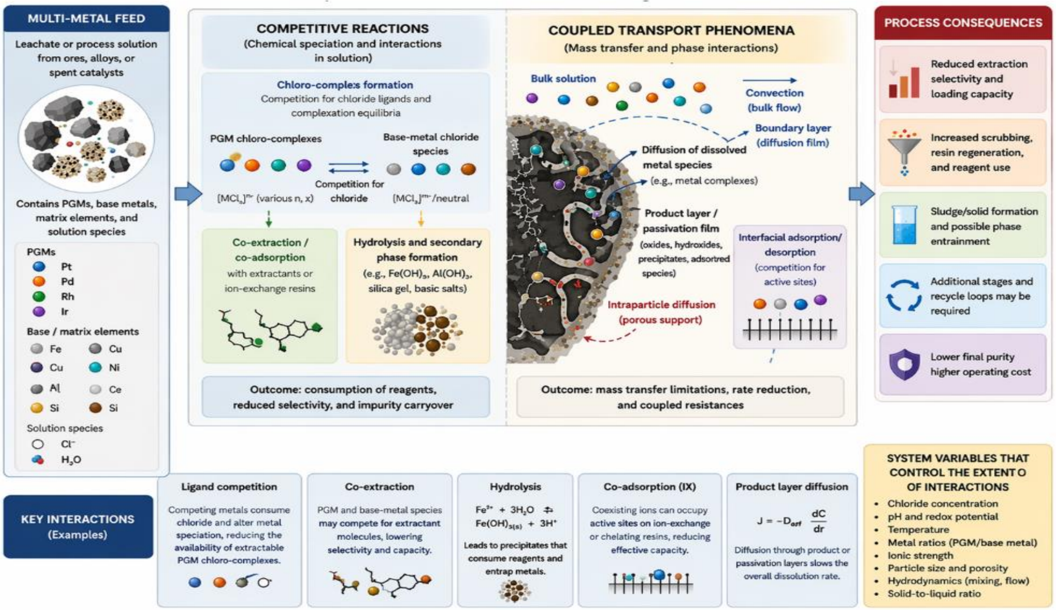


Figure 12. Schematic representation of competitive reactions and coupled transport phenomena in multi-metal PGM systems. Adapted from Paiva et al. (2022) and Yang et al. (2023).

Figure 12 shows that multi-metal PGM systems are governed by chemical reactions and coupled transport phenomena. PGMs and base metals compete for ligands, extractants, and sites, leading to co-extraction, co-adsorption, and reduced selectivity (Paiva et al., 2022; Pianowska et al., 2023). Hydrolysis and secondary phases, especially involving Fe, Al, and Si, produce solid residues that complicate separation (Yang et al., 2023; Goc et al., 2024b).

Mass transfer limitations such as boundary layer diffusion, intraparticle transport, and passivation layers resist metal transfer, slow reactions, and may cause diffusion-controlled systems (Nguyen et al., 2026; Braga et al., 2025).

These interactions increase operational costs and reduce efficiency due to more reagent use, scrubbing, sludge, and processing (Phakoukaki et al., 2025; Paiva et al., 2022). Impurity carryover and incomplete separation threaten product purity. Additionally, competitive reactions and transport limitations complicate multi-metal PGM system optimization. Effective process design must address chemical selectivity and mass transfer together.

Kinetic and mechanistic constraints slow PGM processing, leading to slow dissolution, passivation, and complex interactions. This causes high reagent use, long times, and reduced selectivity and recovery (Demarco et al., 2020; Yakoumis et al., 2020; Nguyen et al., 2026). These issues hinder scaling despite lab success.

The complexity of multi-metal systems worsens impurity problems during separation, especially with Fe, Cu, and Ni, which hinder extraction and reduce selectivity (Goc et al., 2023; Fan et al., 2023). The next section reviews impurity effects and limits to selectivity.

Impurity and Selectivity Issues

Impurity control is a key challenge in PGM processing since PGMs rarely recover alone; they coexist with elements like Fe, Cu, Ni, Al, Ce, Si, affecting extraction and purity. Secondary resources add complexity due to ceramic supports, washcoats, alloy phases, and contamination causing chemically heterogeneous leachates (Paiva et al., 2022; Yang et al., 2023; Srivastava et al., 2025).

From a process perspective, the main challenge is selective separation under high impurity loads, not dissolution. Over 90% Pt or Pd recovery may be ineffective if reagents deplete, extractants overload, resins are poisoned, or co-precipitate. Thus, selectivity, not just yield, is the key performance measure (Goc et al., 2023; Goc et al., 2024a).

Fe, Cu, and Ni are key interfering elements. Iron is especially problematic due to its high levels and ability to hydrolyze, precipitate, or form chloro-complexes. Copper and nickel also compete for extractants and adsorption sites, mainly in chloride systems from catalyst and alloy processing (Fan et al., 2023; Paiva et al., 2022; Wan et al., 2025). In industrial streams, base metals often exceed PGM levels, quickly reducing separation efficiency even in moderately selective systems.

Impurity interference in solvent extraction causes co-extraction of base metals, leading to more scrubbing and multistage separation to isolate Pt, Pd, Rh, and Ir. This raises solvent use, equipment size, degradation, and OPEX (Pianowska et al., 2023; Mokhodoeva et al., 2023; Phakoukaki et al., 2025).

Ion exchange performance suffers from impurities. High Fe and Cu levels change breakthrough, lower resin capacity for PGMs, and boost regeneration. Effective for dilute streams, but impurity-rich solutions need pre-treatment for stability (Goc et al., 2023; 2024b).

Precipitation is simpler but less selective, especially with Rh and Ir, where slow kinetics and complex speciation reduce purity. High recovery doesn't always mean high purity. Impurity control is vital in PGM processing, from leaching to purification. Early impurity management is crucial. Table 6 lists common impurities and their effects.

Table 6. Main effects of common impurities on PGM separation processes. Adapted from Goc et al. (2023), Goc et al. (2024a), Paiva et al. (2022), and Yang et al. (2023).

Impurity	Main source	Main effect	Consequence
Fe	Alloys, catalyst supports, ores	Competes in extraction, hydrolysis, and sludge formation	Lower selectivity, higher reagent demand
Cu	Ni-Cu matte, e-waste, catalyst alloys	Co-extraction, resin competition	Lower purity, more scrubbing stages
Ni	Sulfide ores, alloys	Complexation and co-loading in SX/IX	Reduced PGM separation efficiency
Al/Ce/Si	Washcoats, ceramic supports	Solid residues, entrainment, and downstream contamination	Difficult polishing and filtration
Rh/Ir vsPt/Pd	Intrinsic PGM system issue	Slower kinetics and distinct speciation	Fine separation remains difficult

Table 6 shows that impurities affect PGM separation through competitive extraction, co-loading, and secondary phase formation. Iron causes hydrolysis and sludge, reducing selectivity and increasing reagent use. Copper and nickel compete for active sites, reducing purity and necessitating additional stages.

Matrix elements such as Al, Ce, and Si cause residue, entrainment, and contamination, complicating filtration. Variations among PGMs, especially Pt/Pd versus Rh/Ir, affect separation due to different speciation and slower kinetics. The table shows impurity control limits impacting processing efficiency. Separating PGMs from other metals in multi-metal systems increases complexity.

The latter is often underestimated. Separating Rh and Ir from Pt/Pd is harder due to slower ligand exchange, inert species, and limited responsiveness, making high-purity metals difficult to recover and increasing costs. Many circuits recover bulk PGMs but struggle with pure metals (Nguyen et al., 2026; Pianowska et al., 2023; Fan et al., 2023).

This complexity arises from upstream processing, like Fe–PGM alloys or mixed slagging residues, which improve recovery but pose separation challenges during refining (Yang et al., 2023; Ye et al., 2025; Wan et al., 2025). Hybrid recycling systems can enhance metal capture but require complex downstream chemistry.

High recovery doesn't always indicate high process quality. A flowsheet with >95% recovery that requires extensive purification, high reagent use, and recycle loops may be less attractive than a slightly lower-yield process with better selectivity and simpler downstream steps. Recovery alone can be misleading without considering impurities.

Fe, Cu, and Ni interference hinder efficient PGM refining, making fine separation, especially for Rh and Ir, technically challenging. This explains why industrial flowsheets use leaching, impurity removal, solvent extraction, ion exchange, precipitation, and recycling—rather than single-unit processes. The next section discusses integrating pyrometallurgy, hydrometallurgy, impurity control, and secondary resource processing into cost-effective flowsheets.

Process Integration

Process integration is vital in PGM recovery, combining methods to overcome their limits. Pyrometallurgy efficiently concentrates but lacks selectivity; hydrometallurgy is selective but chemically intensive and impurity-sensitive. Therefore, industries prefer integrated pyro-hydrometallurgical flowsheets over standalone units (Aleksandrova & O'Connor, 2020; Han et al., 2023; Nguyen et al., 2026).

Two key integration levels are crucial. First, coupling pyrometallurgical concentration with hydrometallurgical refining allows efficient transition from bulk recovery to selective separation. Second, integrating primary and secondary PGM sources into broader systems maximizes resource use while controlling CAPEX, OPEX, and environmental impact.

Primary PGM processing uses an integrated approach: ore beneficiation and flotation concentrate PGMs into sulfide-rich fractions, then smelt into matte or alloy. Hydrometallurgical refining dissolves and separates metals, reflecting a flowsheet no single process can replace (Aleksandrova & O'Connor, 2020; Alexandrova & O'Connor, 2021).

A similar strategy is increasingly used for secondary resources. In spent catalyst recycling, pyrometallurgical stages often collect PGMs into Fe-, Cu-, or Ni-rich phases, followed by hydrometallurgical leaching and separation (Ding et al., 2020; Morcali, 2020; Liu et al., 2021). This is effective for heterogeneous feeds or materials with strong metal–support interactions, where thermal processing simplifies structures and hydrometallurgy offers selectivity.

Integrated pyro-hydro routes can recover over 95% of Pt, Pd, and Rh through collector-based smelting with chemical refining (Ding et al., 2020; Han et al., 2023). However, this increases process complexity, adding equipment, controls, and streams, which raises costs. Success depends on whether better metal concentration and selectivity offset the extra energy and reagent needs.

Recovery of PGMs uses pyrometallurgical and hydrometallurgical methods. Pyrometallurgy creates alloys; hydrometallurgy dissolves and purifies metals. This combination improves recovery, selectivity, and cost in complex systems. Figure 13 shows a typical flowsheet.

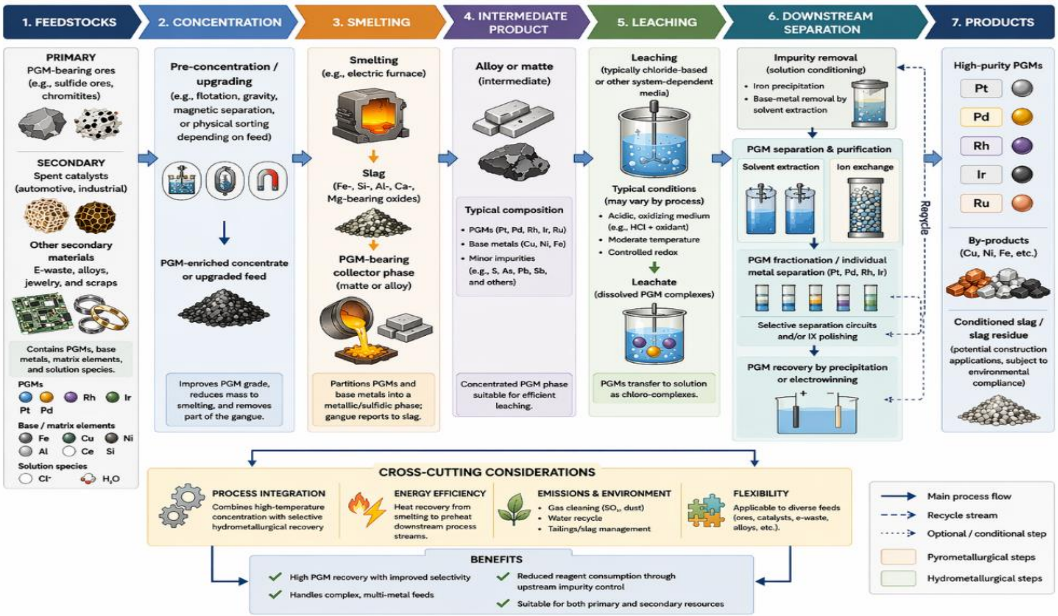


Figure 13. Conceptual integrated pyro-hydrometallurgical flowsheet for PGM recovery from primary concentrates and secondary resources. The scheme highlights the functional role of each processing stage: (i) feed preparation and concentration, (ii) pyrometallurgical upgrading through smelting and collector-phase formation, (iii) generation of an intermediate matte or alloy enriched in PGMs, (iv) hydrometallurgical dissolution of the enriched intermediate, and (v) downstream separation and purification by solvent extraction, ion exchange, or precipitation. The figure is intended to show how concentration, impurity transfer, recycling loops, and downstream selectivity are interconnected at the flowsheet level rather than to represent a plant-specific mass balance. Adapted from Aleksandrova and O'Connor (2020), Han et al. (2023), and Nguyen et al. (2026).

Figure 13 shows PGM recovery is a multi-stage process: feed prep, concentration, smelting, intermediate formation, leaching, and separation. Pyrometallurgy concentrates PGMs into metallic phases like alloys or mattes, rejecting gangue into slag. This improves downstream efficiency but adds complexity to refining.

The hydrometallurgical stage enables selective dissolution and separation of PGMs. Chloride-based leaching systems are used to transfer PGMs into solution as stable complexes, then impurities are removed and separated via solvent extraction, ion exchange, or precipitation. These steps produce high-purity metals but require strict control of chemistry and impurity levels.

The flowsheet shows integration is a system-level need, not just a sequence of operations. Recycling streams, impurity control, energy efficiency, emissions, and water management must be handled together for stability and cost-effectiveness. Handling various feedstocks like ores, catalysts, and e-waste highlights the importance of integrated design. Figure 13 is a conceptual diagram, not a detailed flowsheet. It clarifies each stage's role: pyrometallurgy for bulk concentration, hydrometallurgy for selectivity via dissolution and purification, showing how process stages interact.

This integrated view is especially important with new pyrometallurgical strategies like co-smelting with printed circuit boards, slag engineering, or electrometallurgical enrichment of Fe–PGM intermediates. These are not standalone solutions but preconditioning steps that can either ease or hinder downstream hydrometallurgical processing depending on impurity transfer and phase behavior (Huang et al., 2024; Wen et al., 2020; Yang et al., 2023). Therefore, process performance should be evaluated at the flowsheet level, not just by isolated recovery metrics.

A second and increasingly important dimension of integration involves the combined processing of primary and secondary PGM sources. Primary mining provides supply scale, whereas secondary resources offer higher grades and shorter recovery cycles, contributing to more resilient supply chains (Tang et al., 2023; Wang et al., 2026). However, this integration introduces significant metallurgical challenges. Secondary materials may contain chlorine, alkalis, ceramics, and other contaminants that can disrupt slag chemistry, refractory performance, and downstream refining stability (Yang et al., 2023; Liu et al., 2023).

Co-processing depends on metallurgical compatibility, not just feed availability. It's beneficial only if intermediate phases are processable, impurity levels stay manageable, and downstream circuits handle variability. Otherwise, benefits of higher-grade secondary materials might be negated by process instability and purification costs.

Recent developments show a shift toward integrated processing concepts like co-smelting of catalyst scrap with other wastes, zero-waste recovery for PGMs, integrated thermal treatments for spent catalysts, and hybrid recycling linking fuel-cell and electrocatalyst applications (Huang et al., 2024; Liu et al., 2022; Liu et al., 2023; Khalili et al., 2025). Most are still at the lab or pilot scale; their industrial success depends on maintaining high recovery and simplifying flowsheets.

The increasing complexity of PGM resources and methods highlights the need for integrated strategies that combine multiple units and sources. While integration boosts recovery, flexibility, and resource efficiency, it also introduces technical and operational challenges. These trade-offs need careful evaluation to select the optimal flowsheet. Table 7 presents the main benefits, limitations, and industry impacts of key PGM processing strategies.

Table 7. Main advantages and limitations of integrated PGM processing routes. Adapted from Morcali (2020), Nguyen et al. (2026), Wang et al. (2026), and Izatt et al. (2021).

Integration strategy	Main benefit	Main limitation	Industrial implication
Pyro + hydro	High overall recovery + selective downstream refining	High energy plus chemical demand	Technically robust, but capital-intensive
Primary + secondary feed integration	Better feed flexibility and asset utilization	Greater impurity variability	Attractive where smelting/refining infrastructure already exists
Co-processing with other waste streams	Improved collector efficiency and added value recovery	More complex chemistry and impurity control	Promising, but needs strict process control
Zero-waste / multi-product integration	Better resource efficiency	Higher flowsheet complexity	Strong sustainability appeal, uncertain scale-up

Table 7 reinforces a critical point: integration is not inherently beneficial. It becomes advantageous only when it reduces total system cost or environmental burden without compromising process stability. In this sense, a more integrated flowsheet is not necessarily better.

Integration strategies in PGM processing are intrinsically associated with trade-offs between performance, complexity, and cost. The combination of pyrometallurgical and hydrometallurgical routes enables high overall recovery and selective downstream refining, but requires substantial energy input and chemical consumption, resulting in capital-intensive systems.

Similarly, integrating primary and secondary feedstocks enhances operational flexibility and improves asset utilization, particularly in existing smelting and refining infrastructures. However, increased impurity variability introduces additional challenges in process control and may necessitate pre-conditioning or more robust downstream separation.

Co-processing with other waste streams can improve collector efficiency and enable recovery of additional value streams. However, it also increases chemical complexity and demands stricter control of impurity behavior and phase equilibria. Likewise, zero-waste and multi-product strategies offer strong sustainability benefits, yet often lead to more complex flowsheets that are difficult to scale and operate consistently.

Overall, no single integration strategy is universally optimal. The effectiveness of integrated PGM processing depends on achieving a balance between recovery efficiency, selectivity, process stability, and economic viability. Successful implementation therefore requires a system-level perspective that prioritizes robustness and scalability alongside metallurgical performance.

Critical perspective

The literature often presents process integration as an inherently advantageous solution; however, this perspective is frequently overly optimistic. In practice, integration redistributes trade-offs rather than eliminating them. Pyro-hydrometallurgical integration enhances concentration and selectivity but couples high energy demand with increased chemical complexity. Similarly, the integration of primary and secondary resources improves feedflexibility but introduces greater variability and more demanding impurity management. Multi-waste integration may enhance circularity, yet it also increases process control requirements and scale-up challenges.

For this reason, the effectiveness of process integration should be evaluated using system-level performance metrics rather than isolated recovery values. These include total recovery of each PGM, intermediate product purity, energy consumption, reagent demand, recycle loop intensity, waste generation, and capital intensity per tonne of metal recovered. Without such metrics, integration remains a conceptually attractive but technically incomplete proposition.

The following section therefore examines sustainability and circular economy aspects, as many of the arguments supporting integrated PGM processing are ultimately driven by environmental performance and resource efficiency rather than metallurgical considerations alone.

Sustainability and Circular Economy

Sustainability has emerged as a central driver in PGM processing. The traditional paradigm—based on primary mining and energy-intensive refining—is increasingly challenged by resource scarcity, environmental constraints, and tightening regulatory frameworks. As a result, the sector is increasingly shifting toward urban mining, recycling, and circular-economy strategies (Grilli et al., 2023; Zhang et al., 2024).

PGMs are critical raw materials due to limited availability and high strategic importance. Over 70–80% of the primary supply is concentrated in South Africa and Russia, causing significant supply risks (Hughes et al., 2021; Zhang et al., 2024). Demand rises for automotive emissions, hydrogen tech, and electronics, boosting the need for alternative sources.

Regulatory frameworks are also becoming increasingly important in shaping PGM recycling flowsheets and investment decisions. In the European context, the Critical Raw Materials Act, Regulation (EU) 2024/1252, reinforces supply-security and circularity objectives for strategic materials, while end-of-life collection and dismantling policies remain closely linked to the End-of-Life Vehicles Directive 2000/53/EC and WEEE-related regulation. These frameworks do not determine metallurgical performance directly, but they strongly influence collection efficiency, secondary-feed availability, traceability requirements, and the economic attractiveness of recycling infrastructure.

Reported LCA (Life Cycle Assessment) advantages for secondary PGM recovery should also be interpreted cautiously. The magnitude of CO_2, waste, and water-use reductions depends strongly on methodological choices, including system boundaries, allocation rules between co-products, electricity mix, transportation distance, pre-treatment intensity, and whether pyrometallurgical pre-concentration is included in the inventory. For this reason, environmental gains reported for one recycling route should not be transferred uncritically to other feed types or regional contexts.

Urban mining and recycling

Urban mining recovers valuable metals from human-made sources such as electronic waste, spent catalysts, and industrial residues, which contain PGM levels 10–100 times higher than those in natural ores, offering economic and environmental benefits (Grilli et al., 2023; Radojević et al., 2025).

Recycling supplies about 20–30% of global PGM, with expected growth (Zhang et al., 2024). Automotive catalysts in developed markets can recycle over 90% (Generowicz, 2022).

Recycling significantly benefits the environment: reduces CO_2 emissions by 40–80%, solid waste by over 90%, and lowers water and energy use compared to primary production. Lifecycle assessments indicate that hydrometallurgical methods usually have lower environmental impact than pyrometallurgical methods, though thermal processing is often still necessary for initial concentration (Lord et al., 2025).

Environmental impact reduction

Primary PGM production requires high energy inputs (above 1500 °C) and generates large volumes of waste, as well as emissions of SO_2, CO_2, and particulates. Secondary processing reduces mining disruption, land-use impacts, and logistics impacts.

Recycling isn't inherently low-impact; hydrometallurgical processes rely on acids, oxidants, and solvents, generating waste. Sustainability in PGM processing depends on improving chemistry, reagent efficiency, and waste management, not just replacing mining.

Emerging approaches seek to cut environmental impact via bioleaching, DES, ILs, and closed-loop systems. Though promising, these are still not widely industrialized and need more validation.

Circular economy perspective

The shift to sustainable PGM processing promotes a circular economy, focusing on value retention, resource efficiency, and supply security. It integrates mining, use, and recycling into a closed-loop system, crucial for PGMs due to their high value, supply risk, and dependence on secondary sources. Figure 14 illustrates this framework from primary production to reuse.

Circular strategies extend beyond recycling by maintaining material value longer through reuse, remanufacturing, and reduced resource extraction. For PGMs, this includes recovering metals from end-of-life catalysts, reintegrating them into new systems, incorporating recycling into hydrogen supply chains, and developing closed-loop manufacturing and recovery systems (Zagoraiou et al., 2025; Khalili et al., 2025).

Circular approaches boost resource efficiency and supply resilience by integrating collection, processing, and refining systems for impurity-rich feedstocks. Implementing these principles in PGM processing is a complex metallurgical and systems challenge needing coordinated optimization across the value chain.

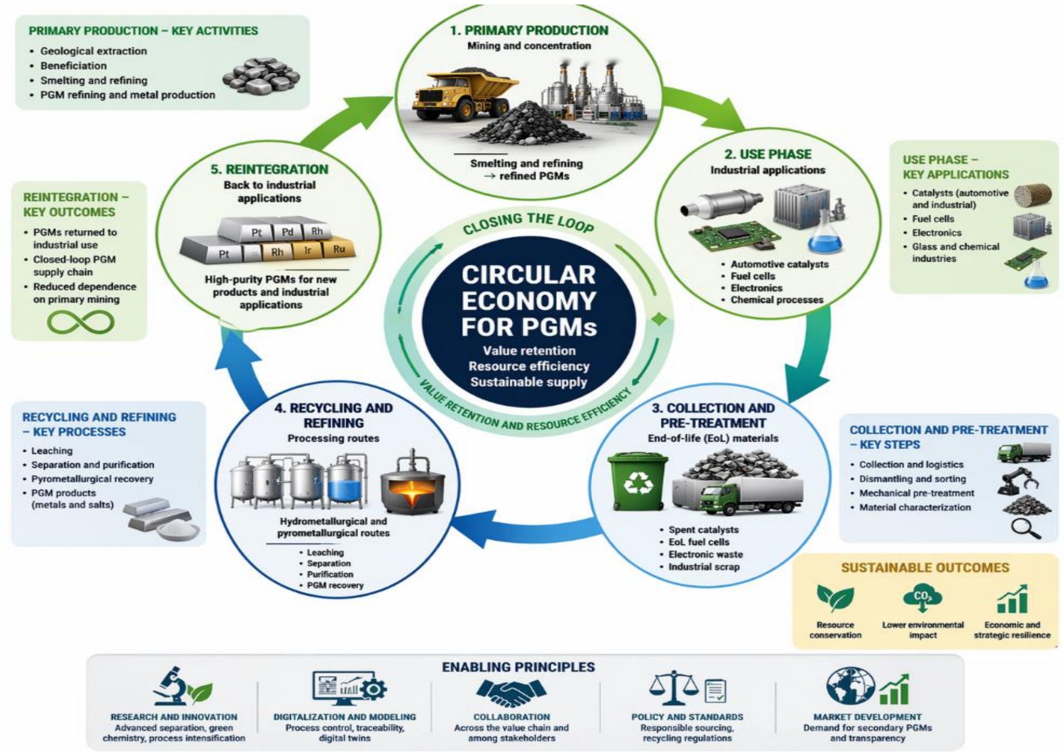


Figure 14. Conceptual circular-economy framework for PGMs linking primary production, use phase, collection, secondary processing, recycling, and reintegration into industrial applications. The diagram emphasizes that circularity in PGM systems depends not only on end-of-life recovery, but also on collection efficiency, feed traceability, pre-treatment, metallurgical compatibility of secondary feeds, and the ability of refining routes to manage impurity-rich materials. Policy support, market structure, and process innovation are shown as enabling conditions because losses at any stage can reduce both overall recovery and economic viability. Adapted from Grilli et al. (2023) and Zhang et al. (2024).

Figure 14 shows that PGM value chains can be structured as interconnected loops linking primary production, use, collection, recycling, and reintegration. Primary mining and refining provide the initial metal supply, which is then distributed across industrial applications such as automotive catalysts, fuel cells, electronics, and chemical processes. At the end of their service life, PGM-containing products enter collection and pre-treatment systems, where materials are sorted, concentrated, and prepared for recycling.

Recycling and refining stages—typically combining pyrometallurgical and hydrometallurgical processes—enable the recovery of PGMs and their reintegration into the production cycle. This closed-loop flow reduces dependence on primary mining and improves overall resource efficiency. The figure also highlights enabling factors such as process innovation, digitalization, policy frameworks, and market development, which are essential to sustain circularity.

However, the diagram also reflects important constraints. The efficiency of the circular system depends on robust collection infrastructure, effective management of feed variability, and the capability of processing routes to handle impurity-rich materials. Losses at any stage—collection, processing, or refining—can significantly reduce overall recovery and undermine economic performance.

Overall, the circular economy framework demonstrates that sustainable PGM supply cannot rely on recycling alone, but requires coordinated integration of primary production, secondary recovery, and process innovation. Effective implementation therefore depends on system-level optimization that balances metallurgical performance, economic viability, and environmental impact.

Figure 14 further emphasizes that PGMs are particularly well suited to circular economy models due to:

- their high economic value, which justifies recovery even at low concentrations,
- their strong catalytic functionality, enabling repeated reuse without loss of performance,
- their concentration in identifiable and recoverable products (e.g., catalysts, electronics),
- and their compatibility with both pyrometallurgical concentration and hydrometallurgical refining routes.

Critical perspective

Sustainability and circular economy efforts in PGM processing face limitations. Recycling depends on collection effectiveness, but variability in secondary feed complicates control and reduces predictability. Not all PGM products are economically recyclable, especially with low metal content or processing issues. Advanced recovery technologies are promising but not yet fully scalable or mature.

Recycling alone can't meet PGM demand; primary mining remains necessary due to rising demand and limited secondary resources (Zhang et al., 2024; Hughes et al., 2021). Sustainability should be assessed at the system level, focusing on recovery efficiency, environmental footprint, economic viability, and resource security. Improvements in one area may not boost overall sustainability if offset by higher costs or complexity.

Sustainability fosters PGM processing innovation, but industry adoption hinges on economic feasibility, influenced by capital, operating costs, and market factors. The next section covers techno-economic aspects, highlighting CAPEX, OPEX, and main cost drivers.

Techno-Economic Considerations

The technical feasibility of PGM recovery doesn't ensure industrial adoption. Process choice is limited by capital, reagents, energy, and market volatility. PGMs are especially complex, with small flowsheets, low production volumes, and economic sensitivity to losses and purity (Hughes et al., 2021; Mettler et al., 2023; Zhang et al., 2024).

Primary mining involves costly steps like mining, flotation, smelting, and refining, resulting in high fixed costs. Secondary recovery skips mining and comminution but focuses on feed prep, leaching, and purification, with recycling's economic benefits depending on process design and feed properties.

Primary PGM production is highly CAPEX-intensive, requiring mine development, concentration circuits, high-temperature furnaces, gas treatment, and refining infrastructure. These systems need large throughputs for economic viability, favoring centralized, capital-intensive operations with long investment cycles (Hughes et al., 2021; Mettler et al., 2023). Secondary recovery, especially hydrometallurgical methods, usually has a smaller footprint and lower thermal capacity, enabling modularity and lower entry barriers (Generowicz, 2022; Grilli et al., 2023; Cieszyńska, 2023).

Lower nominal CAPEX in recycling requires caution, as costs can increase with multi-stage solvent extraction, impurity control, effluent treatment, or feed heterogeneity. Comparisons should be made at the flowsheet level, not based on individual units. In hydrometallurgical and hybrid routes, OPEX mainly comes from chemical use—including acids, oxidants, extractants, and reagents for neutralization and waste. High recovery rates can be misleading if reagent and solvent costs are high, which can undermine economic viability (Paiva et al., 2023; Zhang et al., 2024). OPEX is often driven more by chemical support systems—such as pH control, impurity removal, scrubbing, stripping, and waste management—than by leaching.

Alternative methods like solvometallurgy, bio-assisted systems, and greener solvents aim to reduce chemical use and environmental impact but often raise costs due to longer residence times, expensive solvents, or complex controls (Nguyen et al., 2020; Lord et al., 2025; Zagoraiou et al., 2025). Thus, better sustainability doesn't always mean lower costs.

Energy consumption differentiates processing routes. Pyrometallurgy is effective for bulk processing but costly due to high energy needs above 1200 °C, making it sensitive to prices (Lord et al., 2025; Zhang et al., 2024). Hydrometallurgy uses lower temperatures, reducing energy use, but needs more chemicals and takes longer.

This leads to a fundamental techno-economic trade-off:

- **Pyrometallurgy:** high CAPEX and energy demand, robust concentration, limited selectivity
- **Hydrometallurgy:** lower thermal demand, high chemical dependence, improved selectivity, higher process sensitivity
- **Hybrid pyro-hydro flowsheets:** enhanced overall recovery and flexibility, but increased system complexity

In practice, no route is universally optimal; the preferred process depends on feed grade, impurity level, product purity needs, infrastructure, and local energy and reagent costs (Bediako & Repo, 2025; Grilli et al., 2023; Zhang et al., 2024).

Choosing the right PGM processing route requires a holistic techno-economic assessment. Primary, secondary, and hybrid strategies have different costs and trade-offs, important for scalability, resource efficiency, and long-term viability amid variable feeds and markets. Table 8 summarizes these trade-offs.

Table 8. Main techno-economic trade-offs among primary, secondary, and hybrid PGM processing routes. Adapted from Hughes et al. (2021), Lord et al. (2025), Zhang et al. (2024), and Nguyen et al. (2020).

Route	CAPEX profile	Main OPEX driver	Main strength	Main limitation
Primary mining + refining	Very high	Energy + integrated refining	Large-scale supply	Low ore grade, long value chain
Secondary hydrometallurgical recovery	Moderate	Chemicals + waste treatment	High selectivity, smaller scale	Feed variability, reagent cost
Secondary pyrometallurgical recovery	High	Energy + thermal treatment	High collection efficiency	Limited selectivity
Hybrid pyro-hydro route	High to very high	Energy + chemicals	Strong overall recovery	Complex integration

Table 8 demonstrates that techno-economic evaluation of PGM processing routes cannot rely on recovery percentage alone. A process with slightly lower yield may be preferable if it reduces solvent inventory, shortens residence time, or minimizes costly impurity management.

Each processing route is defined by a specific balance between capital intensity, operating costs, and metallurgical performance. Primary mining and refining remain the dominant pathway for large-scale supply, but are associated with very high CAPEX, energy-intensive operations, declining ore grades, and extended value chains.

Secondary hydrometallurgical recovery offers improved selectivity and lower capital requirements, making it attractive for decentralized or smaller-scale applications. However, its performance is highly sensitive to feed variability and reagent consumption, particularly in impurity-rich systems.

Secondary pyrometallurgical processing offers efficient collection of heterogeneous materials but has limited selectivity and high energy use. Hybrid pyro-hydrometallurgy combines both methods' advantages, enabling high recovery and flexibility. However, this increases flowsheet complexity, and capital costs. Simultaneously manage thermal and chemical inputs.

No single route is universally best; choosing an effective process depends on recovery efficiency, cost, feed characteristics, and integration. Hybrid strategies are often preferred when their complexity yields measurable improvements in recovery, selectivity, and cost-effectiveness.

Market exposure and value concentration

PGM economics are shaped by market concentration and price volatility. As high-value, low-volume commodities, PGMs are sensitive to small variations in recovery. Marginal 1–2% losses in Pt or Pd recovery can cause significant economic penalties, especially in secondary processing, where metal concentrations reach kilograms per tonne rather than grams (Hughes et al., 2021; Grilli et al., 2023). In such conditions, process stability is a key economic factor, not just an operational issue.

Secondary resources cut costs by streamlining the value chain—reducing inert material and feedstock-to-product steps—enhancing capital efficiency and turnaround (Generowicz, 2022; Cieszyńska, 2023). This makes catalyst recycling more cost-effective than processing low-grade ores.

This advantage isn't guaranteed; high feed variability and complex downstream separation can offset the benefits of higher metal grades. Impurities and process issues may increase reagent use, extend residence times, and require extra purification, reducing economic efficiency. Therefore, the viability of secondary PGM processing depends on the feed grade and on stable, selective, integrated process conditions.

Critical perspective

Techno-economic evaluation in PGM processing is often incomplete. While many studies report extraction yield, phase distribution, or laboratory-scale selectivity, they often omit key variables like solvent losses, reagent recycling, residence time, corrosion costs, impurity management, and waste treatment.

This omission is a major limitation. Without these parameters, process claims are technically relevant but economically vague. For industrial decisions, the key is not just recovering PGMs, but doing so with consistent purity, acceptable cost, and scalable infrastructure.

A thorough techno-economic assessment must include element-specific recovery, reagent use per tonne, energy needs, impurity removal, recycle-loop strength, and feed variability sensitivity. These factors influence process stability, costs, and industrial viability.

The gap between lab performance and industrial use shows a structural issue in current research. Many technologies work well in controlled settings but lack validation under real-world conditions, where factors like variability, impurities, and long-term stability are constraints. This section highlights research gaps and emphasizes that many unresolved challenges are scientific and critical barriers to industrial competitiveness, scale-up, and supply resilience.

Research Gaps

Significant gaps exist in selectively separating PGMs from complex systems, especially in leaching, reagent selectivity, and process integration. Although research on PGM recovery has increased, it mainly targets isolated unit improvements rather than integrated flowsheets (Banerjee &Chakrabortty, 2024; Nguyen et al., 2026; Wang et al., 2026). Industrial recovery faces challenges such as mineralogy, kinetics, impurities, intermediate chemistry, and separation issues.

Selectivity between Pt, Pd, and Rh

A key challenge in PGM processing is the precise separation of metals, especially Pt, Pd, and Rh. Pt and Pd can be separated effectively in chloride media, but Rh is difficult due to slower ligand exchange, lower extraction response, and inert aqueous chemistry (Fan et al., 2023; Paiva et al., 2022; Pianowska et al., 2023). Literature shows Pt and Pd recoveries often exceed 90%, while Rh recovery remains incomplete or inconsistent.

This limitation is significant; incomplete Rh recovery can greatly impact process viability. Many studies focus mainly on Pt and Pd, with Rh separation as a secondary goal (Nguyen et al., 2026; Radojević et al., 2025).

Addressing this gap demands targeted research, including developing selective Rh recovery strategies from Pt–Pd-rich chloride liquors, studying Rh ligand exchange and extraction mechanisms, and designing integrated purification routes that incorporate Rh separation earlier rather than relying solely on downstream polishing.

Kinetics and process intensification

A key gap in PGM processing is slow kinetics, making many routes operationally unattractive due to long dissolution times, high reagent use, and mass transfer issues (Braga et al., 2025; Griffiths, 2025; Nguyen et al., 2026). These are especially problematic for low-reactivity PGM phases, deactivated catalysts, and passivated systems.

Process intensification is a key research priority. Promising methods include intensified solvent extraction in small channels, mechanochemical activation, electro-assisted leaching, and hybrid solvent systems to optimize kinetics and selectivity (Phakoukaki et al., 2025; Ye et al., 2025; Lanaridi et al., 2022).

The literature remains fragmented, with studies showing localized improvements like extraction yield or contact time, but failing to quantify overall process benefits. Key parameters such as residence time, solvent use, energy, and downstream compatibility are often not evaluated.

Multi-metal modeling and real-feed complexity

A major gap in PGM processing is the absence of comprehensive multi-metal models. Real feedstocks are complex, containing Pt, Pd, Rh, Ir, base metals, rare earths, and matrix compounds. Despite this, much research uses simplified, single-metal systems, reducing applicability to industrial settings (Mokhodoeva et al., 2023; Nguyen et al., 2026).

This limitation is both experimental and conceptual. In real systems, multiple interactions happen simultaneously and are interconnected. Chemical species compete for oxidants, impurity loads affect extractant performance, intermediate phases impact dissolution, and recycle streams modify the local environment. These combined effects are seldom captured in integrated models.

Addressing this gap requires developing thermodynamic–kinetic models for multi-metal systems, especially in chloride media with complex speciation. Predictive tools linking impurity levels to extraction selectivity are crucial for rational process design. Dynamic simulation of recycle streams, phase accumulation, and solution chemistry should also be incorporated to reflect realistic operating conditions.

Without integrated modeling, process scale-up relies on trial-and-error, raising development time, cost, and uncertainty (Mokhodoeva et al., 2023; Nguyen et al., 2026).026).

New solvents and alternative media

A significant gap exists in developing and validating alternative solvents like deep eutectic solvents (DES), ionic liquids (ILs), and bio-derived media, which can lessen reliance on mineral acids and improve selectivity. Some systems show high recovery of Pt and Pd, with promising phase selectivity.

The field lacks industrial maturity, facing challenges like high viscosity, mass-transfer issues in DES systems, costs and recyclability of ionic liquids, limited understanding of long-term stability, and no benchmarking against chloride-based hydrometallurgical routes (Banerjee & Chakrabortty, 2024; Griffiths, 2025; Riaz, 2025).

A limitation is dependence on proof-of-concept studies with isolated extraction. Many solvents target specific PGM species, but this does not guarantee industrial feasibility. Issues like stripping, regeneration, impurity rejection, and recyclability are often neglected. Future research should shift from simply demonstrating solvents to designing integrated solvent systems, emphasizing process integration, lifecycle performance, and techno-economic validation. This change is crucial for properly evaluating alternative solvent systems for industry.

Integration between upstream and downstream processing

A limitation in PGM processing is the weak link between upstream concentration and downstream refining. Studies on mineralogy, flotation, smelting, and catalyst characterization are often separate from those on leaching and separation (Corin et al., 2021; Sahu et al., 2021; Baloyi et al., 2024).

This separation is artificial and limits process optimization. In reality, feed features—like texture, alloy formation, collector chemistry, and slag carryover—affect dissolution, impurity distribution, and downstream selectivity.

Secondary processing faces similar issues. While pyrometallurgical concentration boosts PGM recovery, it can transfer impurities to the refining step, adding to hydrometallurgical separation challenges (Yang et al., 2023; Wang et al., 2026). Hence, upstream gains don't always improve overall process performance.

Future research should prioritize evaluating PGM processing routes as integrated systems rather than as disjointed units. This is crucial for catalyst-to-refining flowsheets, fuel-cell recycling, and hybrid metallurgical systems, where upstream–downstream interactions influence efficiency, selectivity, and economic viability.

Need for better techno-economic evidence

A final challenge is the lack of solid techno-economic evidence. Many studies report efficiencies but skip key parameters like reagent use, solvent losses, energy costs, corrosion, impurity, and residue management. This weakens the practical relevance of chemical and process advances.

Technologies that seem effective in labs may be economically unviable in real-world conditions. Future research should include a preliminary techno-economic analysis, especially for new solvents, systems, or flowsheets. A technology isn't transformative if its costs and constraints are unclear.

More broadly, this gap reflects the interconnected nature of challenges in PGM processing. Limitations in selectivity, kinetics, multi-metal behavior, solvent performance, and process integration are interconnected—they directly impact cost, scalability, and industrial feasibility. Addressing these issues separately is insufficient.

A structured evaluation of these challenges is essential to guide research toward impactful, industrial solutions. Table 9 highlights key research gaps in PGM processing, including effects, the associated issues, industrial impacts, and priorities.

Table 9. Main research gaps in PGM processing and their practical implications. Adapted from Nguyen et al. (2026), Paiva et al. (2022), Gholami et al. (2025), and Wang et al. (2026).

Research gap	Main unresolved issue	Industrial consequence	Priority level
Pt/Pd/Rh selectivity	Rh remains difficult to separate efficiently	Lower product value, more recycling loops	Very high
Slow kinetics	Long leaching times and high reagent consumption	Higher OPEX, limited throughput	Very high
Multi-metal modeling	Poor prediction under real impurity load	Difficult scale-up and unstable flowsheets	High
New solvents	Good proof-of-concept, weak full-process validation	Uncertain industrial adoption	High
Process integration	Weak coupling between concentration and refining	Recovery gains may be offset downstream	Very high
Techno-economic evidence	Lack of comparable cost metrics	Weak basis for industrial decision-making	Very high

Table 9 synthesizes this review, shifting from descriptive analysis to critical evaluation. Instead of merely stating that more research is needed, it presents a structured, actionable research agenda based on practical limitations.

The table shows that key challenges in PGM processing are systemic. Main issues include limited selectivity among Pt, Pd, and Rh, slow kinetics, weak process integration, and a lack of techno-economic validation, all of which restrict performance and industrial feasibility. Difficulties in Rh separation, slow usage and reaction rates, and high reagent consumption hinder recovery and cost-effectiveness. The absence of robust multi-metal models hampers the stable design of flow sheets under real impurity loads, increasing reliance on empirical, iterative scale-up methods.

Emerging solvent systems and alternative processing routes offer promising advances but remain constrained by limited validation at the full-process level. Similarly, the weak coupling between upstream concentration and downstream refining continues to reduce the overall effectiveness of otherwise well-performing unit operations.

Most critically, the lack of standardized techno-economic metrics hampers comparing technologies and weakens industrial decision-making. Consequently, many solutions stay promising but lack practical validation.

Overall, future progress in PGM processing depends on addressing gaps by advancing selectivity, kinetics, modeling, and process integration, and on rigorous techno-economic evaluation to enable scalable, efficient, and viable recovery.

In summary, the field has extraction concepts but lacks selective, efficient, impurity-tolerant, and cost-effective process systems. This gap separates laboratory progress from industrial use. The next section offers the Conclusion, summarizing key findings and promising directions for scalable PGM recovery.

Conclusions

The processing of platinum group metals remains inherently complex. This complexity arises from the combination of low metal concentrations, strong chemical stability, and the presence of multi-metal systems in both primary ores and secondary resources. Even after decades of technological development, no single route provides a universal solution across all feed types.

Hydrometallurgical processing dominates PGM refining because of its high selectivity in chloride systems, enabling over 95% recovery of platinum and palladium, though rhodium remains harder to recover. Its drawbacks include high reagent use, effluent treatment needs, and kinetic issues.

Recycling is the key for future PGM supply. Spent automotive catalysts contain much higher PGM levels than primary ores, boosting economic feasibility and lessening environmental impact. Growing hydrogen and fuel cell tech will boost demand, emphasizing the need for efficient recycling and urban mining.

Selectivity is the main challenge in PGM processing. Separating platinum, palladium, and rhodium from complex matrices is hindered by interference from base metals like iron, copper, and nickel. These elements complicate leaching and purification, often needing multi-stage flowsheets and tight control of conditions.

The field is shifting from individual process optimization to full process integration, with future advances relying on improved selectivity in multi-metal systems, faster reaction kinetics, lower chemical use, and combined pyrometallurgical and hydrometallurgical methods. Emerging technologies look promising but need more industrial validation.

In conclusion, PGM recovery is limited not by technology availability but by integrating them into efficient, selective, and cost-effective systems. Hydrometallurgy will probably stay central to refining, with recycling shaping future supply. The main challenge is bridging the gap between laboratory innovation and industrial application through improved integration, modeling, and scale-up.

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Author Contributions

Antonio Clareti Pereira: Conceptualization, methodology, investigation, data curation, writing—original draft, writing—review and editing.

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Compliance with Ethical Standards

This article does not contain any studies with human participants or animals performed by the author.

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