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Hydrometallurgical Recovery of Rare Earth Elements from Metallurgical Slags (2020–2026): A Critical Review

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ABSTRACT: Metallurgical slags generated from ironmaking, steelmaking, ferroalloy production, and molten salt electrolysis are increasingly recognized as secondary resources for critical raw materials, particularly rare earth elements (REEs) such as scandium, yttrium, and light REEs, which are incorporated into complex silicate, aluminate, and fluoride phases formed at high temperatures. This review critically evaluates hydrometallurgical routes for REE recovery across a wide range of slag systems, including blast furnace, basic oxygen furnace, electric arc furnace, bauxite residue–derived, FCC catalyst, and molten salt electrolytic slags, covering direct leaching approaches (acidic, alkaline, and ammoniacal), hybrid roast–leach processes (sulfation, chlorination, and alkali roasting), and downstream separation techniques such as selective precipitation and solvent extraction. Particular emphasis is placed on the role of slag mineralogy, phase assemblage, and glassy matrices in controlling leaching kinetics, selectivity, and impurity co-dissolution, with silicate-rich slags identified as the most challenging systems due to their polymerized structure, which limits reagent accessibility and often requires thermal pretreatment to achieve recoveries above 80–90%, typically at high reagent consumption (>50–300 kg/t). Comparative evaluation reveals that reported performance is frequently dominated by recovery metrics, while key parameters such as selectivity, reagent intensity, and process integration remain underreported, such that high extraction efficiencies do not necessarily translate into industrial feasibility. The main limitations across existing approaches include silica gel formation, extensive co-dissolution of matrix elements, and the generation of secondary residues, all of which negatively impact process stability and economic viability; moreover, most reported systems remain constrained by poor selectivity, high reagent intensity, and lack of continuous pilot-scale validation, limiting their industrial transferability. Future progress, therefore, depends on shifting from isolated process optimization to integrated, mineralogy-driven process design, supported by reduced reagent consumption, simplified separation flowsheets, and validation under industrially relevant conditions, positioning metallurgical slags as strategic secondary resources capable of supporting diversified and resilient REE supply chains within circular economy systems.

KEYWORDS: Rare earth elements; Metallurgical slags; Hydrometallurgy; Scandium recovery; Thermal pretreatment; Circular economy.

Highlights

- Metallurgical slags are identified as underexplored secondary sources of rare earth elements, particularly scandium.
- Hydrometallurgical routes for REE recovery are critically compared across diverse slag systems and processing conditions.
- Slag mineralogy and high-temperature phase assemblages strongly control leaching kinetics, selectivity, and impurity dissolution.
- Thermal pretreatment improves REE recovery but increases energy demand, process complexity, and environmental constraints.

Graphical abstract

1. INTRODUCTION

Rare earth elements (REEs) are essential components of advanced technological systems, including permanent magnets, electric vehicles, electronics, and renewable energy infrastructure. Their strategic importance has increased significantly in recent years, driven by the rapid expansion of low-carbon technologies and digitalization (Zhao et al., 2025; Hamzat et al., 2025). However, global supply remains limited and geographically concentrated, reinforcing the need for alternative and more resilient sourcing strategies.

In this context, secondary resources have emerged as a promising complement to primary mining. Industrial wastes, tailings, and metallurgical residues can contain economically relevant concentrations of REEs while offering advantages such as reduced environmental impact, lower permitting barriers, and alignment with circular economy principles (Swain, 2023; Kursunoglu, 2025). Among these resources, metallurgical slags are particularly significant due to their large production volumes in ironmaking, steelmaking, ferroalloy processing, and molten salt electrolysis. Despite their potential, most slags are still utilized in low-value applications such as construction aggregates (Holappa et al., 2021; Mackay et al., 2023), even though they may contain measurable concentrations of scandium, yttrium, and light REEs depending on feed composition and process conditions (Meshram et al., 2023; Chen et al., 2023).

The incorporation of REEs into slags is governed by high-temperature phase equilibria, resulting in their distribution among silicate, aluminate, phosphate, and fluoride phases, or their immobilization within amorphous glassy matrices formed during rapid cooling (Gao et al., 2022; Yi et al., 2023). These structural characteristics significantly limit natural leachability, rendering conventional beneficiation techniques ineffective and requiring chemical or thermo-chemical activation for recovery.

Hydrometallurgical processing has therefore become the primary route for REE recovery from slags. Acid leaching, particularly using H_2SO_4 or HCl, remains the most widely applied approach. However, reagent consumption is often high—frequently exceeding 100–300 kg/t of slag—especially in calcium-rich systems (Duan et al., 2022; Kallio et al., 2022). In addition, substantial co-dissolution of major elements such as Fe, Al, Ca, and Mg reduces selectivity and increases downstream processing complexity (Valeev et al., 2023; Wu et al., 2023). A major operational limitation is the formation of silica gel during acidic leaching of silicate slags, which severely impairs solid–liquid separation and process stability. Although several mitigation strategies have been proposed, no universally applicable solution has yet been established (Botelho Junior et al., 2021; Tsaousi et al., 2023; Wang et al., 2023).

To improve extraction efficiency, thermal pretreatment methods such as sulfation roasting, alkali fusion, and chlorination are frequently applied to modify phase composition and enhance REE liberation. These approaches can increase extraction efficiencies from below 30% to above 80% under optimized conditions (Kim & Azimi, 2020; Huang et al., 2025; Zhou et al., 2022). However, they introduce additional energy demand, increase process complexity, and generate secondary residues requiring further management.

Downstream separation and purification remain equally challenging, as REEs are typically present at low concentrations in leachates and accompanied by high impurity loads. Conventional methods such as selective precipitation and solvent extraction are widely used, but their performance is highly dependent on solution chemistry and impurity content (Han, 2020; Pan et al., 2022).

Emerging approaches, including deep eutectic solvents and biohydrometallurgical systems, offer potential advantages in selectivity and environmental performance, although they remain at low technology readiness levels (Akl et al., 2024; Rasoulnia & Barthen, 2021; Cesaro, 2024).

Despite the increasing number of studies, the field remains fragmented. Most investigations focus on specific slag types or isolated process steps, limiting direct comparison due to variations in composition, operating conditions, and reporting methodologies. Moreover, the integration of upstream pretreatment and downstream purification is rarely addressed within a unified framework (Binnemans et al., 2020; Deblonde et al., 2022). From an industrial perspective, this lack of integration represents a major limitation, as high recovery efficiencies alone do not guarantee process viability. Economic feasibility depends on multiple factors, including reagent consumption, energy demand, residue management, and capital expenditure.

Recent systematic studies have emphasized the importance of integrating thermodynamic, mineralogical, and process-level analyses to recover critical elements from both primary and secondary resources (Pereira, 2025; Pereira, 2026a; Pereira, 2026b). These approaches highlight the need for structured and comparative evaluation frameworks, particularly for complex, multi-phase systems such as metallurgical slags.

In this context, the present review critically examines advances reported between 2020 and 2026 in hydrometallurgical routes for the recovery of REEs from metallurgical slags. The analysis focuses on:

(i) acid, alkaline, and ammoniacal leaching systems;
(ii) integration of thermal pretreatment and leaching;
(iii) downstream separation and purification techniques;
(iv) the influence of slag chemistry and phase assemblage on process performance; and
(v) key technical, environmental, and economic constraints affecting industrial implementation.

This work emphasizes quantitative comparison, process integration, and industrial applicability. Particular attention is given to reagent consumption, extraction efficiency, selectivity, and residue generation, enabling a more realistic assessment of process feasibility. Given the diversity of slag systems and variability in reported data, a transparent and reproducible methodology is required. Accordingly, the following section presents the literature selection strategy based on the PRISMA 2020 framework.

2. METHODOLOGY

This review adopts the PRISMA 2020 framework (Page et al., 2021), adapted to metallurgical and process engineering contexts. Given the significant variability in slag composition, operating conditions, and experimental methodologies, a qualitative and comparative synthesis was performed rather than a formal meta-analysis.

The literature search was conducted in January 2026 across major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, ACS Publications, RSC, and MDPI, covering the period from 2020 to 2026. Search queries were defined using Boolean combinations of keywords such as “rare earth elements” AND slag AND leaching, and “metallurgical slag” AND scandium recovery, with iterative refinement to ensure comprehensive coverage of relevant studies (Page et al., 2021; Binnemans et al., 2020).

An initial dataset of more than 450 records was identified. After duplicate removal and screening based on predefined criteria, 117 peer-reviewed articles were selected for detailed analysis. Inclusion criteria required studies to be published in English, focus on REE recovery from metallurgical slags or related residues, and report quantitative process parameters such as temperature, reagent concentration, or extraction efficiency. Studies lacking sufficient experimental detail, review-only papers without primary data, or those focused exclusively on primary ores were excluded.

Data extraction focused on key process variables, including slag composition, phase assemblage, leaching conditions (25–300 °C), reagent consumption (50–300 kg/t), extraction efficiency (%), and impurity behavior. Due to the heterogeneity of the dataset, results were evaluated using comparative analysis rather than statistical aggregation (Deblonde et al., 2023; Asubonteng et al., 2026).

For consistency, the selected studies were classified into three main categories: (i) direct leaching systems, (ii) thermal pretreatment–leaching routes, and (iii) downstream separation and purification processes. This classification enables structured comparison across different process routes while accounting for variations in slag chemistry and mineralogical characteristics.

The overall literature selection workflow, including identification, screening, eligibility, and inclusion stages, is summarized in Figure 1 to ensure transparency and reproducibility.

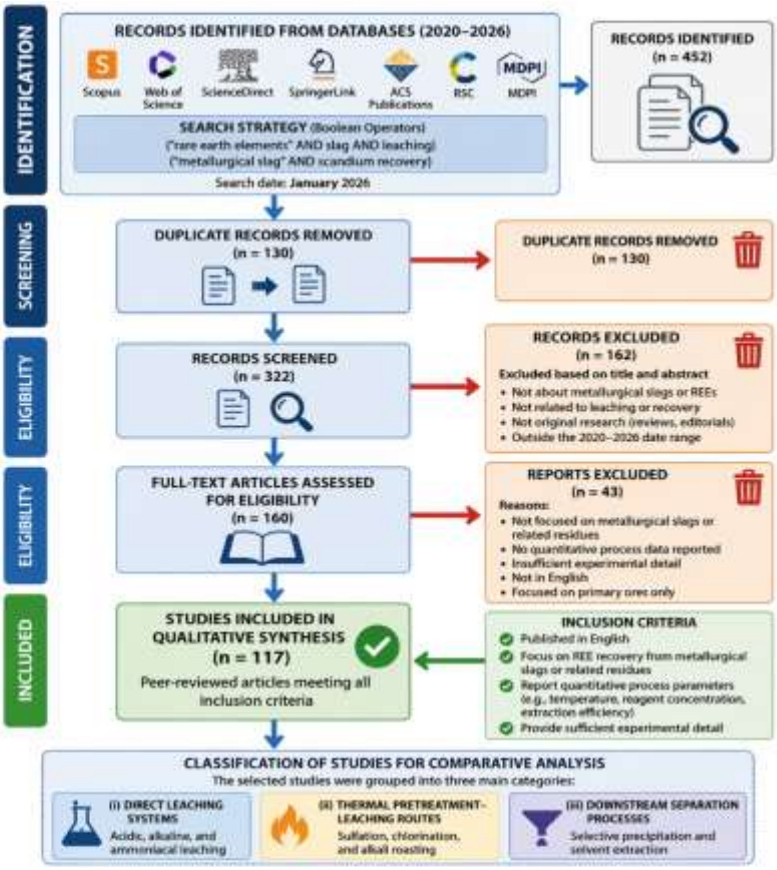

Figure 1. PRISMA flow diagram of literature selection process for REE recovery from metallurgical slags (2020–2026). Adapted from Page et al. (2021).

The dataset reflects current research but has limitations, primarily the absence of economic data and a focus on lab studies. These hinder the assessment of industrial viability and are discussed.

The effectiveness of the processes depends on the slag's mineralogy and chemical composition. The mineralogical and chemical behavior of REEs in slags is examined to interpret process performance.

3. MINERALOGY AND CHEMICAL BEHAVIOR OF REES IN SLAGS

Rare earth element (REE) recovery from slags depends on mineralogy, which affects their accessibility and reactivity, as slags are complex, multiphase systems formed at high temperatures.

3.1. Typical host phases

During high-temperature processing (1300–1600 °C), REEs partition among phases that are influenced by slag composition, oxygen potential, and cooling rate. Network modifiers like CaO, MgO, Na_2O, and fluorides control phase stability and distribution (Chen et al., 2023; Gao et al., 2022).

REEs mostly remain in bound phases such as silicates, phosphates, fluorides, and oxides, thereby limiting chemical accessibility and making direct extraction difficult. Recovery usually requires pre-treatment or improved leaching.

Phase transformations at high temperatures cause the partial breakdown of primary structures and the formation of oxides or oxyfluorides, thereby maintaining the system's heterogeneity. REEs are hosted in phases such as zirconolite, pyrochlore, and eudialyte, influencing leaching, reagent use, and selectivity (Ding et al., 2022; Ilatovskaia et al., 2023).

Figure 2 summarizes the main REE-bearing phases in slags and their evolution at high temperature. It shows a shift toward more reactive forms and the persistence of complex minerals that hinder recovery.

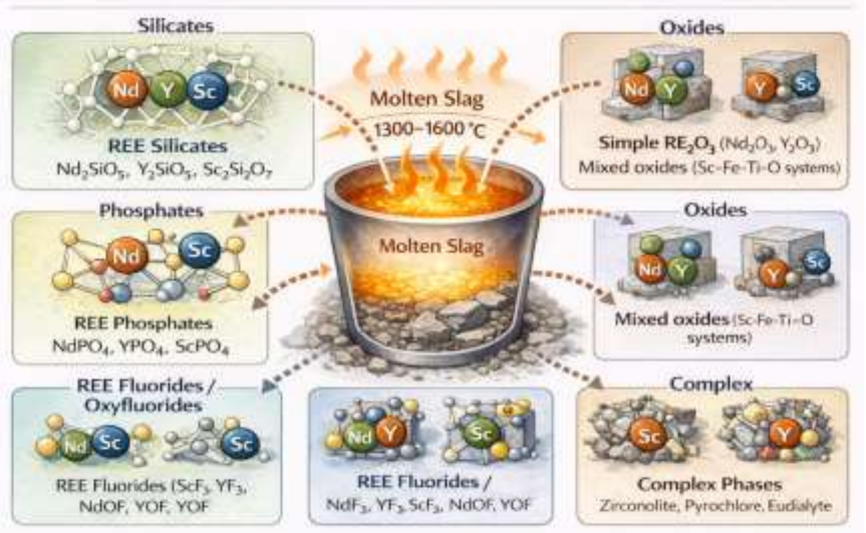

Figure 2. Schematic representation of rare earth element partitioning into silicate, oxide, phosphate, fluoride, and complex phases during high-temperature slag formation (1300–1600 °C). Adapted from Chen et al. (2023) and Gao et al. (2022).

Rare earth elements (REEs) are seldom found as free oxides in slags; instead, they are embedded in crystalline phases or dispersed in glassy matrices, thereby limiting accessibility and reducing beneficiation effectiveness.

REEs typically occur in the following mineralogical forms:

- **Silicate phases** (RE_2SiO_5, $RE_2Si_2O_7$), predominant in steelmaking slags
- **Phosphate phases** ($REPO_4$), highly stable and refractory
- **Fluoride phases** (REF_3, oxyfluorides), comparatively more reactive under acidic conditions
- **Complex phases** (e.g., zirconolite, pyrochlore, eudialyte-derived structures), which are highly resistant to leaching

Many industrial slags mainly contain stable silicate and glassy phases with polymerized Si–O networks, which hinder reagent penetration and slow dissolution. Leaching is typically limited by mass transfer rather than reaction rate. Fluoride phases are less stable and more soluble in acids (Yang et al., 2020; Tian et al., 2021).

The extractability of REEs from metallurgical slags is primarily governed by their mineral host phases, which influence stability, dissolution, and accessibility. Silicate and glassy matrices, with their polymerized structures, hinder reagent access and slow dissolution. Conversely, fluoride-bearing phases are more reactive and more easily leached.

These mineralogical constraints directly affect process selection, reagent use, and achievable recovery. Table 1 summarizes the main REE-hosting phases in metallurgical slags and their implications for hydrometallurgical processing.

Table 1. Typical REE-hosting phases in metallurgical slags and their implications for hydrometallurgical processing. Adapted from Chen et al. (2023), Gao et al. (2022), and Meshram et al. (2023).

REE Host Phase	Typical Composition / Formula	Occurrence in Slags	Chemical Stability	Leachability	Process Implications
Silicates	RE_2SiO_5, $RE_2Si_2O_7$	Steelmaking, BF, EAF slags	High (polymerized Si–O network)	Low (<30–50% without pretreatment)	Requires thermal or chemical activation; prone to silica gel formation
Phosphates	$REPO_4$	Phosphate-rich slags, residues	Very high (refractory)	Very low	Requires aggressive conditions or roasting; slow kinetics

Fluorides / Oxyfluorides	REF_3, REOF	Molten salt, peralkaline slags	Moderate	Moderate–high (>60–90%)	Favorable for acid leaching; requires fluoride handling
Oxides (simple/mixed)	RE_2O_3, (REE–Fe–Ti oxides)	Nb–Ta slags, oxide systems	Moderate–high	Moderate	Can be improved by chlorination or sulfation roasting
Complex phases	Zirconolite, pyrochlore, eudialyte-derived	Peralkaline, Nb–Ta systems	Very high	Low–moderate	Requires targeted pretreatment; mineralogy-specific processing
Glassy/amorphous phase	REEs dispersed in a silicate matrix	Rapidly cooled slags	High (structurally trapped)	Very low	Controls overall process efficiency; limits reagent access

The data presented in Table 1 demonstrate that leachability is strongly dependent on phase type, with silicate and glassy matrices representing the most limiting environments, whereas fluoride-bearing phases exhibit more favorable dissolution behavior. Among these factors, the glassy fraction plays a critical role, as rapid cooling promotes the formation of amorphous phases that encapsulate REEs and restrict access by reagents. In some industrial slags, the glassy content may exceed 60–80 wt%, significantly limiting leaching efficiency. Despite its importance, this parameter is rarely quantified or systematically incorporated into process design, representing a notable gap in current research.

3.2. Implications for hydrometallurgical processing

Mineralogy influences hydrometallurgy by affecting reactivity and dissolution. In silicate slags, Si–O networks hinder reagent penetration, promote silica gel during leaching, raise slurry viscosity, and impair separation and process operability (Kallio et al., 2022; Tsaousi et al., 2023).

Fluoride-bearing slags perform better because REE–F bonds are more prone to acid attack, allowing higher dissolution rates at moderate conditions (e.g., <100 °C, atmospheric pressure). This explains their superior leaching, particularly in slags produced by molten salt electrolysis (Chen et al., 2023; Mubula et al., 2024).

Higher leachability does not necessarily imply simpler processing. Co-dissolution of key elements such as iron, calcium, aluminum, and silica remains challenging across slag types, with these elements constituting 80–95 wt% of the dissolved mass. This leads to high reagent consumption, poor selectivity, and complex downstream purification (Wu et al., 2023; Valeev et al., 2023).

Phase accessibility adds constraints. REEs in reactive phases may still be limited by dense or glassy matrices, hindering contact with leaching agents, especially in slags with crystalline phases in amorphous networks.

Thermal pretreatment helps mitigate limitations by altering the phase structure and increasing REE exposure through processes such as sulfation roasting and alkali fusion. However, these methods increase energy consumption and complexity, often operating above 500–900 °C and requiring additional reagents.

Despite advances, most studies are descriptive. Key parameters like phase abundance, grain size, glass-to-crystalline ratio, and thermodynamic stability are rarely quantitatively linked to extraction performance. Consequently, mineralogy is often seen as a constraint rather than an engineered variable, hindering predictive models and scalable process designs.

The literature shows gaps: limited mineralogical data, poor process integration, and a lack of industrial relevance, which cause variability in extraction results and make comparisons difficult.

Mineralogical constraints set the limits on REE recovery from slags. Overcoming this requires integrated hydrometallurgical strategies with selective leaching, phase transformation, and advanced separation techniques.

Mineralogy should therefore be considered not only a constraint but also a design variable for process optimization.

4. HYDROMETALLURGICAL TECHNIQUES FOR REE RECOVERY FROM SLAGS

Hydrometallurgical processing is the most widely studied method for recovering REEs from slags but depends on slag mineralogy, phase distribution, and the presence of impurities. REEs are often present in silicate, oxide, or complex phases, which affect dissolution and selectivity (Anawati & Azimi, 2022).

Choosing hydrometallurgical methods for REE recovery from slags depends on the mineralogical form of the REEs. Host phases differ in stability and reactivity, requiring tailored strategies. Silicate and complex phases often need aggressive leaching, while oxide and fluoride phases are more accessible. Figure 3 shows a process map that links REE host phases to suitable leaching routes and associated challenges.

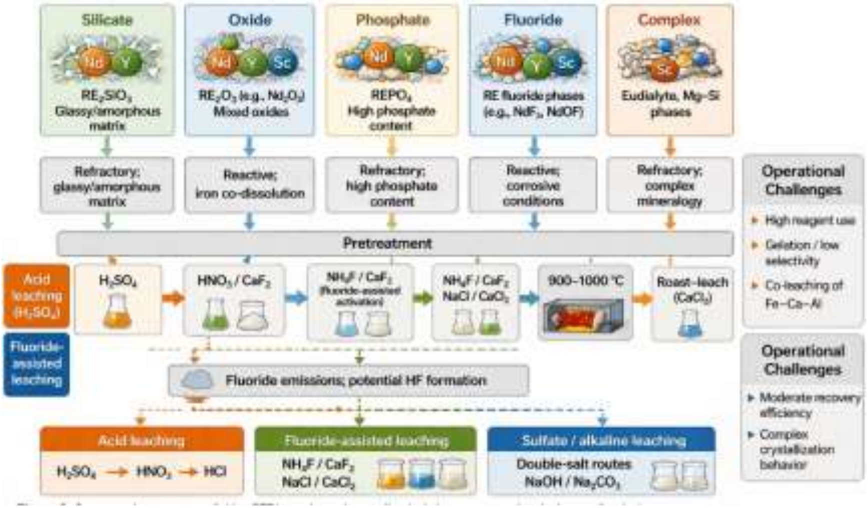

Figure 3. Conceptual process map linking REE host phases in metallurgical slags to suitable hydrometallurgical leaching routes and associated operational challenges. Adapted from Rudnik (2025), Pan et al. (2023), Ray et al. (2025), and Chen et al. (2023).

Figure 3 shows leaching performance mainly depends on phase type. Oxides and fluorides are reactive, while silicates and complex phases need aggressive conditions or pretreatment. This explains the variability in recovery efficiencies.

Acid leaching is widely used due to its simplicity and flexibility but is system-dependent and limited by mineralogy. Typical conditions are 25–95 °C with 1–4 h leaching, but reagent use often exceeds 50–300 kg/t, especially in calcium- and silicate-rich slags (Rudnik, 2025; Akcil et al., 2024). This shows a key limitation: simple conditions often require high reagent consumption and offer limited selectivity.

Hydrochloric acid shows high dissolution of REE oxides and phosphates, with 60–95% recovery in 4–8 M HCl (Kim & Azimi, 2020a; Akcil et al., 2024). However, it co-dissolves Fe, Ca, and Al over 80%, reducing selectivity and raising purification costs (Menad et al., 2024; Tang et al., 2023). Conversely, nitric acid avoids chloride complexation, aiding downstream processing, but causes silica gel formation in silicate slags, hampering filtration and stability (Qu et al., 2022; Wu et al., 2023).

Sulfuric acid systems are cost-effective due to reagent availability but are limited by the low solubility of REE sulfates. Thermal pretreatment is often necessary to achieve 40–80% recoveries, increasing energy use and complexity (Huang et al., 2025; Shoppert et al., 2022). This indicates that lower reagent costs are often offset by increased process intensity.

Aggressive methods such as fluoride-assisted leaching improve REE dissolution by breaking silicate bonds and can recover over 90% of yttrium and heavy REEs, especially in silicate- and peralkaline-rich slags (Yang et al., 2020; Tian et al., 2022; Mubula et al., 2024). However, environmental and operational issues such as fluoride handling, HF formation, and effluent treatment limit practical use, raising costs and regulation challenges.

Chloride-enhanced systems boost dissolution and REE solubility through complexation, achieving 70–95% recoveries with HCl, especially for oxide- and silicate-bound REEs (Kim & Azimi, 2020b; Yang, 2025). Higher process intensity, like chlorination roasting–leaching at 800–1000 °C, converts refractory phases into soluble chlorides, enabling over 90% recoveries in systems like Nb–Ta slags (Pereira, 2025; Zhao et al., 2024). These routes are energy-intensive, demand emission and corrosion control, and increase CAPEX and OPEX.

Alternative sulfate-based systems, such as REE–Na–SO_4, can enhance selectivity by limiting impurity dissolution but are limited to specific slag chemistries and require controlled crystallization (Binnemans et al., 2020; Dong et al., 2021; Liu et al., 2025).

Alkaline systems are ineffective for direct REE dissolution but serve as pretreatment by breaking silicate networks and reducing acid use by 30–50%, though they add processing steps and generate residues (Kokko et al., 2024; Mubula et al., 2026).

Overall, the analysis shows that hydrometallurgical performance depends on a trade-off between recovery, selectivity, and process intensity. High-recovery methods often use aggressive chemicals, more reagents, or heat, while simpler systems are less complex but less efficient and selective (Dodbiba & Fujita, 2023). These trade-offs emphasize choosing processes based on recovery, reagent use, environmental impact, and scalability. Table 2 summarizes key leaching routes, target phases, and their advantages and limitations, aiding comparison across strategies.

Table 2. Comparison of hydrometallurgical techniques for REE recovery from metallurgical slags, including reagents, target phases, recovery ranges, advantages, and limitations. Adapted from Rudnik (2025), Ekstroem et al. (2021), Akcil et al. (2024), Kim and Azimi (2020), and Chen et al. (2023).

Technique	Main reagents / conditions	Target REE host phases	Typical REE recovery*	Main advantages	Key limitations
HCl leaching	4–8 M HCl, 70–95 °C, 1–4 h	REE oxides, phosphates ($REPO_4$)	60–95%	High dissolution efficiency; fast kinetics	Strong co-dissolution of Fe, Ca, Al; high purification cost
HNO_3 leaching	HNO_3, moderate temperature (<90 °C)	Oxides, fluorides	50–85%	Easier downstream precipitation (oxalates/carbonates)	Silica gel formation; limited applicability to silicate-rich slags
H_2SO_4 leaching	H_2SO_4, often after roasting	Phosphates, oxides	40–80%	Low reagent cost; industrial availability	Low solubility of REE sulfates; often requires pretreatment
Fluoride-assisted leaching	NH_4F, CaF_2, AlF_3 in acidic media	Silicates, oxyfluorides	>90% (Y, HREE)	Breaks REE–Si bonds; high recovery	Fluoride handling; HF risk; effluent treatment
Chloride-enhanced leaching	HCl + NaCl / $CaCl_2$	Oxides, partially silicate-bound REEs	70–95%	Improved kinetics; enhanced solubility	Corrosion; impurity co-dissolution
Roast–leach ($CaCl_2$)	800–1000 °C roasting + leaching	Refractory silicates, complex phases	>90%	Converts REEs to soluble chlorides	High energy demand; gas/emission control
Sulfate double-salt routes	Na_2SO_4 systems, controlled crystallization	Phosphates, aluminates	60–85%	Improved selectivity; reduced impurity dissolution	Limited applicability; complex crystallization control
Alkaline pretreatment	NaOH, Na_2CO_3 (pre-leaching step)	Silicate glass / amorphous phases	—	Silica removal; reduces acid consumption (30–50%)	Not selective for REEs; requires additional processing steps

*Recovery values depend on slag composition, phase distribution, and operating conditions.

Table 2 shows a trade-off between recovery efficiency and process complexity. Higher REE recoveries require more aggressive conditions and reagents, while simpler systems are cheaper and easier but less selective. Increasing recovery generally increases reagent use and complexity, while balancing efficiency with practicality.

Despite progress, hydrometallurgical methods face three main issues: low selectivity due to co-dissolution, high reagent consumption, and limited industrial validation, which impact economics and the environment (Cheng et al., 2026; Foppiano et al., 2026).

Much literature emphasizes maximizing recovery in lab settings, often neglecting reagent recycling, residue stability, and continuous operation. This limits scalability and long-term viability assessment, underscoring the need for more integrated, application-focused research (Kanekaputra & Mubarok, 2023).

Hydrometallurgical routes balance recovery and complexity. Aggressive methods like fluoride-assisted and roast–leach achieve high recovery but require more reagents and energy and cause environmental issues. Simplified acid leaching is less complex but has lower selectivity and co-dissolves impurities. Figure 4 compares REE recovery potential versus process complexity for these methods.

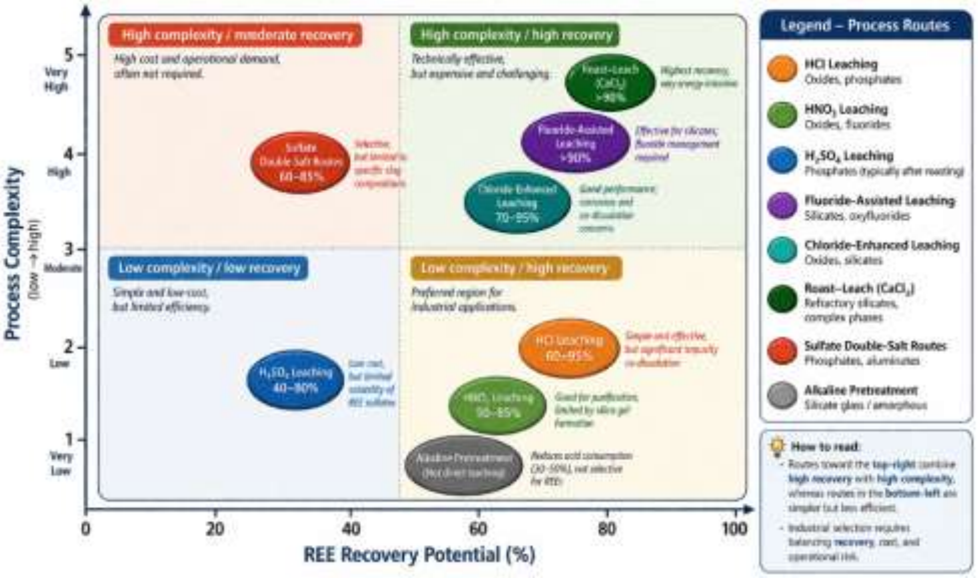

Figure 4. Qualitative comparison between REE recovery potential and process complexity for major hydrometallurgical routes applied to metallurgical slags. Adapted from Rudnik (2025), Ekstroem et al. (2021), and Chen et al. (2023).

Figure 4 shows that higher REE recovery often entails greater process complexity, more reagents, and greater challenges. Fluoride-assisted and roast–leach methods achieve over 90% recovery but need more energy, stricter environmental controls, and complex steps. Conventional acid leaching is simpler and offers moderate recovery but is less selective due to co-dissolution. Chloride and sulfate methods balance performance and feasibility, depending on slag composition and phase distribution.

This comparison shows process choice can't rely only on recovery efficiency; it must also consider reagent use, environmental impact, and scalability. These limits foster interest in hybrid strategies that modify slag mineralogy prior to leaching to enhance selectivity and efficiency.

The following section critically examines downstream separation and purification strategies, focusing on hybrid approaches and on how thermal pretreatment transforms REE-bearing phases into more reactive forms to improve processing.

5. HYBRID ROAST–LEACH PROCESSES

Direct leaching is often limited because REEs are trapped in low-solubility silicates, phosphates, and oxides. Hybrid roast–leach processes help by altering the phase composition prior to leaching.

These routes integrate thermal activation (300–1000 °C) with hydrometallurgical extraction to convert REE phases into more reactive forms, reduce impurity dissolution, and improve selectivity.

5.1. Process principles and transformation mechanisms

Roasting modifies REE-bearing slags by changing phase structures and bonds, depending on the reagent system and atmosphere. It involves sulfation, chlorination, or alkali roasting, which significantly boost REE extraction from less than 30% to 80–95%, based on conditions (Kim & Azimi, 2020; Huang et al., 2025; Zhou et al., 2022).

Direct leaching is limited by refractory phases like silicates and complex oxides, which hinder reagent penetration and slow dissolution. Hybrid roast–leach methods overcome these challenges by altering slag mineralogy through phase transformations that weaken REE bonds and generate reactive intermediates (Chanturia et al., 2022). These depend on roasting chemistry, temperature, and reagent choice. Figure 5 shows the main phase transformation mechanisms, including sulfation, chlorination, and alkali roasting, and their impact on leaching.

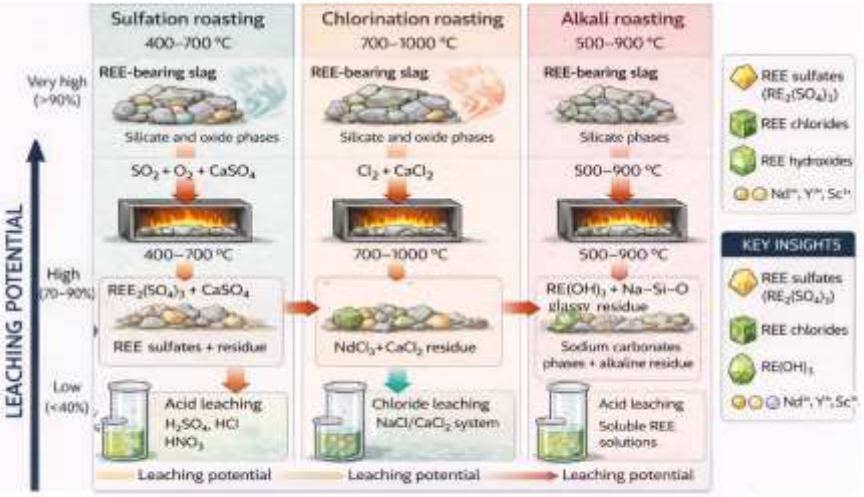

Figure 5. Schematic representation of phase transformation mechanisms during hybrid roast–leach processing of REE-bearing slags. Adapted from Kim and Azimi (2020), Huang et al. (2025), and Zhou et al. (2022).

Figure 5 indicates that roasting changes the REE chemical forms, thereby affecting their dissolution. Sulfation roasting (400–700 °C) forms REE sulfates that are moderately soluble in acid, yielding 70–90% recovery. Chlorination roasting (700–1000 °C) produces soluble chlorides such as $RECl_3$, yielding over 90% recovery but with higher energy consumption, chlorine emissions, and corrosion risks. Alkali roasting (500–900 °C) does not form soluble salts but breaks silicate networks, forming hydroxides or carbonates that improve leaching and reduce reagent use (Ding et al., 2022; Guo et al., 2023).

Overall, the figure shows roasting is a critical stage that affects leaching efficiency, selectivity, and process viability. It underscores the importance of mineralogical control and phase engineering in designing scalable routes for REE recovery from metallurgical slags (Gontijo et al., 2023).

5.2. Sulfation roasting–leaching routes

Sulfation roasting is a well-studied pretreatment for REE recovery from slags. It involves heating with H_2SO_4 or sulfate salts at 400–700 °C, then leaching with water or dilute acid. This process converts REE oxides and phosphates into soluble sulfate forms, improving dissolution.

This transformation increases REE solubility, reduces Fe and Al co-dissolution, and boosts selectivity in downstream processing. Under optimal conditions, recoveries usually range from 70% to 90%, depending on slag composition and roasting parameters (Huang et al., 2025; Shoppert et al., 2022).

Despite these advantages, limitations remain. Sulfation roasting requires a high acid input and produces stable sulfate residues, thereby reducing efficiency. The production of SO_2 and SO_3 gases poses environmental and operational challenges, demanding gas handling and emission controls.

Economically, sulfation is attractive due to the low cost and availability of sulfuric acid, making it preferable to more expensive chloride systems for large-scale use. Its viability hinges on balancing reagent consumption, emissions, and processing requirements.

5.3. Chlorination-based roast–leach routes

Chlorination roasting with $CaCl_2$ or NaCl at 700-1000 °C effectively converts refractory REE phases into soluble chlorides, boosting leaching efficiency, especially when REEs are tightly bound in silicates or oxides.

This approach performs well for silicate-rich slags, Nb–Ta residues, and peralkaline systems, where conventional methods are limited. Reported recoveries often exceed 90% following chlorination roasting and water or dilute-acid leaching (Zhao et al., 2024; Pereira, 2025). Its high efficiency, fast kinetics, and better heavy REE extraction make it technically appealing.

However, these advantages are offset by constraints: the process is energy-intensive, requires high temperatures, involves corrosive environments that require specialized materials, and produces chlorine gas, causing environmental issues. This results in higher capital and operating costs than sulfate routes, mainly due to increased energy use and emission controls.

5.4. Alkali roasting and fusion routes

Alkali roasting with NaOH or Na_2CO_3 is a common pretreatment to break silicate networks in slags. Usually, at 500–900 °C, it depolymerizes Si–O bonds, forms soluble sodium silicates, and releases REE phases.

Although alkali roasting does not directly enable selective REE extraction, it significantly improves acid leaching efficiency, reducing acid consumption by 30–50% and thereby boosting process performance (Sim et al., 2025; Mubula et al., 2026).

However, these benefits are offset by limitations such as high reagent use, large alkaline residues, and additional washing steps, which increase process complexity and costs, limiting its standalone viability.

5.5. Comparative assessment

Hybrid roast–leach processes enhance REE extraction from silicate-rich slag by changing phase structures and improving dissolution and recovery. Effectiveness varies with temperature, reagents, and slag type, often requiring more energy and adding complexity. Table 3 details these methods, conditions, recoveries, benefits, and drawbacks.

Table 3. Comparison of hybrid roast–leach processes for REE recovery from metallurgical slags. Adapted from Kim and Azimi (2020), Huang et al. (2025), Zhao et al. (2024), and Sim et al. (2025)

Route	Temperature (°C)	Typical recovery	Main advantage	Key limitation
Sulfation roasting	400–700	70–90%	Low reagent cost	Gas emissions
Chlorination roasting	700–1000	>90%	High efficiency	Energy + corrosion
Alkali roasting	500–900	— (pretreatment)	Reduces acid consumption	Residue generation

Table 3 demonstrates that hybrid roast–leach processes significantly improve REE recovery compared to direct leaching, especially for refractory and silicate-rich slags. Sulfation roasting balances moderate temperatures (400–700 °C) with low reagent costs but is limited by gas emissions and downstream treatment challenges. Chlorination roasting achieves over 90% recovery by converting REEs into soluble chlorides, but it is energy-intensive and requires careful management of corrosion and chlorine emissions. Alkali roasting facilitates the breakdown of silicate networks and reduces acid consumption in subsequent leaching steps.

Overall, the comparison shows that no single route is best in all cases. Higher recovery usually comes with increased energy use and process complexity. This emphasizes the importance of choosing processes based on slag mineralogy, targeted REEs, and industrial constraints rather than recovery alone.

5.6. Critical analysis

Hybrid roast–leach routes improve REE extraction by transforming refractory phases into more reactive intermediates, but they come with trade-offs. Higher recoveries need temperatures of 600–1000 °C, and better selectivity often adds process steps, raising complexity and costs. Additionally, increased efficiency usually means higher energy use, more emissions, and more residues.

Many studies report recoveries over 90%, but critical metrics like mass balance, reagent recycling, energy use, and techno-economic data are often missing. This limits the assessment of scalability and long-term viability, making many promising routes insufficiently validated for industry. Despite high recovery rates, the lack of full mass closure and continuous data restricts industrial validation.

These observations show mineralogical control is necessary but not enough. Hybrid processing improves REE access but does not inherently resolve downstream challenges, as leachates still contain many impurities needing purification.

The next section examines downstream separation and purification strategies, including selective precipitation, solvent extraction, and emerging technologies, for producing high-purity REE from complex leachates.

6. SEPARATION AND PURIFICATION OF REEs FROM SLAG LEACHATES

Leaching alone does not yield marketable rare earth products because the solutions are complex and contain high levels of Fe, Al, Ca, Mg, and silica. These impurities often comprise over 80–95% of the dissolved mass, leaving REEs at low concentrations (<1–5 g/L). This imbalance is the main challenge in downstream processing.

Effective separation involves selectively removing impurities, followed by concentration and purification of REEs. The route depends on solution chemistry, impurity levels, and target specifications.

6.1. Selective precipitation

Selective precipitation is the primary method for purifying REE leachates, either by removing impurities or by recovering REEs as intermediates via pH-controlled oxalate or carbonate precipitation. Efficiencies exceed 95%, but selectivity is limited by impurity co-precipitation, especially in complex leachates, reducing purity and increasing reagent use. Typically, the industry uses it as a pre-treatment prior to solvent extraction, rather than as a standalone process (Guzhov et al., 2023; Dong et al., 2021).

6.2. Solvent extraction

Solvent extraction (SX) is the primary industrial method for REE separation because it achieves high selectivity, with purities exceeding 99%, using organophosphorus extractants such as P204 and P507 or amine systems, depending on the feed and target elements. Operating under pH 1–3, it involves multi-stage counter-current circuits (10–50 stages) for extraction, scrubbing, and stripping to concentrate and purify REEs. Performance depends on extractant chemistry, phase equilibria, and parameters such as pH, temperature, and phase ratio, with efficiencies typically 90–99% that vary with impurities and solution composition (Pan et al., 2022; Yao et al., 2026). Figure 6 shows a simplified REE separation flowsheet from slag leachates.

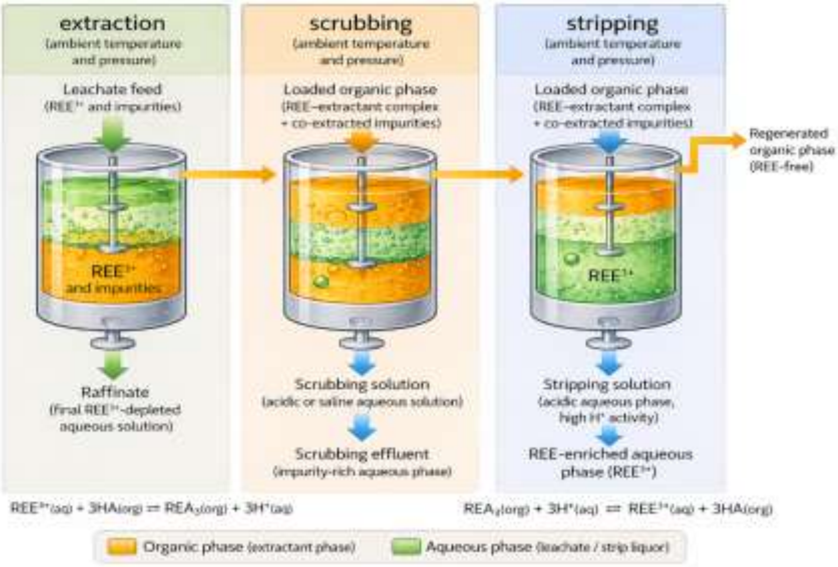

Figure 6. Simplified solvent extraction flowsheet for REE separation from slag leachates, including extraction, scrubbing, and stripping stages. Adapted from Pan et al. (2022) and Yao et al. (2026).

Figure 6 outlines the main stages of solvent extraction (SX) for REE-bearing leachates. REEs are selectively transferred to the organic phase via complexation, leaving impurities in the raffinate. The organic phase is then scrubbed with an aqueous solution to remove co-extracted impurities and stabilize the phase. Finally, REEs are recovered as concentrated aqueous chloride or nitrate solutions, ready for purification or precipitation.

Despite its high performance, SX is inherently complex. Industrial circuits typically require multiple countercurrent stages to achieve 90–99% recovery and high selectivity. This setup increases capital and operational costs and demands precise control of pH, phase ratios, and the extractant. Common issues include phase disengagement, emulsions, and extractant degradation.

From an economic perspective, SX remains effective but cost-intensive. Capital Expenditure depends on large mixer-settler banks or extraction columns, while extractant losses, reagent use, and maintenance drive operating costs. SX is often the highest-cost step in REE processing. Research aims to reduce circuit complexity, the number of stages, and reliance on other separation methods to boost efficiency.

6.3. Emerging separation technologies

Recent studies explore alternative separation methods to boost selectivity and cut environmental impact. These include deep eutectic solvents (DES), bio-based systems, and membrane-assisted processes. DES shows promising selectivity for certain REEs, with benefits such as low volatility and reduced toxicity. However, most research is at lab scale, with concerns about stability, recyclability, and process integration not yet resolved (Akl et al., 2024; Rasoulnia & Barthen, 2021).

Biohydrometallurgical approaches provide an energy-efficient alternative, operating under mild conditions with lower chemical demand. Their application is limited by slow reaction kinetics, sensitivity to conditions, and challenges in maintaining microbial activity in complex leachate systems (Cesaro, 2024). Although these emerging technologies show potential, their industrial use remains uncertain and needs further validation.

6.4. Comparative assessment

Separating and purifying REEs from slag leachates is costly and complex. After leaching, REEs are in dilute solutions with impurities like Fe, Ca, and Al, which can make up over 80–95% of dissolved species. This requires selective methods to get pure products with minimal reagents and low complexity. Different techniques vary in recovery, selectivity, maturity, and scalability. Table 4 compares their performance and limits.

Table 4. Comparison of main separation and purification techniques for REE recovery from slag leachates. Adapted from Han (2020), Pan et al. (2022), Klemettinen et al. (2023), and Yao et al. (2026)

Method	Recovery	Selectivity	Industrial maturity	Key limitation
Precipitation	>95%	Low–moderate	High	Co-precipitation
Solvent extraction	90–99%	High	Very high	High cost, complexity
DES systems	70–95%	Moderate–high	Low	Scale-up uncertainty
Bio-based	<80%	Moderate	Low	Slow kinetics

Table 4 shows that solvent extraction remains the dominant industrial technology. Combining high recovery (90–99%) with selectivity and flexibility is complex and costly, often accounting for 40–60% of processing costs due to multi-stage operation and reagent use. Precipitation methods offer high recovery (>95%) and simplicity but have limited selectivity and co-precipitate impurities, reducing purity.

Emerging approaches such as deep eutectic solvents (DES) and bio-based systems could lessen environmental impact and enhance selectivity, but are not yet fully developed for industrial use. Challenges include scaling up, stability, and kinetics. No method provides the perfect balance of performance, cost, and sustainability, highlighting the need for integrated strategies that combine multiple techniques to achieve high purity and economic viability (Karan et al., 2022; Kanekaputra & Mubarok, 2023).

6.5. Critical analysis

Despite progress, many barriers still hinder the separation of REEs from slag leachates. High Fe, Ca, Al impurities raise reagent use and reduce selectivity. Multi-stage systems increase risks, especially at scale. Lack of integrated flowsheets is a major issue, with many studies treating leaching and separation separately. Economic evaluations are limited, lacking cost per kilogram data or detailed techno-economic analyses.

Separation and purification are the most expensive stages, making up 40–60% of processing costs, especially for high-purity REEs. Their effectiveness relies on upstream choices, such as slag mineralogy and leaching strategy, that influence impurity levels and solution chemistry.

Overall, separation efficiency ultimately determines both product quality and Process viability. Constraints on integrated design and cost optimization emphasize both. The next section assesses large-scale feasibility, considering economic, environmental, and future research for industrial REE recovery from slags.

7. ENVIRONMENTAL, SUSTAINABILITY, AND ECONOMIC CONSIDERATIONS

The recovery of rare earth elements (REEs) from metallurgical slags is often framed as a sustainable alternative to primary mining. This assumption is only partially valid. Environmental and economic performance depends on reagent intensity, energy demand, and process integration.

Slags eliminate mining and beneficiation steps. However, they introduce chemically intensive processing routes. As a result, environmental benefits are not intrinsic. They must be demonstrated at the flowsheet level.

7.1. Reagent consumption and waste generation

Hydrometallurgical slags processing is reagent-intensive, with acid use often 50-300 kg per tonne, depending on mineralogy and process design (Rudnik, 2025; Pan et al., 2023). Acid leaching produces saline effluents rich in dissolved Fe, Ca, Al, sulfate or chloride ions, and residual silica.

Subsequent neutralization steps produce large secondary residues, often over 0.5–1.5 tonnes per tonne of slag, affecting environmental impact and costs (Ray et al., 2025). These residues need stabilization, disposal, or reuse, complicating the process.

Fluoride-assisted systems face environmental and operational challenges, like forming soluble fluoride complexes and producing HF, which need strict control and treatment. Calcium neutralization precipitates CaF_2, but managing, disposing of, or reusing these by-products is difficult (Yang et al., 2020; Chen et al., 2021).

Chloride-based routes face constraints like corrosion, higher maintenance, and need for specialized materials. Chlorine gas emissions demand efficient scrubbing, making gas treatment and material selection vital (Menad et al., 2024; Rudnik, 2025).25).

7.2. Energy demand and carbon footprint

Pure hydrometallurgical routes operate at low temperatures (<100 °C) and usually emit less carbon than pyrometallurgical processes (Jiang et al., 2022; Cempa et al., 2024). However, hybrid roast–leach methods involve thermal pretreatments at 600–1000 °C, increasing energy use to 500–1500 kWh/t depending on conditions (Ekstroem et al., 2021; Kim & Azimi, 2020b).

This increase in energy demand isn't always harmful at the flowsheet level. Hybrid processes can reduce acid use, increase selectivity, and improve recovery, offsetting energy costs. These benefits improve with process integration, like waste heat recovery or low-carbon energy sources (Cempa et al., 2024; Lim & Park, 2024).

The link between recovery efficiency, energy demand, and environmental impact remains a challenge in designing REE recovery from slags. Higher recoveries suggest greater process intensity and environmental impact, highlighting the need for integrated optimization. Figure 7 compares hydrometallurgical and hybrid routes in recovery, energy use, and environmental impact.

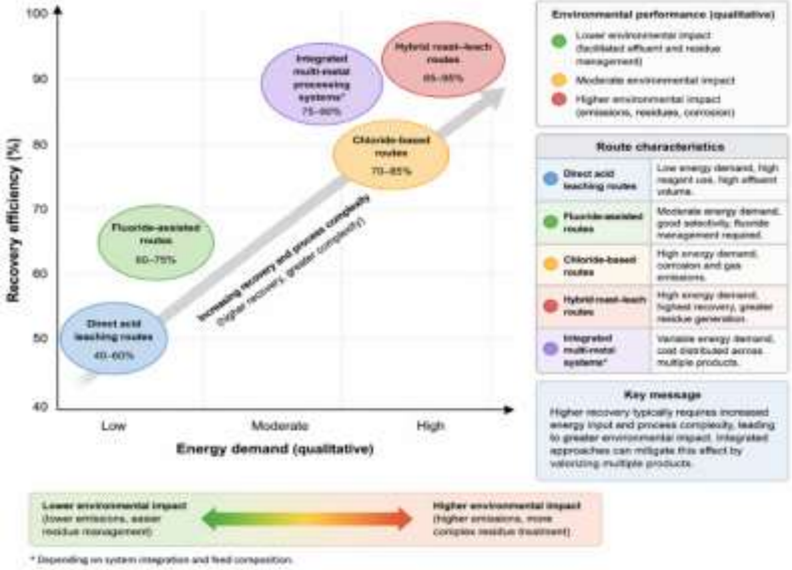

Figure 7. Qualitative relationship between energy demand, recovery efficiency, and environmental performance for hydrometallurgical and hybrid routes applied to REE-bearing slags. Adapted from Rudnik (2025), Pan et al. (2023), and Cempa et al. (2024).

Figure 7 shows a trade-off between recovery and process intensity. Higher efficiencies usually mean greater energy use, reagent consumption, and environmental impact. Direct acid leaching uses less energy but offers moderate recovery and high effluent. Fluoride-assisted methods improve recovery with moderate energy but pose fluoride management issues. Chloride and hybrid roast–leach routes deliver recoveries of 85–95% but entail high energy, emissions, and complexity (Gkika et al., 2024).

Integrated multi-metal approaches offer better economic performance by spreading costs across multiple products, but their success depends on feed composition and process integration. These trends show that process optimization isn't just about maximizing recovery. Effective industrial solutions must balance energy efficiency, environmental impact, and economic return in an integrated flowsheet.

7.3. Circular economy and process integration

Slag processing promotes a circular economy by turning waste into resources and reducing environmental impact (Gargul & Borycza Ko, 2020; Jiang et al., 2022). Its economic viability relies on integration, scale, and multiple value streams.

REE recovery becomes more attractive when combined with co-product extraction (Nb, Ti, Zr, scandium) and the valorization of main components such as iron and aluminum (Kim & Azimi, 2020; Boyarintsev et al., 2021; Kokko et al., 2024). In integrated systems, costs are shared across multiple products, lowering the per-kilogram cost of REE.

Infrastructure also plays a critical role. Integration into existing metallurgical operations reduces capital expenditure, minimizes logistics requirements, and allows partial use of available energy and utilities, improving overall process efficiency (Rudnik, 2025; Cempa et al., 2024).

The performance of hydrometallurgical routes depends on reagent use, energy consumption, and process integration. Strategies that maximize recovery often increase environmental impact and costs, requiring a balance among efficiency, sustainability, and economics. Table 5 compares the main trade-offs in REE recovery from slags.

Table 5. Environmental, sustainability, and economic trade-offs for hydrometallurgical processing routes applied to REE-bearing metallurgical slags. Adapted from Rudnik (2025), Pan et al. (2023), Ekstroem et al. (2021), Jiang et al. (2022), and Cempa et al. (2024).

Processing route	Reagent intensity	Energy demand	Main environmental challenge	Economic implication
Direct acid leaching	High	Low–moderate	High effluent load	Low CAPEX, high OPEX
Fluoride-assisted	Moderate–high	Moderate	Fluoride management	Higher recovery, higher OPEX
Chloride-based	Moderate	High	Emissions, corrosion	High CAPEX
Hybrid roast–leach	Moderate	High	Energy + residues	Best overall recovery
Integrated multi-metal	Variable	Variable	Process complexity	Highest economic potential

Table 5 shows a trade-off: simpler routes, such as direct acid leaching, require less capital but consume more reagents and produce more effluent, thereby raising costs. Advanced systems recover more but cost more and require tighter control.

No single route optimizes recovery, cost, and environment. Fluoride-assisted systems improve dissolution but pose challenges for fluoride management and compliance. Chloride routes enable effective phase change but entail high energy use, corrosion, and emissions, thereby raising costs. Hybrid roast–leach methods achieve high recovery by altering slag mineralogy prior to leaching, yet they increase energy use and residue generation.

Integrated multi-metal recovery strategies provide significant economic benefits by spreading costs over multiple valuable products, but they involve complex flowsheets and operations. Ultimately, choosing a process requires balancing technical performance, environmental impact, and economic viability, not just recovery efficiency.

7.4. Critical assessment

Despite growing research, important limitations still exist: limited economic data, infrequently reported full mass balances, ignored reagent recycling, and underestimated environmental effects. As a result, reported recovery rates—often over 90%—do not truly represent industrial performance.

Industrial viability hinges on cost per kg of REE, energy efficiency, residue stability, and environmental compliance. Without these, lab results have limited value for scale-up. This underscores the need for broader assessments beyond recovery efficiency as the key performance metric (Akcil et al., 2021).

The sustainability of REE recovery from slags depends on mineralogy, process design, and economics, not just a single factor.

Direct leaching is simple but uses more chemicals. Hybrid methods enhance efficiency but consume more energy. Integrated systems offer the best long-term potential but are complex to implement.

The next section explores industrial and pilot-scale case studies, highlighting how trade-offs are managed in real systems and how lab concepts are applied practically. (Karan et al., 2022).

8. INDUSTRIAL CASE STUDIES

The industrial implementation of REE recovery from slags is limited despite steady progress. Lab studies show high efficiency, but industrial cases reveal constraints like scale, feed variability, and process integration. Real-world applications highlight the importance of slag mineralogy, infrastructure, and economics in feasibility (Guo et al., 2023).

Bridging the gap between lab research and industrial deployment is challenging. Many routes achieve high recoveries under controlled conditions but vary in technological maturity. A disconnect often exists between recovery performance and readiness, with efficient routes still in their early stages of development. Systematic evaluation is vital for assessing industrial viability. Figure 8 compares TRL and REE recovery for hydrometallurgical and hybrid process routes.

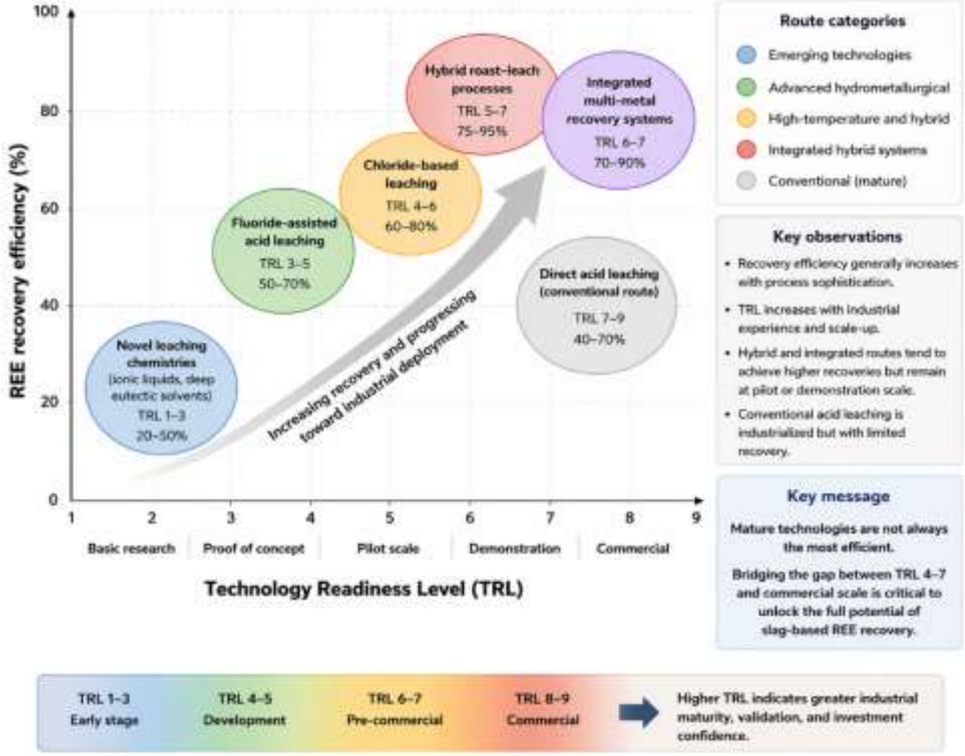

Figure 8. Qualitative comparison of technology readiness level (TRL) versus REE recovery efficiency for representative industrial and pilot-scale slag processing routes. Adapted from Xie et al. (2023), Kim and Azimi (2020), Tian et al. (2022), and Mubula et al. (2024).

Figure 8 shows a mismatch between recovery and technology maturity. Conventional acid leaching has high TRL (7–9) but moderate recovery. Hybrid roast–leach and multi-metal systems achieve 75–95% recovery but are at intermediate TRLs (5–7), requiring further validation and scale-up.

Emerging approaches, such as new leaching chemistries and separation technologies, are at low TRLs (1–4). While promising in selectivity, their industrial use is uncertain due to limited data and scalability issues. This highlights a gap between tech performance and industrial readiness.

Bridging this gap needs pilot demonstrations, long-term stability, and techno-economic assessment. Figure 8 shows that high recovery does not equal industrial maturity. The most efficient processes are often underdeveloped, and mature ones do not achieve optimal recovery. Deployment depends on technologies that balance performance, reliability, and cost.

8.1. Peralkaline slag systems

Peralkaline slags from eudialyte processing exemplify advanced industrial and pilot-scale REE recovery, featuring high alkali and fluoride levels, with REEs mainly in silicate structures, and thus requiring targeted processing strategies.

Pilot-scale operations in Northern Europe and Greenland show fluoride-assisted leaching achieves 85–95% recovery of yttrium and heavy REEs (Xie et al., 2023; Tian et al., 2022; Chen et al., 2023). This success results from controlled mineralogy, fluoride chemistry disrupting REE–Si bonds, and optimized conditions.

Despite technical advantages, industrial use is limited by operational and regulatory challenges. Handling fluoride, effluent treatment, and environmental compliance increases complexity and cost. While these systems are efficient, they are demanding and need careful integration to be viable.

8.2. Nb–Ta processing slags

Slags from niobium–tantalum processing are good feedstocks for industrial REE recovery. Made at high temperatures, they contain REEs attached to Nb–Ti oxide phases, which are more easily transformed than silicates.

Industrial and pilot-scale studies show chlorination roasting with acid leaching recovers 80–90% of Ce, Nd, and Y (Rudnik, 2025; Menad et al., 2024; Zhao et al., 2024). This method benefits from existing infrastructure, such as chlorination units and high-temperature systems, lowering capital costs compared to standalone methods.

Several challenges remain, including high operating temperatures (>800–1000 °C), handling of chlorine gases, and the need for corrosion-resistant materials. These factors increase complexity and maintenance requirements, offsetting some of the infrastructure benefits.

8.3. Fluoride-based industrial residues

Fluoride-rich residues such as spent pot lining (SPL) and catalyst slags are industrial materials with both recovery potential and environmental risks. They usually contain moderate REE levels, have complex compositions, and contain hazardous components, demanding careful processing.

Leaching with nitric acid or controlled fluoride-based systems can achieve REE recoveries between 40% and 75%, depending on feed composition and pretreatment steps (Yang et al., 2020; Yan et al., 2023; Tang et al., 2023). A key benefit of these materials is their dual functionality, enabling simultaneous REE recovery and stabilization of hazardous waste streams, thereby enhancing environmental performance within circular economy models.

However, their industrial use is limited by factors such as low selectivity, complex impurities, and variable feed composition, which reduce predictability, increase uncertainty, complicate flowsheet design, and limit scalability.

Industrial and pilot studies assess REE recovery from slags, with an emphasis on mineralogy, process conditions, and infrastructure. Performance varies by slag type, requiring comparison to find industrial pathways. Table 6 reviews case studies from 2020-2025, noting recovery, scale, benefits, and limitations.

Table 6. Representative industrial and pilot-scale case studies for REE recovery from metallurgical slags (2020–2025). Adapted from Xie et al. (2023), Tian et al. (2022), Chen et al. (2024), Mubula et al. (2024), and Lim and Park (2024).

Slag system	Recovery	Scale	Key advantage	Main limitation
Peralkaline slags	85–95%	Pilot	High selectivity	Fluoride management
Nb–Ta slags	80–90%	Pilot/industrial	Existing infrastructure	Energy + corrosion
Molten salt slags	>80%	Pilot	Favorable mineralogy	Process complexity
SPL / fluoride residues	40–75%	Pilot	Waste remediation	Low selectivity
Catalyst slags	50–70%	Pilot	High REE content	Impurity load

Table 6 shows process performance varies with slag type and mineral properties. Peralkaline slags have high recoveries (85–95%) but pose fluoride and environmental issues. Nb–Ta slags offer a balanced recovery (80–90%) with existing infrastructure, though energy use and corrosion are concerns.

Molten salt slags have high recovery (>80%) and good mineralogy but require complex processing. Fluoride-rich residues such as SPL yield moderate recoveries (40–75%) and stabilize waste, though their lower selectivity and variability hinder predictability. Catalyst slags contain high REE but have complex impurities, complicating separation.

The comparison shows no slag system can optimize recovery, scalability, and simplicity all at once. Industrial viability depends on aligning mineralogy, infrastructure, and process integration, not just on recovery efficiency.

8.4. Critical assessment

Industrial case studies cite three main constraints in REE recovery from slags: feed variability affecting stability, process integration challenges between pretreatment and hydrometallurgy, and economic sensitivity to market prices and co-product recovery.

Most REE recovery isn't economically viable on its own. It requires large processing volumes, co-recovery of other metals, and integration into existing infrastructure. Market factors matter too; high-value elements like scandium, dysprosium, and yttrium boost economics, while low-value REEs like La and Ce add little revenue.

Overall, industrial experience shows REE recovery from slags is feasible but highly context-dependent. Successful systems combine mineralogy, infrastructure, and processing strategies. Scalability is limited, with most technologies still pilot stage. Barriers include high energy, reagent use, and long-term residue challenges.

The next section consolidates these findings, addressing the critical challenges, knowledge gaps, and future directions required to enable reliable and scalable industrial deployment of REE recovery from metallurgical slags.

9. CRITICAL CHALLENGES AND KNOWLEDGE GAPS

Despite progress in REE recovery from slags, key barriers limit industrial use. Challenges now stem from mineralogy, process design, environmental constraints, and scale-up limits, not just chemistry.

9.1. Mineralogical constraints and reaction kinetics

The main limitation in REE recovery from slags is mineralogical, as rare earths are often trapped in polymerized silicates or complex oxides, which limit reagent access and hinder dissolution.

In silicate-rich systems, leaching is governed by diffusion through dense, stable matrices, resulting in reaction times of 2–4 hours or longer, higher temperatures (70–100 °C+), and increased reagent consumption (Rudnik, 2025; Li et al., 2025).

Without pretreatment, these constraints limit extraction efficiency, with recoveries below 30–50%.

9.2. Silica behavior and process instability

Silica gel formation is a key challenge in the hydrometallurgy of slags. During acid leaching, silica re-polymerizes, forming gels that raise slurry viscosity, hinder separation, and disrupt operation.

This phenomenon is evident in slags with high SiO_2 (>30–40 wt%), where silica dissolution and reprecipitation affect process stability. Despite strategies like alkaline pretreatment and pH control, no robust industrial solution exists, especially for continuous systems (Pan et al., 2023; Sun et al., 2025).25).

9.3. Selectivity limitations

Selectivity hinders REE recovery from slags, as direct leaching dissolves mainly Fe, Ca, and Al (80–95%), while REEs stay low (<1–5 g/L).

This imbalance boosts reagent use, adds more separation stages, and raises costs (Ekstroem et al., 2021; Chen et al., 2023). Without prior phase transformation, selective REE recovery is difficult, especially in silicate-rich systems dominated by matrix elements.

9.4. Environmental and regulatory constraints

Advanced leaching systems often depend on aggressive chemical reagents to break down refractory REE-bearing phases. Fluoride- and chloride-based methods improve dissolution but pose environmental and operational risks.

Key concerns include HF formation, fluoride toxicity, chlorine gas emissions, and increased corrosion, which complicate operations, raise costs, and increase regulatory burden (Yang et al., 2020; Menad et al., 2024).

Furthermore, limited long-term environmental data creates uncertainty in permitting and large-scale use, hindering industrial adoption of these advanced leaching systems.

9.5. Scale-up and techno-economic gaps

Most studies on REE recovery from metallurgical slags are limited to the lab scale, with scarce, incomplete pilot data. This hinders realistic evaluation and reliable scale-up, with missing info on reagent recycling, long-term stability, continuous operation, and costs (Xie et al., 2023; Cempa et al., 2024). Without these parameters, techno-economic assessment and industrial feasibility prediction are constrained.

Despite advances in REE extraction, industrial applications remain limited. Research often focuses on isolated improvements in leaching or separation, neglecting the interdependence of mineralogy, chemistry, selectivity, and environmental constraints.

In practice, these factors are tightly coupled. Mineralogical characteristics govern reaction pathways and kinetics, which in turn influence impurity co-dissolution, reagent consumption, and downstream processing complexity. As a result, optimizing individual unit operations in isolation is insufficient to achieve scalable and economically viable solutions.

To address these limitations, a structured, integrated development strategy is needed. Figure 9 shows a roadmap aligning research priorities across short-, medium-, and long-term goals, connecting fundamental understanding to process integration and industrial deployment.

Figure 9. Integrated bottlenecks affecting REE recovery from metallurgical slags across the processing chain, from mineralogy to scale-up. Adapted from Rudnik (2025), Pan et al. (2023), and Xie et al. (2023).

Figure 9 shows that key challenges in REE recovery from slags are interconnected. Mineralogy affects leaching, which impacts separation and economic viability. Therefore, optimizing individual units alone isn't enough for scalable, efficient processes.

The roadmap highlights systemic barriers to industrial implementation, as improvements in one area often create constraints elsewhere, emphasizing the need for integrated process design and multi-objective optimization.

In the short term, research should focus on mineralogical characterization and on understanding critical mechanisms such as silica gel formation and impurity co-dissolution. Medium-term efforts should prioritize integrating pretreatment, leaching, and separation, with support from modeling and life-cycle assessment. Long-term shifts focus on digitalization, real-time control, and designing slag to improve REE release and process efficiency.

Ultimately, REE recovery from metallurgical slags depends on balancing high selectivity, low environmental impact, and proven techno-economic performance to support circular and resilient critical materials supply chains.

9.6. Fragmentation of process design

A major limitation in REE recovery from slags is fragmented research. Many studies optimize individual steps such as leaching or roasting without considering their integration, leading to suboptimal performance, inefficient reagent use, and inconsistent results, as improvements at the unit level don't always translate into overall gains.

The challenges in this field are multifaceted and interconnected, involving mineralogical, chemical, environmental, and process-integration issues. These affect extraction, scalability, cost, and long-term viability. Addressing them requires strategies that consider phase behavior, reaction chemistry, separation, and economics. Table 7 summarizes the main challenges and knowledge gaps, linking their causes to process impacts.

Table 7. Summary of critical challenges and knowledge gaps in REE recovery from metallurgical slags. Adapted from Rudnik (2025), Pan et al. (2023), and Chen et al. (2023).

Category	Challenge	Root cause	Impact
Mineralogy	Low kinetics	Silicate networks	High reagent demand
Process chemistry	Silica gel	SiO_2 polymerization	Filtration issues
Selectivity	Co-dissolution	Lack of phase control	Complex separation
Environmental	Fluoride/chloride use	Toxicity, emissions	Regulatory barriers
Scale-up	Lack of pilot data	Lab-scale focus	Uncertain economics
Integration	Fragmented flowsheets	Isolated studies	Inefficient processes

Table 7 shows that the main challenges are interconnected and stem from mineralogical constraints affecting the entire process. Polymerized silicate networks limit reaction kinetics, raising reagent needs and affecting separation. Silica gel formation and impurity co-dissolution also complicate solid–liquid separation and reduce selectivity.

Environmental and scale-up constraints, especially with aggressive reagents or a lack of pilot validation, worsen these limitations. Fragmented process design, where unit operations are optimized separately, also leads to inefficient flowsheets.

Overall, the table emphasizes that these challenges cannot be addressed in isolation. Effective solutions require integrated approaches that simultaneously consider mineralogy, process chemistry, environmental impact, and economic performance.

9.7. Critical synthesis

The main challenge shifts from the feasibility of REE extraction to doing it efficiently, selectively, and at scale. Current research often focuses on maximizing recovery, neglecting cost, environmental impact, and process integration. As a result, many high-efficiency methods are impractical for large-scale use, highlighting the need for more balanced, application-oriented development.

The challenges highlight future research priorities, focusing on integrating mineralogy with process design, reducing reagent and energy use, improving selectivity and separation, and developing robust pilot and industrial data.

The next section discusses future directions, emphasizing technological strategies and research needed for scalable, cost-effective REE recovery from metallurgical slags.

10. FUTURE DIRECTIONS

Future REE recovery from slags requires an integrated, mineralogy-driven approach, rather than isolated optimization. The main challenge is now achieving selective, efficient, and scalable processing in industrial conditions, not chemical feasibility.

A key priority is actively controlling slag mineralogy through strategies such as controlled cooling, phase separation, and enrichment of REE-bearing phases, thereby modifying phase distribution before leaching. This approach focuses on engineering slag composition to improve reactivity and accessibility, leading to reductions in acid use (20–50%), faster leaching, and better selectivity.

Advancing REE recovery requires coordinated, system-level research due to interconnected challenges across mineralogy, chemistry, environmental science, and scale-up. A structured framework linking understanding, process, and validation is needed. Table 8 outlines key research priorities, actions, and impacts on performance and scalability.

Table 8. Key research priorities for advancing sustainable and industrial-scale REE recovery from metallurgical slags. Adapted from Rudnik (2025), Pan et al. (2023), Cempa et al. (2024), and Chen et al. (2023)

Research domain	Current limitation	Priority action	Expected impact
Slag mineralogy	Highly polymerized silicate networks limit REE accessibility	Phase engineering (controlled cooling, selective crystallization)	Improved leaching kinetics and reduced reagent consumption
Leaching chemistry	Low selectivity and high reagent consumption	Targeted roast–leach strategies and optimized reagent systems	Enhanced selectivity and lower chemical demand
Silica control	Gel formation during acid leaching	Anti-gel strategies (alkaline pretreatment, additives, pH control)	Improved filtration and process operability
Separation processes	Complex and multi-stage flowsheets	Integrated and simplified separation systems (SX–IX–precipitation)	Reduced cost and higher product purity
Environmental performance	Dependence on fluoride/chloride systems	Closed-loop reagent management and emission control	Improved regulatory compliance and reduced environmental impact
Scale-up	Limited pilot-scale and continuous operation data	Long-term pilot and demonstration-scale campaigns	Increased technology readiness level (TRL)
Techno-economics	Fragmented cost data and lack of integration	Combined LCA–TEA evaluation and process optimization	Improved investment readiness and decision-making

Table 8 shows that future progress depends mainly on process integration, not just incremental improvements in units. Mineralogy, leaching, separation, and environmental factors must be addressed together in a unified framework.

Future developments should prioritize low-impact leaching by reducing the use of fluoride and chloride reagents, increasing the use of recyclable chemicals, and adopting closed-loop management. Hybrid roast–leach methods remain relevant but need lower operating temperatures (<700 °C) and reagent use to enhance sustainability and cost-effectiveness.

Thermodynamic and kinetic modeling will play a critical role in this transition. Predictive tools can support the estimation of phase transformations, optimization of reagent systems, and improved reliability during scale-up (Liu et al., 2025). These approaches are particularly important for managing complex, multi-phase slag systems.

Separation technologies require simplification. Complex, costly flowsheets hinder industrial adoption. Future systems should be modular, adaptable, and less reliant on multi-stage, reagent-heavy processes. Emerging methods such as membrane-assisted solvent extraction, ionic liquids, and deep eutectic solvents are promising for their selectivity but remain at low readiness levels and require validation of stability, recyclability, and cost under industrial conditions (Habibi et al., 2023).

A major bottleneck is the lack of pilot-scale validation. Most studies are limited to batch lab experiments, missing the challenges of continuous operation. Industrial deployment requires demonstration of reagent recycling, water balance, long-term stability, and performance under variable feed conditions. Without this data, techno-economic assessments are uncertain, and investment risks stay high.

From a systems perspective, the strongest opportunity lies in integrated multi-metal recovery. REE extraction alone is often insufficient to ensure economic viability. However, co-recovery of elements such as scandium, niobium, zirconium, and titanium can significantly enhance process economics and reduce overall risk. Integration with existing metallurgical infrastructure further improves feasibility by reducing capital investment, minimizing logistical requirements, and leveraging available energy and utilities.

Finally, future development must align with circular economy principles. Metallurgical slags should be seen as secondary resources, not waste. This involves recovering valuable metals, valorizing construction residues, and minimizing long-term environmental risks. These strategies boost environmental performance and social acceptance.

The limiting factor for REE recovery from metallurgical slags is no longer chemistry, but system-level integration. Future success will depend on integrating mineralogical engineering, reduced reagent intensity, simplified separation, pilot-scale validation, and economic integration into coherent, scalable process designs.

The following section consolidates the key findings of this review, highlighting technical insights, industrial readiness, and strategic implications for REE recovery from metallurgical slags within the global critical materials supply chain.

11. CONCLUSIONS

Hydrometallurgical methods for REE recovery from metallurgical slags have evolved from laboratory-scale studies to early-stage industrial applications between 2020 and 2026. Although acid leaching remains the primary approach, its effectiveness is fundamentally limited by mineralogical factors, especially in silicate-rich and refractory slags, where restricted reagent access and extensive co-dissolution reduce selectivity and process efficiency. In this context, chloride- and fluoride-based chemistries have proven crucial for breaking down polymerized silicate networks and improving REE accessibility.

Hybrid roast–leach processes consistently achieve the highest recoveries by transforming REE-host phases into more reactive and leachable intermediates. However, these gains are accompanied by increased energy demand, process complexity, and environmental burden. Likewise, downstream separation technologies—including advanced solvent extraction, membrane-assisted processes, and ion-exchange systems—have improved product purity and operational stability, but remain challenged by high impurity loads and the need for multi-stage processing.

Despite these advances, large-scale implementation remains limited by high reagent consumption, environmental challenges, and the lack of continuous pilot-scale testing. Notably, many reported systems focus on recovery efficiency but overlook critical factors such as mass balance closure, reagent recycling, energy efficiency, and long-term operability, all of which are vital for industrial use.

Future progress requires shifting from isolated process optimization to integrated, mineralogy-driven process design. This involves controlling slag composition and phase assemblage, reducing reagent use, simplifying separation flowsheets, and validating under industrial conditions. In this context, metallurgical slags should no longer be seen as passive waste but as engineered secondary resources whose value depends on coordinated advances in mineralogy, process chemistry, and process integration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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