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Laboratory Methods for Metal Recovery from Red Mud: Extraction Strategies and Technological Insights

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ABSTRACT

Red mud, the highly alkaline residue of the Bayer process, is generated at about 120 million t yr^{-1} and represents both an environmental liability and a secondary resource. This study had two objectives: (i) to synthesize evidence from 162 publications on recovery routes for Fe, Al, Na, and Ti, and (ii) to demonstrate two laboratory-scale applications on a representative residue. Methods included a combined pyrometallurgical–hydrometallurgical flowsheet—carbothermic reduction smelting at 1450–1500 °C with fluxes, followed by sintering–leaching of the resulting slag—and a materials route in which red mud served as a filler in release coatings for metal molds. In smelting tests at 1450 °C, iron extraction to the metallic phase reached 88.5–91.5%, producing cast iron with 93.8 wt% Fe and 4.99 wt% C, and slags with ≤ 0.2 wt% Fe. From this Fe-depleted slag, alumina recovery by the sintering route was 69.8%, with reagent consumptions of ~309 kg Na_2CO_3, 300 kg CaO, and 282 kg NaOH per tonne of slag; sodium partitioned predominantly to sublimates and dust, indicating the need for alkali capture and recycle. In the coating application, incorporating up to 10 wt% red mud delivered densities of ~1016–1123 kg m^{-3}, nominal viscosities of ~10–11 mPa·s, and ~96% sedimentation stability; higher loadings reduced stability. We conclude that integrated, site-specific flowsheets can simultaneously valorize metal values (iron to saleable metal; alumina from slag) and support direct materials uses, while scale-up success will depend on alkali management, reagent and energy intensity, and standardized performance testing. The results align with pilot-scale experience and suggest a credible pathway from laboratory data to industrial implementation.

Keywords: red mud, recycling of alumina production waste, red mud processing, recovery of metals from red mud, leaching of metals from red mud.

1. Introduction

The large-scale production of alumina by the Bayer process generates vast quantities of bauxite residue, commonly referred to as red mud. Global alumina production currently generates on the order of 120 million tonnes of red mud annually, and cumulative stockpiles worldwide exceed several billion tonnes (Klauber et al. 2011; Liu and Li 2015). Due to its high alkalinity, fine particle size and complex chemical and mineralogical composition, red mud represents a long-term environmental liability, requiring extensive land use for storage and posing risks related to groundwater contamination, dust emissions and accidental releases (Klauber et al. 2011; Trushko et al. 2017). Although improved residue management practices such as filtration and dry stacking have reduced some immediate hazards, the fundamental challenge of sustainable red mud utilization remains unresolved (Wang et al. 2018).

At present, only a small fraction of annually generated red mud—typically below 2–3%—is utilized, predominantly in low-value applications such as construction materials, fillers or land reclamation (Zinoveev et al. 2018). In contrast, red mud contains substantial concentrations of valuable and critical elements, including iron, aluminium, titanium and sodium, and in certain deposits strategic metals such as scandium and other rare-earth elements (Liu and Li 2015; Borra et al. 2016). From a resource-efficiency and circular-economy perspective, red mud should therefore be regarded as a secondary raw material rather than a waste stream. However, its mineralogical complexity, the strong binding of elements within refractory oxide and aluminosilicate phases, and the presence of residual alkalis significantly complicate selective extraction and large-scale process implementation (Klauber et al. 2011).

Over the past decade, considerable research effort has been devoted to laboratory-scale methods for red mud valorization. These include physical beneficiation and magnetic separation for iron concentration, pyrometallurgical routes based on carbothermic reduction and smelting, hydrometallurgical leaching schemes employing mineral or organic acids and alkaline solutions, as well as hybrid and emerging approaches such as bioleaching, ionic liquids and sequential extraction flowsheets (Borra et al. 2016; Zinoveev et al. 2018). While many of these techniques demonstrate high extraction efficiencies at laboratory scale, only a limited number have progressed to pilot or industrial demonstration, largely due to challenges related to energy consumption, reagent intensity, alkali volatility and corrosion, as well as difficulties in integrating red mud processing into existing alumina or metallurgical value chains (Wang et al. 2018).

The objectives of the present short review paper are therefore twofold. First, it aims to synthesize and critically assess recent laboratory-scale strategies reported in the literature for the recovery of Fe, Al, Na, Ti and selected rare and rare-earth elements from red mud, with emphasis on process principles, achievable recoveries and key technological limitations. Second, the paper presents and analyses two laboratory-scale processing routes developed by the authors: (i) a combined pyrometallurgical–hydrometallurgical flowsheet involving carbothermic reduction smelting of red mud followed by alumina recovery from Fe-depleted slag, and (ii) a materials-based utilization route in which red mud is employed as a functional filler in mould release coatings.

2. Origin, Properties and Current Utilization of Red Mud

2.1. Generation in the Bayer Process and Global Inventory

Red mud is generated as an insoluble residue during alumina production by the Bayer process, which accounts for approximately 95% of global alumina output. In the Bayer process, crushed bauxite is digested in concentrated sodium hydroxide solution at elevated temperature and pressure, leading to the dissolution of aluminium-bearing phases such as gibbsite, boehmite and diaspore and the formation of sodium aluminate liquor. The undissolved fraction—composed mainly of iron oxides, aluminosilicates, titanium-bearing phases and residual alkalis—is separated from the liquor as a fine-grained solid residue and discharged as red mud (Klauber et al. 2011; Liu and Li 2015).

The amount of red mud generated depends strongly on the mineralogical composition of the processed bauxite and the operating conditions of

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digestion, including temperature, caustic concentration and lime addition. Typical red mud generation rates range from approximately 0.8 to 2.0 tonnes per tonne of alumina produced, with higher values commonly associated with diasporic and boehmitic bauxites (Klauber et al. 2011; Borra et al. 2016). As a consequence, global alumina production currently generates on the order of 120 million tonnes of red mud annually, contributing to cumulative stockpiles exceeding several billion tonnes worldwide (Wang et al. 2018).

Red mud is discharged from the Bayer process as a highly alkaline slurry, typically characterized by a liquid-to-solid ratio of about 2.5–3.0. The liquid phase contains dissolved sodium species, commonly expressed as Na_2O concentrations in the range of 1–3 g L^{-1}, while additional sodium remains structurally bound within solid phases such as sodalite- and cancrinite-type aluminosilicates (Liu and Li 2015; Trushko et al. 2017). Even after multi-stage washing and thickening, this retained alkali contributes to the persistently high pH of red mud and represents a key challenge for its storage, handling and subsequent processing.

2.2. *Chemical and Mineralogical Characteristics*

The chemical and mineralogical composition of red mud is highly variable and reflects both the composition of the parent bauxite and the specific Bayer process parameters, including digestion temperature, caustic concentration and lime addition. As a result, red mud from different alumina refineries exhibits substantial differences in bulk chemistry, phase assemblage and physicochemical properties. Nevertheless, most red muds are dominated by iron oxides, alumina, silica, calcium oxide, titanium dioxide and sodium oxide, with iron typically representing the most abundant metallic constituent.

Iron is predominantly present in the form of hematite and, to a lesser extent, goethite, while aluminium occurs mainly within refractory aluminosilicate phases formed during digestion, such as cancrinite, sodalite-type phases, kaolinite residues and calcium aluminate hydrates (e.g. katoite). Titanium is commonly distributed among anatase and rutile, with perovskite ($CaTiO_3$) forming under conditions of elevated calcium activity. Sodium is incorporated both as soluble alkali and, more importantly, as a structural component of aluminosilicate phases such as cancrinite and sodalite, which contributes to the persistence of alkalinity even after extensive washing.

Red mud is a fine-grained material, with particle sizes typically below 100 μm and average values most commonly in the range of 5–30 μm. The specific surface area usually varies between approximately 10 and 25 m^2 g^{-1}, depending on bauxite type, grinding practice and the extent of phase transformation during digestion (Liu et al. 2017; Trushko et al. 2017). This fine particle size enhances the apparent reactivity of red mud in leaching and thermal processes but also creates challenges related to slurry rheology, filtration, sedimentation and dust generation during handling and storage.

In addition to the major oxide components, red mud contains a wide spectrum of minor and trace elements, including manganese, chromium, vanadium, gallium, zirconium and, in certain deposits, scandium and other rare earth elements. The concentrations of these elements vary by orders of magnitude depending on the geological origin of the bauxite and processing history, making site-specific characterization essential when evaluating red mud as a potential secondary raw material for metal recovery. To illustrate this variability, Table 1 summarizes typical composition ranges of red mud reported in the literature.

Table 1. Typical composition ranges of red mud reported in the literature

Component	Typical range (wt%)
Fe_2O_3	15–60
Al_2O_3	5–30
SiO_2	3–20
CaO	2–20
TiO_2	2–10
Na_2O	2–10
REE + Sc	0.05–0.3

2.3. *Environmental Issues and Storage Practices*

The environmental impact of red mud is primarily associated with its high alkalinity, fine particle size and the presence of trace metals. Fresh red mud typically exhibits pH values above 11, which can lead to severe ecological damage if released into soil or water systems. The large-scale spill in Ajka, Hungary, in 2010 demonstrated the potential consequences of red mud storage failures, including widespread contamination of surface waters, agricultural land and settlements (Klauber et al. 2011).

Historically, red mud was often disposed of in lagoons or, in some coastal regions, discharged directly into the sea. These practices have largely been abandoned due to environmental regulations and public concern. Modern residue management increasingly relies on filtration and dry stacking technologies, in which red mud is dewatered to produce a filter cake with a moisture content of approximately 25–30% (Wang et al. 2018). This approach reduces the risk of dam failure, lowers transport costs and improves the prospects for subsequent utilization or processing.

Despite these improvements, dry-stacked red mud remains chemically reactive and alkaline, and long-term storage still requires careful management to prevent dust emissions, leaching of alkalis and migration of trace elements. Consequently, residue storage should be regarded as an interim solution rather than a final disposal strategy.

2.4. *Existing Utilization and Applications Routes*

Current industrial utilization of red mud remains limited and is dominated by low-value applications. After washing or neutralization, red mud has been incorporated into building materials such as bricks, cement clinker, tiles and paving stones, where it serves primarily as an iron-rich filler or fluxing component (Figure 1). Additional applications include pigments, additives in glass production, soil amendments for land reclamation and weighting agents in drilling fluids (Zinoveev et al. 2018).

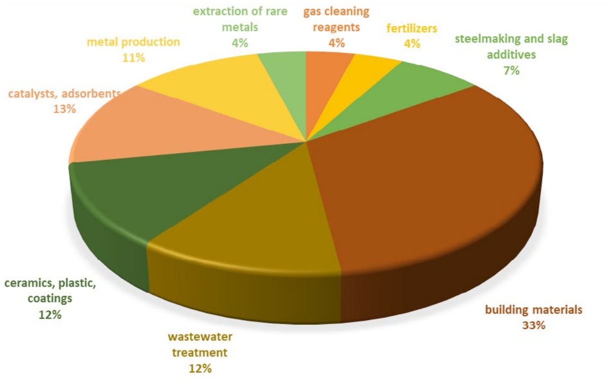

Fig. 1. Current application routes for red mud residue

While these application routes can be locally relevant, they do not scale to the global residue generation rate and they often lack strong economic drivers. This mismatch between (i) the very large annual red mud flow and (ii) the limited capacity and value of bulk applications is a central motivation for shifting attention to metal and critical-element recovery, where smaller product tonnages can carry higher value and better justify process complexity (Klauber et al. 2011; Borra et al. 2016).

3. Classification of Metal-Recovery Routes from Red Mud

Red mud is mineralogically complex and typically contains Fe mostly as hematite/goethite, Al in aluminosilicates and/or hydroxides, Ti in rutile/anatase/perovskite, and alkalis partially dissolved and partially locked in Na-bearing aluminosilicate phases. Because of this, most recovery routes either (a) separate Fe early (physical beneficiation or reduction + magnetic separation) to simplify downstream hydrometallurgy, or (b) smelt/reduce to produce an Fe metal and an engineered slag for further extraction, or (c) apply selective leaching/roasting–leaching sequences aimed at Sc/REE/Ti/Al while controlling Fe and silica gel formation (Figure 2).

The literature indicates that no single processing route can universally address the challenges posed by red mud. Physical beneficiation can reduce iron content but is limited by mineralogical constraints; pyrometallurgical routes offer robust iron recovery but demand careful slag and alkali management; hydrometallurgical routes provide flexibility and selectivity but often suffer from high reagent consumption and complex residue handling. Recovery of critical elements such as scandium typically requires deliberately designed, multi-step flowsheets rather than simple leaching.

These findings support the growing consensus that integrated and site-specific processing strategies, combining elements of physical, thermal and chemical treatment, represent the most promising path toward meaningful red mud valorization. Such integrated approaches form the basis for the laboratory-scale flowsheets presented and analysed in the following sections of this paper.

Among the valuable components of red mud, scandium has received particular attention due to its high market value and strategic importance. Although present only at trace levels, scandium is often more readily leached than bulk elements under carefully controlled conditions. Narayanan et al. (2018) demonstrated that selective, staged processing combining leaching and targeted separation steps can achieve high scandium recovery while suppressing iron dissolution.

Dry digestion or roasting-assisted routes followed by water or mild acid leaching have also been proposed as effective strategies for scandium and rare earth element recovery, as they reduce acid consumption and improve leachate manageability (Rivera et al. 2018). The growing number of patents related to scandium recovery from red mud further indicates sustained industrial interest, even though most concepts remain at laboratory or early pilot scale.

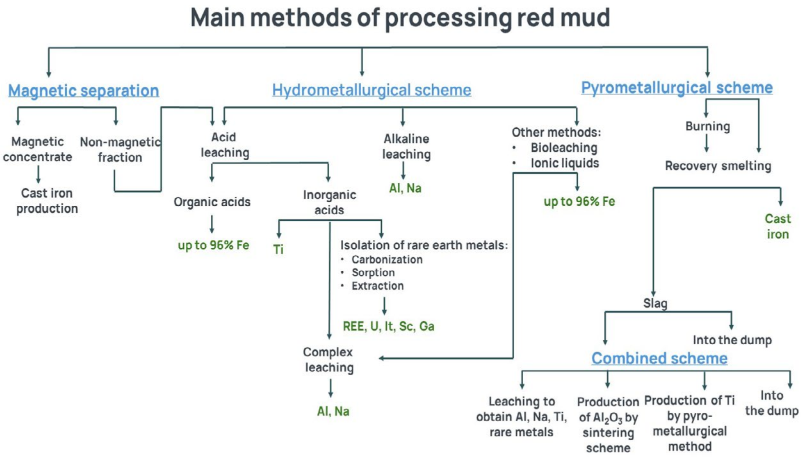

Fig. 2. Principal industrial and technological routes proposed for red mud processing and metal recovery

3.1. Physical beneficiation and magnetic separation

Physical beneficiation routes are conceptually attractive because they avoid extensive chemical reagent consumption and seek to exploit intrinsic differences in magnetic or density properties. In untreated red mud, however, iron is predominantly present as hematite or goethite, which are weakly magnetic and often finely intergrown with aluminosilicate phases. Consequently, direct magnetic separation generally yields low-grade iron concentrates and limited recoveries.

To overcome this limitation, many laboratory studies combine reductive roasting with subsequent magnetic separation, converting hematite and goethite into magnetite or metallic iron prior to separation. Cardenia et al. (2019) demonstrated that controlled reductive roasting followed by wet magnetic separation can achieve high conversion of iron oxides into magnetically responsive phases, enabling effective partitioning of an iron-rich fraction. Nevertheless, even under optimized conditions, iron concentrate grades and recoveries remain strongly dependent on particle liberation and the extent of phase intergrowth, which vary widely between residues.

From a process perspective, physical beneficiation is best viewed as a pre-treatment step rather than a stand-alone solution. While it can reduce iron content in the residue and improve the selectivity of subsequent hydrometallurgical processing, its effectiveness is constrained by mineralogical complexity and by the additional energy input required for roasting (Zinoveev et al. 2018).

3.2. Pyrometallurgical routes

Pyrometallurgical processing represents one of the most robust approaches for iron recovery from red mud, as it enables direct separation of iron into a metallic phase through carbothermic reduction and smelting. Laboratory and pilot-scale studies consistently report iron recoveries exceeding 85–95% when red mud is smelted at temperatures above 1400–1500 °C in the presence of carbonaceous reductants (Balomenos et al. 2011; Ekström et al. 2021). The resulting iron product typically corresponds to pig iron or cast iron, while the accompanying slag contains residual aluminium, titanium, calcium and silica.

Beyond iron recovery, the principal scientific challenge in pyrometallurgical routes lies in slag engineering. The chemical composition and phase assemblage of the slag determine whether aluminium and titanium are rendered accessible for subsequent extraction or become immobilized in refractory phases such as gehlenite or perovskite. Studies inspired by the Pedersen process concept demonstrate that calcium-rich slags dominated by calcium aluminates can be efficiently leached to recover alumina, whereas poorly engineered slags exhibit limited reactivity (Ekström et al. 2021).

A recurring issue in high-temperature processing is the behavior of sodium. Alkalis often volatilize or report to fine dust during smelting, leading to corrosion, off-gas treatment challenges and reagent losses (Zinoveev et al. 2018). While this volatilization can contribute to dealkalization of the slag, it introduces additional complexity that must be addressed for scale-up. Despite these challenges, pyrometallurgical routes remain among the most mature options for large-scale iron recovery from red mud, particularly when integrated with downstream slag processing.

3.3. Hydrometallurgical routes

Hydrometallurgical processing has been investigated extensively due to its lower operating temperatures and greater potential for selective metal recovery. Direct leaching with mineral acids such as hydrochloric, sulfuric or nitric acid can dissolve significant fractions of aluminium, iron and titanium, but selectivity is often poor and silica gel formation presents a persistent operational problem (Liu and Li 2015; Karimi et al. 2023). Organic acids have been explored as milder alternatives, though their effectiveness is typically limited by slow kinetics and reagent cost.

Alkaline leaching routes, including NaOH or Na_2CO_3 systems, are better suited for aluminium recovery but generally require prior thermal activation or sintering to break down aluminosilicate structures. Roasting or sintering with alkali and/or lime converts aluminium into soluble sodium or calcium aluminates, enabling subsequent leaching (Borra et al. 2016). However, these routes are reagent-intensive and often generate secondary residues that still require management.

More recent laboratory studies increasingly emphasize stepwise or sequential leaching schemes, in which iron is either removed first or deliberately retained in the solid phase while aluminium, titanium or scandium are selectively dissolved. Such approaches aim to reduce reagent consumption and improve downstream separations, but they require careful control of pH, redox conditions and solid–liquid interactions (Zinoveev et al. 2021).

3.4. Bio-hydrometallurgical and emerging solvent systems

Bio-hydrometallurgical approaches, including bioleaching and biosorption, have attracted attention as potentially lower-energy alternatives for red mud valorization. Microorganisms can generate acidic environments or complexing agents capable of mobilizing selected metals, particularly rare earth elements. Although promising results have been reported at laboratory scale, bio-based routes are generally limited by slow kinetics, sensitivity to residue composition and challenges in process control, which currently restrict their industrial relevance (Akcil et al. 2024).

In parallel, emerging solvent systems such as ionic liquids and deep eutectic solvents have been investigated for selective metal extraction, particularly for scandium and rare earth elements. These systems offer high selectivity in controlled environments, but their viscosity, cost and recyclability remain significant obstacles for large-scale application. At present, such solvents are best viewed as specialized separation tools rather than primary leaching media.

4. Case Study I – Combined Pyrometallurgical–Hydrometallurgical Processing

A combined pyrometallurgical–hydrometallurgical processing route has been developed and investigated by the authors as a means of valorizing red mud through sequential iron recovery and alumina extraction. This approach builds on the recognition that iron represents the dominant metallic component of most red muds and that its early removal can substantially simplify downstream processing of the remaining oxide matrix. The proposed flowsheet integrates carbothermic reduction smelting for iron recovery with subsequent slag treatment based on alkaline sintering and leaching, and has been evaluated at laboratory scale using representative red mud from an alumina refinery.

The feed material used in these studies was a fine-grained Bayer residue characterized by high iron content and a complex mineralogical assemblage dominated by hematite, cancrinite, kaolinite and calcium-bearing phases. Typical chemical and phase compositions are summarized in Tables 1 and 2, which illustrate both the high iron content and the substantial proportions of aluminium, calcium, silicon, sodium and titanium present in the residue. Prior to smelting, red mud samples were dried at moderate temperature to remove free moisture, after which they were mixed with carbonaceous reductant and fluxing agents. Lime-bearing fluxes were used to adjust slag basicity and viscosity, while soda was introduced in selected experiments to further modify slag chemistry and melting behavior. Reduction smelting was carried out in high-temperature laboratory furnaces at temperatures in the range of approximately 1420–1500 °C, chosen to ensure complete reduction of iron oxides and adequate slag fluidity.

Table 1. Average chemical composition of red mud

Content of elements in material, % (mass.)											
Fe	O	Al	Si	Ca	Ti	C	Na	Mn	Cr	S	P
28.15	41.29	8.35	7.12	6.29	2.36	1.20	2.12	0.78	0.05	0.71	0.23
Content of elements in material, % (mass.)											
Cu	Zr	Pb	Zn	Ni	Ga	Cl	Sr	Mg	K	REM	
0.02	0.17	0.04	0.07	0.0 6	0.007	0.056	0.09	0.28	0.34	0.22	

Table 2. Average phase composition of red mud

Phase	Content, % (mass.)	Name
Fe2O3	38.5	Hematite
CaCO3	8.16	Calcite
Na6[Al6Si6O24]•(CaCO3)•(H2O)2	22.80	Cancrinite
Ca3Al2•(SiO2)•(OH); Ca3Al2(SiO4)3–*x*(OH)4*x* (*x* = 1.5–3.0)	11.40	Katoite
(Fe, Al)•O•(OH)	4.00	–
AlO(OH)	2.04	Diaspore
CaTiO3	1.43	Perovskite
Al2Si2O5•(OH)4	18.00	Kaolinite
TiO2	1.10	Anatase
TiO2	1.96	Rutile

Under these conditions, iron was effectively transferred from the oxide matrix into a metallic phase, forming pig iron or cast iron depending on carbon activity and cooling conditions. Across the investigated temperature range, iron extraction into the metal phase consistently exceeded approximately 88%, with maximum values above 90% achieved at around 1450 °C. The resulting metal typically contained about 94 wt% Fe and approximately 5 wt% C (Table 3), corresponding to hypereutectic white cast iron, and exhibited microstructures composed primarily of ledeburite and graphite, with no significant non-metallic inclusions detected (Vasyunina et al. 2020; Vasyunina et al. 2023; Vasyunina et al. 2024). These results are consistent with reported iron recoveries in other carbothermic smelting studies of red mud, confirming that reduction smelting is a robust route for iron separation when sufficient temperature and reductant availability are ensured.

Table 3. Chemical composition of obtained cast iron

Component	Fe	C	Si	P	S	Mn
Content, % (mass.)	93,8	4,99	0,01	0,33	0,03	0,37

Table 4. Slag chemical composition

Processing method of red mud	Content of the elements, % (mass.)							
	Fe	Al	Ti	C	S	Na	Ca	Si
Initial red mud	28.15	8.35	2.36	1.20	0.71	2.12	6.29	7.12
Reduction smelting without soda	0.22	13.71	2.94	1.97	0.51	0.26	28.70	10.67
Reduction smelting with soda	0.16	13.54	2.95	1.41	0.51	1.82	27.64	11.23

The behavior of the slag phase was found to be strongly influenced by flux composition, particularly by the presence or absence of soda. In the absence of soda, slags were highly viscous and mechanically hard, which complicated tapping and subsequent comminution. The addition of soda lowered the effective liquidus temperature and reduced slag viscosity, thereby improving metal–slag separation and slag handling. At the same time, soda addition altered the distribution of sodium during smelting, as discussed below. In all cases, residual iron contents in the slag were low, typically below 0.2 wt%, indicating near-complete transfer of iron to the metallic phase and confirming the suitability of the slag as a feedstock for further processing (Table 4).

Following iron removal, the Fe-depleted slags were subjected to alumina recovery via an alkaline sintering–leaching route. In this stage, the slags were mixed with sodium carbonate and lime and sintered at elevated temperature to promote the formation of leachable calcium and sodium aluminates. Subsequent leaching with sodium hydroxide solution enabled dissolution of aluminium into the liquid phase, while silica, titanium-bearing phases and residual iron oxides largely remained in the solid residue. Using this approach, alumina extraction levels approaching 70% were achieved, with typical reagent consumptions on the order of 300 kg Na_2CO_3, 300 kg CaO and 280 kg NaOH per tonne of slag (Vasyunina et al. 2020; Vasyunina et al. 2024). These values are comparable to those reported in other studies based on Pedersen-type or sinter–leach concepts, although they also highlight the substantial reagent intensity inherent to alkaline alumina recovery from complex oxide slags (Borra et al. 2016; Ekström et al. 2021).

A key observation arising from the combined processing route concerns the behavior of sodium during reduction smelting. Mass balance considerations and slag analyses indicate that only a minor fraction of sodium remains in the slag after smelting, while a significant portion is transferred to sublimates and fine dust. This alkali volatilization contributes to partial dealkalization of the slag, which is beneficial for downstream leaching, but simultaneously introduces challenges related to off-gas treatment, alkali capture and equipment corrosion. Similar alkali behavior has been reported in other high-temperature processing studies of red mud and alkali-rich residues, underscoring the need for closed-loop sodium recovery and robust gas-cleaning systems in any scaled implementation (Zinoveev et al. 2018; Wang et al. 2018).

The combined pyrometallurgical–hydrometallurgical flowsheet developed by the authors demonstrates that sequential iron recovery and alumina extraction from red mud is technically feasible at laboratory scale and can achieve high iron recoveries while generating an alumina-rich intermediate suitable for further processing. At the same time, the results highlight key scale-up challenges, particularly with respect to energy demand, reagent consumption and alkali management. These findings align with broader trends in the literature, which increasingly emphasize integrated, multi-step processing routes as the most promising pathway toward meaningful red mud valorization.

5. Case Study II – Red Mud as Functional Filler in Release Coatings

In parallel with metal-recovery-focused research, the authors have investigated an alternative valorization route in which red mud is used directly as a functional component in mould release coatings for metal casting. This approach addresses a different but complementary challenge in red mud utilization: the need for economically viable applications that can absorb residue streams without requiring extensive chemical transformation or high energy input. Unlike bulk construction applications, release coatings represent a technically demanding niche where material performance, stability and cost must be carefully balanced.

The developed coating systems were formulated using red mud as a partial replacement for conventional mineral fillers. The residue was incorporated into water-based coating suspensions together with binders and additives typical for industrial mould release formulations. Coatings of metal moulds are complex, and coating wear and degradation can strongly influence the interfacial heat transfer conditions and casting surface quality, motivating systematic evaluation of coating rheology, stability and durability (Antunes et al. 2019; Roorda 2021). Standard laboratory methods were therefore employed to assess coating density, nominal viscosity, sedimentation stability, surface roughness and abrasion resistance, providing a consistent basis for comparing red mud loading levels (Yagodin et al. 2022).

The results demonstrate that red mud can be successfully incorporated into release coatings at moderate loadings without compromising functional properties. At red mud contents up to approximately 10 wt%, coatings exhibited densities in the range of about 1016–1123 kg m^{-3}, nominal viscosities on the order of 10–11 mPa·s and sedimentation stability of around 96% after 24 hours. These values are comparable to those of commercial mould release coatings, indicating that red mud can function effectively as a mineral filler within this composition window. Surface roughness and abrasion resistance remained within acceptable limits, confirming that the presence of iron oxides and aluminosilicate phases did not adversely affect coating integrity at these loadings.

At higher red mud contents, however, a clear deterioration in suspension stability was observed. Increasing the residue content beyond approximately 10 wt% led to a progressive reduction in sedimentation stability, dropping to around 93% at 17 wt% and to below 40% at 20 wt% red mud loading. This behavior is attributed to particle aggregation and increased solid–solid interactions within the suspension, which promote settling and disrupt the uniform distribution of components. These findings highlight the importance of optimizing particle interactions and rheology when incorporating fine-grained industrial residues into functional coatings, particularly when the residue exhibits high surface area and complex surface chemistry (Antunes et al. 2019; Roorda 2021).

From a broader perspective, the use of red mud in mould release coatings occupies an intermediate position between low-value bulk applications and resource-intensive metal recovery routes. Unlike cement or brick production, which can consume large quantities of residue but generate limited added value, coating applications require only modest amounts of material but offer higher value per unit mass and fewer processing steps. Compared with geopolymers or mineral wool, which often require high-temperature treatment or stringent compositional control, the coating route benefits from relatively simple processing and compatibility with existing industrial formulations. At the same time, the volume of red mud that can be absorbed by coating applications is inherently limited, making this route unsuitable as a standalone solution for large-scale residue management.

Nevertheless, when viewed as part of an integrated valorization strategy, the coating-based utilization of red mud offers clear advantages. It enables direct use of the residue with minimal pre-treatment, provides a pathway for partial substitution of imported or virgin raw materials, and aligns with circular-economy principles by embedding industrial waste into functional products. In this context, the coating application developed by the authors complements metal-recovery-focused flowsheets by offering a practical outlet for selected residue streams or processing by-products, thereby contributing to a diversified and flexible approach to red mud utilization.

6. Challenges, Scale-Up Considerations and Research Priorities

The combined analysis of recent laboratory-scale literature and the two case studies presented in this work highlights a set of recurring technological constraints that must be addressed before red mud valorization can move beyond isolated demonstrations. One of the clearest conclusions concerns iron recovery targets and residual iron levels in slag. Both the literature and the authors' experiments indicate that effective downstream processing requires near-complete iron removal, typically corresponding to residual iron contents in slag below approximately 0.5 wt%, and preferably below 0.2 wt%. At these levels, slag reactivity toward alkaline or acidic leaching increases markedly, and issues related to iron co-dissolution, gel formation or excessive reagent consumption are substantially reduced. The key challenge is therefore not whether iron can be reduced and separated—which is well established—but how consistently such low residual iron levels can be achieved across variable red mud compositions while maintaining acceptable energy input and operational stability.

Closely linked to iron removal is the design of slag chemistry for subsequent aluminium and titanium recovery. The case study presented here confirms trends observed in Pedersen-type and calcium-aluminate-based approaches: slag mineralogy, rather than bulk composition alone, controls leachability. Calcium-rich slags dominated by aluminates offer higher aluminium extraction potential, whereas excessive silica or perovskite formation can immobilize aluminium and titanium. The open question is not the feasibility of slag engineering, but rather how narrowly slag composition must be controlled under industrial conditions and whether such control is compatible with fluctuating red mud feed chemistry. Addressing this requires systematic linking of slag phase equilibria, viscosity, and leaching kinetics.

Alkali behavior, particularly sodium volatility and redistribution, emerges as a central cross-cutting issue. In high-temperature processing routes, sodium tends to partition preferentially to dust and off-gas phases rather than remaining in the slag. While this can be advantageous for slag dealkalization, it introduces challenges related to corrosion, fouling, and alkali recovery. Similar observations have been reported in pilot-scale smelting studies in Greece and China, where alkali management proved to be one of the dominant operational constraints. The critical question is therefore not whether sodium volatilization occurs, but whether it can be transformed from a liability into a controlled recycle loop. This implies the need for integrated off-gas treatment, alkali capture, and reuse strategies, rather than viewing sodium losses as an unavoidable side effect of high-temperature processing.

An important insight from combining metal-recovery-focused routes with materials-based applications is that no single utilization pathway is likely to be sufficient on its own. The mould release coating case study illustrates that direct material use of red mud can generate higher value per unit mass than bulk construction applications, while requiring minimal processing. However, such applications can only absorb limited quantities of residue. Conversely, metal recovery routes can process large volumes but demand high energy and reagent inputs. The design principle that emerges is therefore one of complementarity, in which integrated flowsheets combine bulk metal recovery with targeted material applications to absorb specific streams or by-products. The challenge is to define how these routes can be practically coupled and whether such coupling improves overall process economics and robustness.

From a scale-up perspective, energy and reagent intensity remain major barriers. Pyrometallurgical routes benefit from metallurgical robustness and clean phase separation but are inherently energy-intensive, whereas hydrometallurgical routes reduce temperature demands at the expense of reagent consumption and complex effluent management. Integration with existing alumina refineries or steel plants—through shared energy infrastructure, reductant sources, or waste heat utilization—appears essential to reduce overall process intensity. Pilot-scale experience suggests that stand-alone red mud plants are unlikely to be competitive unless embedded within larger industrial systems, yet few studies explicitly quantify these integration benefits.

Another underexplored area concerns the standardization of testing and evaluation methods. Reported values for coating performance, leaching efficiency, residue stability, or abrasion resistance often rely on laboratory-specific protocols, making cross-comparison difficult. Without standardized testing frameworks—particularly for materials applications and long-term product stability—it remains challenging to assess whether reported laboratory successes translate into industrially relevant performance. Establishing such standards would significantly improve the comparability and credibility of red mud utilization studies.

Finally, despite extensive experimental work, data gaps remain in techno-economic analysis, life-cycle assessment, and long-term performance evaluation. Many laboratory studies, including those reviewed here, demonstrate technical feasibility but stop short of quantifying cost drivers, environmental trade-offs, or product durability. The key research question is therefore no longer "can metals be recovered from red mud?" but rather "under what conditions does recovery deliver net environmental and economic benefit compared to existing disposal or low-value use?". Addressing this requires moving beyond isolated experiments toward integrated assessments that combine process performance, material flows, energy use, and environmental impact over realistic operating lifetimes.

Conclusion

This review has examined recent laboratory-scale approaches to red mud utilization, integrating advances in metal-recovery technologies with emerging material applications. The analysis confirms that red mud should be considered a complex secondary resource rather than a waste, while also demonstrating that its valorization is fundamentally constrained by mineralogical heterogeneity, alkali content, and the high energy or reagent intensity of many processing routes.

Across the reviewed literature, effective utilization consistently relies on early separation or transformation of iron, careful control of phase chemistry, and deliberate management of alkalis. High-temperature routes provide robust iron recovery and clean phase separation but introduce challenges related to energy demand and alkali volatilization, whereas hydrometallurgical approaches offer greater selectivity at lower temperatures but are often limited by reagent consumption and secondary residue generation. Material-based applications, while unable to absorb large residue volumes, can provide higher-value outlets when integrated into broader utilization strategies.

The findings indicate that no single processing concept can address red mud utilization at scale. Instead, progress depends on integrated, site-specific flowsheets that combine complementary processing routes, are compatible with existing industrial infrastructure, and are evaluated using standardized performance metrics. Future research priorities lie in clarifying alkali management strategies, linking laboratory results to techno-economic and environmental assessments, and establishing long-term stability and performance criteria for red mud–derived products. These steps are essential to transition red mud utilization from laboratory feasibility toward industrial relevance.

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