

Review

Advancing Iron Recovery from Red Mud: Green Pathways, Synergistic Valorization, and High-Value Total Component Utilization

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Abstract

Facing the severe environmental challenge of massive red mud (RM) stockpiles, iron extraction research is accelerating from traditional pyrometallurgy and other conventional processes toward green low-carbon, multi-source synergistic, and total-component high-value utilization approaches—a transition that continues to evolve. This review systematically examines three frontiers: green reduction technologies, synergistic valorization via waste-treating-waste, and integrated cascading strategies for total-component high-value utilization. Evaluation focuses on the principles, advantages, and challenges of biomass reduction, hydrogen metallurgy, selective flocculation, advanced heating techniques, co-processing with other solid wastes, and multi-metal cascading extraction. Evidence suggests that future RM iron extraction technology lies in establishing cross-industry circular economy networks, transforming RM from a singular waste into a resource hub linking aluminum, steel, and construction industries to maximize environmental and economic benefits.

Keywords: iron recovery from red mud; low-carbon reduction technology; waste-treat-waste; cascade utilization

1. Introduction

Red mud (RM), the strongly alkaline bauxite residue inevitably generated as a by-product of the Bayer process for alumina production, constitutes one of the most severe and intractable environmental challenges confronting the global metallurgical sector [1–4]. Cumulative global RM stockpiles have exceeded 4 billion tons, and annual RM generation continues to increase with the growth of global alumina production. According to recent statistics, global alumina production increased from approximately 142 million tons in 2024 to about 150 million tons in 2025; based on a typical generation coefficient of 1.0–1.5 t RM per ton of alumina, the annual global RM generation remains close to 200 million tons [5,6]. This challenge is particularly pronounced in China, which dominates global alumina production. In 2024, China generated approximately 115 million tons of RM, and although the comprehensive utilization rate has increased to about 12%, the pressure for large-scale valorization remains substantial relative to the massive annual generation



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volume [7–9]. Beyond occupying valuable land resources, the massive accumulation of this highly alkaline waste, laden with potentially toxic elements, poses persistent and severe threats to soil quality, groundwater systems, and adjacent ecosystems [10–13].

From a resource circularity perspective, however, RM is not a worthless waste but rather an undeveloped “urban mine” awaiting exploitation. It is rich in multiple valuable components, most notably iron, with concentrations as high as 30–60%, far exceeding the mining grades of many lean iron ores and positioning RM as a highly promising iron resource [14–16]. In addition, RM contains co-existing aluminum, titanium, sodium, and critical strategic metals such as scandium, gallium, and rare earth elements, demonstrating extremely high comprehensive recovery value [17–22]. Consequently, developing safe and efficient strategies to recover these resources, with iron as the core value element, has become a critical scientific imperative for advancing sustainable development of the aluminum industry, resolving environmental risks, and ensuring national resource security.

Historically, efforts to extract iron from RM have primarily relied on conventional technical pathways [23–25]. Physical separation methods (such as magnetic and gravity separation), although operationally simple, struggle with the residue’s fine particle size and complex mineral embedment, generally yielding low recovery rates and inferior concentrate grades. Similarly, hydrometallurgical routes (acid leaching), while achieving high iron extraction rates, face prohibitive acid consumption due to the residue’s inherent alkalinity, and the complex subsequent waste liquid treatment risks secondary pollution. Meanwhile, traditional pyrometallurgical approaches (e.g., high-temperature smelting and coal-based reduction roasting), while capable of producing high-quality iron products, are universally plagued by high energy consumption, substantial carbon emissions, and severe equipment corrosion, rendering them incompatible with increasingly stringent environmental regulations and carbon neutrality goals [10,15,26]. These inherent defects severely constrain the large-scale industrial application of existing technologies.

Faced with increasingly severe environmental pressures and resource constraints, the research approach for RM treatment is undergoing a profound paradigm shift—transitioning from the past “waste management” model that solely pursued harmless disposal to a novel circular economy-oriented framework that pursues “total-component resourceization” to maximize both environmental benefits and economic value [27–29]. Around this transition, previous reviews have systematically summarized RM utilization from the perspectives of comprehensive utilization, metal resource recovery, and process chemistry, providing important references for understanding the resource attributes, major utilization pathways, and key technical bottlenecks of RM [8,9,17]. However, under the increasing demand for green low-carbon development and solid-waste circularity, RM iron recovery is no longer limited to the efficient separation and enrichment of iron. Instead, it has been further extended to broader system-level issues, including low-carbon process construction, multi-source solid-waste synergistic conversion, total-component value release, and integrated environmental–economic assessment. Therefore, it is necessary to revisit the development trajectory of RM iron recovery technologies and establish a more integrated analytical framework from the perspectives of greening, synergistic utilization, and high-value valorization.

Against this background, this review aims to move beyond the framework of traditional technical classifications and systematically review recent breakthrough developments in RM iron extraction from a novel and more forward-looking perspective. Starting from three frontier themes: “green low-carbon reduction technologies”, “synergistic valorization and ‘waste-treating-waste’ approaches”, and “integrated cascading strategies for total-component high-value utilization”, the review will deeply analyze the principles, achievements, and challenges of key technologies to reveal the latest dynamics and fu-

ture directions of RM iron recovery research. Specifically, biomass reduction, hydrogen metallurgy, selective flocculation, microwave heating, and flash Joule heating are mainly directed toward the green and low-carbon transformation of RM iron recovery, promoting iron phase conversion and enrichment through low-carbon reduction, selective separation, or process intensification. Multi-source solid-waste co-processing emphasizes the use of reducing or mineralizing components from other wastes to realize the “waste-treating-waste” concept. Total-component cascading utilization further targets the sequential recovery of valuable components such as Fe, Al, Ti, and Sc, as well as the high-value utilization of final residues. To improve the comparability and systematic evaluation of different technical routes, this review further summarizes the key feedstock characteristics and process parameters of representative technologies to clarify their applicable boundaries. Meanwhile, life cycle assessment (LCA) and techno-economic analysis (TEA) perspectives are introduced to complement traditional iron grade and recovery indicators, particularly in assessing environmental impacts, economic feasibility, and industrialization potential. Overall, this review provides a scientific reference for constructing cross-industry solid waste valorization networks and promoting the green transformation of related industries.

It should be noted that all key performance metrics cited in this review (such as grade and recovery) are based on the specific experimental conditions reported in the original literature. However, due to variations in feedstock characteristics (e.g., total Fe content and particle size distribution of red mud) and process parameters across different studies, the applicable boundaries of these technical approaches should be fully considered when comparing technologies. Therefore, this review has systematically compiled the feedstock characteristics and key operating parameters (such as reduction temperature, time, and reagent ratios) of representative studies. Meanwhile, based on the characteristics of major components such as Fe, Al, Si, Ca and particle size (PS) in RM, the feedstock characteristics of the RM used in the relevant processes are compiled to facilitate the illustration of the applicable boundaries of different processes. In addition, to establish a consistent comparison basis, “iron grade” in the text refers to the mass percentage of total iron (TFe) in the magnetic concentrate, and “iron recovery” refers to the ratio of Fe mass in the magnetic concentrate to the total Fe mass in the reduction roasting product.

2. Green Low-Carbon Reduction Technologies

In light of stringent global carbon neutrality targets, the high energy consumption and substantial carbon emissions inherent in traditional fossil fuel-dependent pyrometallurgy have emerged as the core bottlenecks restricting iron recovery from RM. Consequently, in recent years, research attention has increasingly shifted toward the development of cleaner and more efficient green low-carbon reduction technologies [30–33]. This innovation wave primarily unfolds along the following directions: substituting biomass for fossil energy, exploring hydrogen metallurgy pathways, employing selective flocculation techniques, and intensifying reaction processes through advanced technologies such as microwave heating and flash Joule heating (Figure 1). These frontier explorations aim not only to reduce the carbon footprint of the processes, but also to improve the energy efficiency and economic viability, thereby opening up a new technical paradigm for the large-scale valorization of RM.

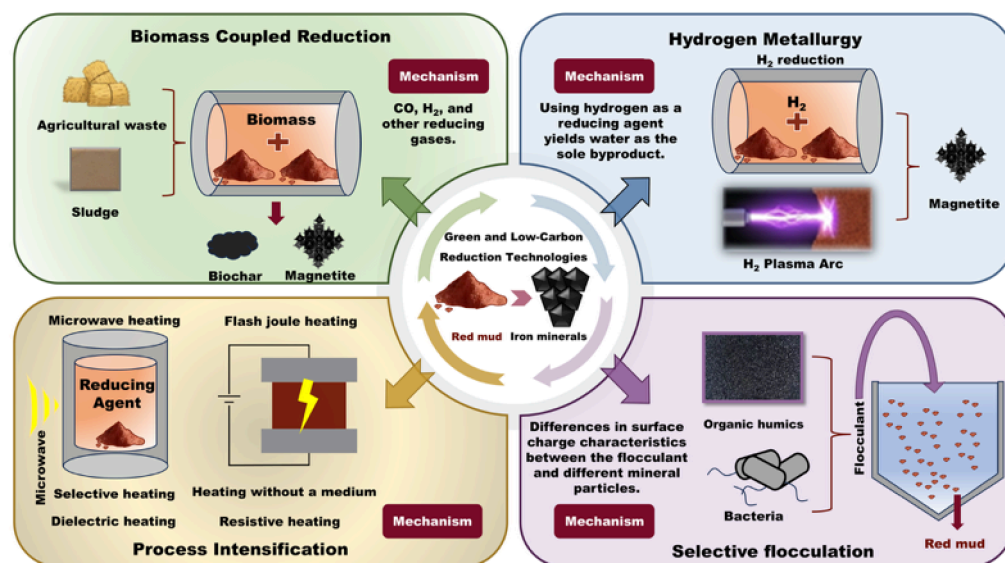


Figure 1. Framework of green and low-carbon reduction technologies, including biomass reduction, hydrogen metallurgy, selective flocculation, microwave heating, and flash Joule heating pathways.

2.1. Biomass Reduction

Biomass, including agricultural biomass (e.g., straw, rice husks, corn stover), forestry biomass (e.g., sawdust, bark, wood chips), and aquatic biomass (e.g., algae, water hyacinth), is increasingly recognized as an ideal alternative to conventional coal-based reductants in iron recovery from RM, owing to its abundant reserves, low cost, and renewability. In particular, its high reactivity and low-temperature reduction characteristics make it a promising sustainable option [34,35]. Biomass can be utilized for iron recovery through two primary routes: direct use as a raw feedstock, or indirect use after conversion to biochar. Agricultural and aquatic biomass, characterized by high proportions of cellulose and hemicellulose, facilitate rapid pyrolysis and the release of reducing gases at lower temperatures, enabling the gradual reduction of iron oxides. In contrast, forestry biomass is rich in lignin; the biochar produced from its pyrolysis, with a higher fixed carbon content and lower volatiles, can directly participate in reduction reactions at elevated temperatures while also generating CO through gasification, thereby further enhancing the reducing atmosphere and providing more stable and sustained reduction performance. These compositional features endow biomass with distinct advantages in terms of high reactivity and low-temperature reduction capability, making it a highly promising candidate for sustainable metallurgical processes [36–39].

The current literature indicates that agricultural residues (e.g., straw, rice husks, sawdust) undergo pyrolysis at relatively low temperatures (200–400 °C), releasing reducing gases rich in CO, H₂, and CH₄. These pyrolysis products can effectively convert weakly magnetic hematite (Fe₂O₃) and goethite (FeO(OH)) in RM into strongly magnetic magnetite (Fe₃O₄) at temperatures (typically 550–650 °C) far lower than those required for conventional coal-based reduction (900–1100 °C), thereby facilitating subsequent magnetic separation [40,41]. The practical viability of biomass-assisted reduction has been substantiated by several empirical studies, demonstrating that its low-temperature, high-efficiency advantages are progressively transitioning from theory to practice. For instance, Aslam et al. used wheat straw and other biomass as reductants through magnetization roasting, achieving an efficient and cost-effective (0.81 USD/kg Fe) iron extraction strategy for low-iron RM (TFe 28.69%), with 77% concentrate grade and 72% recovery [42]. In magnetization roasting processes, biochar (e.g., from rice husks or banana peels) typically exhibits recovery rates (80.76–88.22%) generally higher than those of raw biomass precursors

(66.10–72.93%) [37]. In addition, Xu et al. achieved an iron recovery rate of up to 90.92% using corn stover in a biomass-reduction alkaline roasting process for synergistic iron-aluminum recovery [43]. Similarly, biochar derived from algae such as *Chlorella* sp. and *Sargassum* sp. has been demonstrated to enable the efficient conversion of hematite to metallic iron at elevated temperatures, thereby further expanding the feedstock spectrum for biomass in RM iron extraction [38,39]. The role of biomass in RM iron extraction may extend far beyond preliminary reduction at low-to-moderate temperatures. De Souza et al. proposed a sophisticated stepwise mechanism for the synergistic thermochemical conversion of RM-biomass mixtures: first, biomass pyrolysis and RM magnetization occur below 650 °C; subsequently, CO₂ evolved from carbonate decomposition in RM gasifies the biomass char, enhancing the reducing atmosphere; finally, at higher temperatures (775–950 °C), the char and gasification-produced CO drive the deep reduction of magnetite to metallic iron [6].

Based on the above evidence, biomass reduction converts iron oxides to magnetite or metallic iron at temperatures lower than traditional coal-based reduction. Regardless of whether the intergrowth relationship between iron minerals and gangue in RM is simple or complex, biomass reduction can, through mild reduction conditions, promote the layer-by-layer transformation of hematite to magnetite and induce iron grain growth, thereby effectively overcoming the separation barriers posed by physical encapsulation. However, the practical application of biomass-based iron extraction technology still faces challenges: on the one hand, the dynamic variation of pyrolytic gases and the formation of tar by-products complicate the control of indirect reduction systems; on the other hand, the high volatile content and low fixed carbon content of certain types of biomass may fail to provide a sustained and sufficient reducing atmosphere without process optimization (e.g., alkali-roasting coupling), thereby hindering the deep reduction and high-grade enrichment of iron. Overcoming these challenges is crucial for its industrial implementation [37,42,43].

2.2. Hydrogen Metallurgy

Hydrogen metallurgy, which yields water as its primary by-product, fundamentally eliminates carbon emissions at the source. Recent advancements have significantly deepened the field's understanding of hydrogen-based reduction mechanisms, process innovation, and system optimization. As a low-carbon pathway characterized by fast reaction kinetics and environmentally friendly by-products, hydrogen reduction, with its core in the multi-step sequential reduction of iron oxides by hydrogen for iron conversion and enrichment, has been progressively applied in the direct reduction of iron oxides in RM [44]. In terms of technical pathways, hydrogen metallurgy has evolved into two distinct routes: conventional molecular hydrogen thermal reduction and plasma/radical-enhanced reduction. Conventional thermal reduction employs molecular H₂ as the reductant, operating in solid-state or gas–solid fluidized conditions, but is constrained by the adsorption-dissociation efficiency of H₂ molecules and solid-state diffusion limitations [45]. Pilla et al., utilizing response surface methodology (RSM), determined that reduction at 600 °C for 120 min boosted iron recovery to 74.4% with a grade of 63.6% [46]. In contrast, hydrogen gas can be activated by plasma to generate highly reactive hydrogen radicals (H·), which significantly lower the activation energy, enabling more efficient reduction of iron oxides [47,48]. Liang et al. employed plasma-enhanced chemical vapor reduction at 900 °C, utilizing in situ generated hydrogen radicals to achieve an iron recovery of 88.1% and a grade of 71%. Crucially, this process also neutralized the residue (pH near neutral), delivering dual benefits of metal extraction and waste detoxification [49]. Notably, microwave-driven atmospheric hydrogen plasma can reduce hematite in RM at even lower temperatures (280–500 °C). Here, the intervention of H· reduces the apparent activation energy to approximately 50 kJ/mol,

nearly half that of conventional thermal hydrogen reduction (92 kJ/mol), effectively circumventing thermodynamic constraints. Furthermore, high-energy electrons and ions within the plasma facilitate the cleavage of Fe-O bonds, enabling a stepwise transformation from hematite to magnetite (Fe_3O_4) and metallic iron (Fe), providing a novel pathway for low-temperature, high-efficiency extraction [50].

It must be emphasized that the “green” credentials of hydrogen metallurgy are highly dependent on the hydrogen source: only when using green hydrogen (from renewable electrolysis) and green electricity does it possess near-zero carbon emission potential. Current laboratory studies predominantly employ gray hydrogen (from fossil fuel reforming), and their significance lies primarily in validating technical feasibility rather than environmental benefits. Despite hydrogen metallurgy demonstrating promising low-carbon potential in RM iron extraction and holding prospects for coupling with the extraction of other valuable elements (e.g., Al, Na, Ti) to achieve total component valorization, its industrial application still faces multiple engineering and economic constraints, including: (i) limited plasma action zones, leading to difficulties in reactor scaling and continuous feeding; (ii) risks of material hydrogen embrittlement and alkali metal corrosion in high-temperature, high-activity hydrogen environments; (iii) stringent requirements for tail gas dehydration, hydrogen purification and reintroduction, and waste heat recovery to maintain system energy efficiency; and (iv) the high costs of green hydrogen production and energy-intensive reaction processes remaining key bottlenecks, restricting large-scale deployment. Future development needs to rely on cross-scale validation platforms, focusing on advancing multi-physics reactor design, hydrogen-resistant material development, gas circulation separation systems, and coupling with renewable energy sources to enhance the economic viability, environmental benefits, and industrial feasibility of hydrogen metallurgy in RM valorization [46,49].

2.3. Selective Flocculation

Selective flocculation offers a milder, physical separation alternative to energy-intensive thermal and chemical processes. This technique operates by adding flocculants that selectively adsorb onto iron minerals, causing the iron mineral particles in RM to preferentially flocculate and settle from the suspension, while gangue minerals such as aluminum and silicon remain dispersed. This enables efficient iron enrichment, making the method particularly suitable for processing fine-grained materials like RM [51]. Characterized by low energy consumption, environmental compatibility, and the biodegradability of reagents, this technique is gaining traction as a sustainable substitute for traditional iron extraction modes that rely on high temperatures and chemical reactions.

Huang et al. first demonstrated the feasibility of using organic humics, a natural mixture of macromolecular compounds, as a flocculant for the selective flocculation of iron minerals in alkaline slurry via an adsorption bridging mechanism, utilizing functional groups such as phenolic hydroxyl and carboxyl on their molecular chains. By optimizing process parameters, they achieved an iron concentrate grade of $61.12 \pm 0.10\%$ and a recovery rate of $86.25 \pm 1.31\%$ without roasting or strong acid treatment, attaining a separation index of 0.69 ± 0.02 , thereby providing a feasible pathway for the mild and efficient recovery of iron resources from RM [52]. In addition, researchers have directly employed bacteria, specifically *Bacillus nitratreducens* strain SKC/L-2, as a bioflocculant for RM iron extraction. This strain secretes extracellular polymeric substances (EPSs) and organic acids that act synergistically to enhance selective adsorption onto iron minerals while also showing potential as a pH regulator. Jeremy et al. found that by pre-adjusting the bioflocculant to an acidic pH (pH = 3), the resulting iron concentrate grade exceeded 60% with a recovery of 69.34%. It is noteworthy that this strategy of “reagent pH adjustment” reduced the acid

consumption by approximately 281-fold compared to neutralizing the entire residue slurry, significantly improving both the economic feasibility and environmental sustainability [53].

Despite its promise, transitioning selective flocculation from the laboratory to industrial application faces multiple hurdles. First, the screening and cultivation of highly efficient, specific strains remain insufficient; current research is limited to a few bacterial species, necessitating broader screening and genetic engineering for strain improvement. Second, the complex matrix of RM (high alkalinity, ionic strength, and multi-mineral coexistence) poses a severe test for microbial activity and flocculant stability. Chemical flocculants (such as organic humics) can maintain selectivity within a certain alkalinity range through chemical bonding with iron mineral surfaces, whereas bioflocculants that rely on EPSs are prone to conformational changes and deactivation under high ionic strength conditions, typically requiring localized acidification pretreatment to improve applicability. Both systems are limited by low pulp densities, and industrial scale-up faces challenges of high water consumption and large equipment footprints. Moreover, flocculant regeneration and recycling technologies are not yet mature, and residual organic components may cause secondary pollution such as elevated BOD/COD. Therefore, future research should focus on enhancing stability under high-alkali, high-salt conditions, developing reagent circulation systems, and controlling organic residues in tailings. Nevertheless, as a disruptive green separation technology, selective flocculation provides a novel solution for processing low-grade, difficult-to-separate residues, aligning perfectly with urban demands for energy conservation and sustainable development.

2.4. Process Intensification

Intensifying the reaction process itself is equally critical for achieving low-carbon objectives. Microwave heating and flash Joule heating (FJH), as two efficient process-intensification technologies, demonstrate significant technical advantages over conventional reduction roasting for iron recovery from RM, while also showing transferable industrial foundations. Microwave heating leverages “selective heating” and “volumetric heating” mechanisms to preferentially target carbonaceous reductants and polar minerals (such as iron oxides) within the RM, resulting in rapid, uniform internal heating that dramatically accelerates reaction kinetics [54,55]. For instance, Huang et al. reported that microwave-assisted reduction roasting at 900 °C for just 10 min achieved an iron recovery rate of 92.1% in subsequent acid leaching, far surpassing the efficiency of traditional muffle furnace heating [56].

The principle of flash Joule heating is to apply high-power, short-duration electrical pulses to the target iron minerals to generate heat directly within the material, bypassing the need for external heating media. This approach offers a wide temperature control range, ultra-fast processing, high energy efficiency, and reduced carbon emissions [57]. Liu et al. pioneered a combined FJH and chlorination process (FJH-Cl₂) capable of removing over 96% of iron from RM as volatile FeCl₃ within one minute. The volatile product contained 75–88% iron, while approximately 99% of aluminum was retained in the residue, highlighting the dual potential for iron recovery and aluminum purification [58]. FJH-Cl₂ exploits the large differences in boiling points of different metal chlorides; under ultra-fast heating in a non-equilibrium state, iron is preferentially chlorinated and volatilized at approximately 1000 °C. Despite the remarkable performance of the FJH-Cl₂ process, its industrialization is highly dependent on stringent control of the extreme chlorine-containing system. The system must thoroughly overcome core barriers such as high-temperature chlorine corrosion resistance, interception of trace halogenated organic by-products, and closed-loop chlorine gas circulation, and truthfully incorporate the derived safety and exhaust gas treatment costs into the techno-economic assessment boundaries. If coupled with renewable energy

electricity and a chlorine gas recycling system, the process is expected to achieve near-zero carbon emissions.

In the field of iron recovery from RM, there is an evolution from traditional heating methods characterized by high energy consumption and low efficiency toward novel electric-based heating modes that are efficient, energy-saving, and selective. The advantage of microwave heating lies in its selective internal heating characteristic, which can significantly improve the energy utilization efficiency and reaction rates, positioning it as one of the frontier technologies relatively close to practical application. Flash Joule heating, on the other hand, represents a more cutting-edge exploratory direction; its ultra-fast speed and extreme non-equilibrium reaction conditions offer disruptive possibilities for the efficient, low-carbon valorization of RM. Although both technologies have achieved pilot-scale and larger industrial validation in fields such as iron ore processing and graphene synthesis, their application in RM iron extraction remains at the laboratory research stage.

3. Synergistic Valorization and the “Waste-Treating-Waste” Paradigm

As the principles of the circular economy become deeply entrenched in industrial practice, the scope of research on RM iron extraction has expanded beyond single-stream waste management to encompass synergistic co-disposal with other industrial solid wastes. This approach aims to leverage the complementary physicochemical properties of different waste components to achieve a resource valorization effect where the whole is greater than the sum of its parts (“1 + 1 > 2”). This emerging “waste-treating-waste” philosophy not only simultaneously addresses the stockpiling challenges of multiple waste streams, but also optimizes reaction processes, enhances product value, and reduces the overall treatment costs through synergistic interactions. It represents a critical link in building a cross-industry solid waste recycling system. Currently, related studies mainly focus on the co-utilization of RM with organic solid wastes, phosphogypsum (PG), other iron-bearing industrial residues, and coal-based solid wastes, demonstrating broad application prospects (Figure 2).

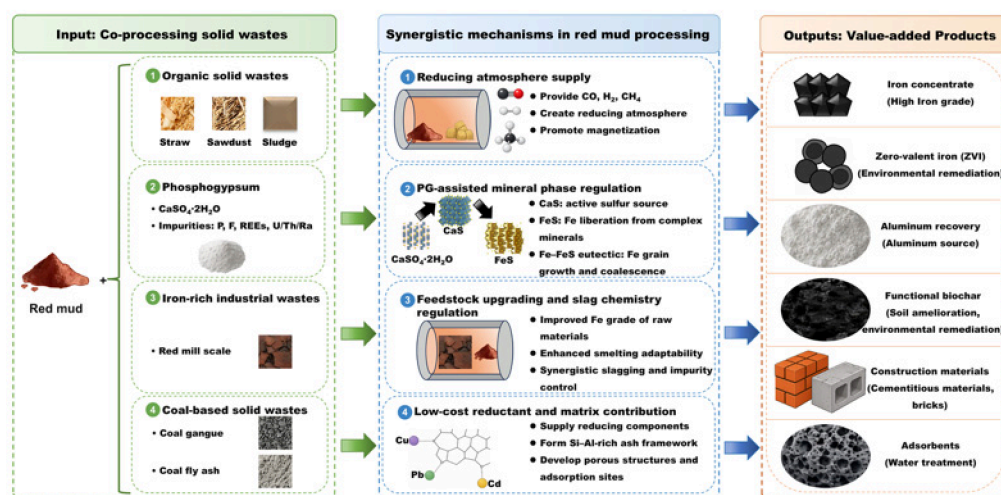


Figure 2. Waste-control-by-waste valorization mechanisms for the synergistic resource utilization of red mud with multi-source solid wastes, including organic solid wastes, phosphogypsum, iron-rich industrial wastes, and coal-based solid wastes.

3.1. Organic Solid Wastes

Efficient valorization of RM hinges on the recovery of its iron content. While traditional pyrometallurgy is effective, it is burdened by high energy consumption and carbon emissions [59–61]. Concurrently, vast quantities of organic solid wastes, such as agricul-

tural straw and sludge, are generated annually. Their thermochemical conversion (e.g., gasification, pyrolysis) produces abundant reducing agents (CO , H_2 , CH_4) and biochar. This presents a unique opportunity for synergy: utilizing organic wastes as clean reductants to efficiently reduce iron oxides in RM while simultaneously disposing of the organic waste, and producing high-value functional materials, truly embodying the concept of “synergistic valorization through waste-treating-waste” [62,63].

Recent advances have elucidated the transformation mechanisms and value-added potential of this synergy. De Souza et al. first systematically proposed the “Simultaneous Red Mud Reduction and Biomass Gasification” (SRG) pathway, validating its feasibility for preparing zero-valent iron (ZVI), thereby offering a novel framework for integrating RM reduction with biomass energy conversion [6]. Similarly, Liu et al. conducted an in-depth investigation into the optimal conditions and application potential of ZVI materials prepared via the pyrolysis-reduction of RM with various biomass sources [64]. Crucially, the role of organic waste in this synergistic system extends beyond merely providing reducing gases; it not only facilitates reduction but also enables the realization of additional material value conversion. Wang et al. explored a coupling process of biomass reduction and high-value-added material preparation, synergistically producing high-performance biochar while utilizing biomass to reduce RM. The CO_2 and H_2O released during the RM reduction process served as ideal in situ activating agents for the biochar, significantly enhancing its specific surface area (up to $2179.73 \text{ m}^2/\text{g}$). This inherent coupling relationship constructs a highly efficient utilization system for carbon and hydrogen elements, forming an integrated “waste-energy-material” high-value transformation mode, which provides a crucial pathway for enhancing the overall economic and environmental benefits of the process [65]. Furthermore, the synergistic value of organic solid wastes can be further extended to the field of hazardous waste valorization. Research has found that using RM and steel slag as catalysts can lower the activation energy for the catalytic pyrolysis of oily sludge (a type of hazardous organic solid waste), accelerating petroleum hydrocarbon degradation to produce high-quality oil and hydrogen-rich gas, thereby achieving the dual goals of solid waste valorization and clean energy conversion [66]. Similarly, the present research group has found that water treatment plant activated sludge can serve as an effective organic reductant in RM co-reduction systems, achieving relatively high iron recovery rates and good iron concentrate grades under suitable conditions, further demonstrating that bulk organic solid wastes have good application potential in synergistic utilization for RM iron extraction.

While the potential of co-processing RM with organic wastes is evident, most current studies remain at the laboratory scale. Future efforts must focus on large-scale experimental verification, specifically addressing engineering challenges related to heat and mass transfer efficiency in mixed feedstocks. Given the significant variability in RM and organic waste compositions across different regions and processes, a systematic process parameter database should be established to quantify the potential benefits of energy saving, carbon reduction, and pollution control. Furthermore, by comparing the energy consumption and environmental performance of this synergistic technology with traditional pyrometallurgy, the critical economic and sustainability thresholds for its large-scale application can be defined.

3.2. *Phosphogypsum*

A critical impediment to iron recovery lies in the complex mineralogy of RM, where a fraction of iron is locked within chemically stable, refractory mineral phases, such as hercynite (FeAl_2O_4) and Fe-Al-Si composite phases, rather than existing as simple oxides. These phases are resistant to decomposition under conventional reduction conditions,

severely constraining liberation efficiency and recovery rates [67]. To overcome this bottleneck, Xiao et al. introduced PG to co-process with RM via a sintering–leaching–magnetic separation framework. In this system, PG serves a dual purpose: it facilitates the decomposition of iron-bearing minerals while simultaneously enhancing aluminum solubility during the leaching stage. This approach has successfully achieved the co-recovery of iron and aluminum, with specific metrics of 83.8% (Fe grade), 78% (Fe recovery), and 69% (Al recovery), validating the feasibility of incorporating PG into residue valorization under the “waste-treating-waste” concept [68].

Building on this foundation, Liu et al. systematically elucidated the dual synergistic mechanism of PG during reduction roasting. First, CaSO_4 in PG is preferentially reduced to CaS under a reducing atmosphere, promoting iron liberation from Fe–Al and Fe–Si matrices and FeS formation; subsequently, FeS forms a low-melting Fe–FeS eutectic with metallic iron, accelerating reduction and enhancing iron separation efficiency. Second, its decomposition products foster the formation of a low-melting-point Fe–FeS eutectic, which assists in the growth and coalescence of metallic iron grains, thereby significantly improving magnetic separation performance. Experimental results demonstrated that a 6% PG addition yielded an iron concentrate grade of 75.27% with a recovery of 89.88% [69]. Furthermore, Yu et al. verified the enhanced efficacy of a binary additive system comprising PG and sodium sulfate (Na_2SO_4). This combination proved superior in promoting reduction, decomposition, and grain growth, achieving an iron grade of 89.02% and a recovery of 87.46%, significantly outperforming single-additive systems [67].

Overall, PG, as an industrial solid waste with massive output, when co-processed with RM, can simultaneously promote the consumption and resource transformation of two bulk solid wastes, representing a successful practice of the “waste-treating-waste” concept with both environmental and economic benefits. It should be noted, however, that PG is not a simple $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ system. Its composition is strongly affected by the source of phosphate rock and the wet-process phosphoric acid route, and it commonly contains soluble phosphorus, fluorine, heavy metals, rare earth elements, and naturally occurring radionuclides such as U, Th, and Ra [70–72]. Therefore, in the RM–PG synergistic reduction process, in addition to iron grade and iron recovery, attention should also be paid to the migration and enrichment behavior of these rare elements, trace elements, and radionuclides. If P, S, F, or certain metallic impurities enter the magnetic concentrate or metallic iron product together with the iron phase, they may increase the difficulty of dephosphorization, desulfurization, impurity removal, and slag chemistry control in subsequent smelting, thereby affecting the quality stability of iron products. Enrichment of radionuclides may further raise concerns regarding product safety and residue utilization. Future studies should establish mass-balance relationships for key impurity elements and radionuclides, clarify their final distribution among iron products, residues, and gas/liquid phases, and evaluate the industrial applicability of this route in terms of impurity limits in iron products, leaching toxicity, and radioactivity.

3.3. Iron-Rich Industrial Wastes

Globally, not all RM is iron-rich. In fact, “iron-lean red muds” (10–30 wt% Fe_2O_3) constitute approximately 70% of global stockpiles. Due to their low iron grade and high impurity content, these residues have received comparatively less attention and pose greater processing challenges. Addressing this reality, Khanna et al. proposed a pragmatic synergistic strategy: blending iron-lean residue with iron-rich industrial waste (such as red mill scale, a by-product of steel rolling) in appropriate proportions for co-processing [73]. As sustainable development gains increasing attention, this approach represents not only

an innovative practice in resource recovery, but also an effective model for advancing the circular economy.

The advantages of co-processing iron-lean residue with iron-rich wastes are twofold. First, this directly enhances the feedstock grade and synergistically mitigates processing challenges. Although iron-lean red mud has a relatively low iron content, its iron exists primarily as hematite, exhibiting excellent potential for carbothermic reduction. Iron-rich waste, inherently acting as a high-quality secondary iron resource, significantly elevates the Fe_2O_3 content of the blended mixture from 29.3 wt% to 53.0 wt%. This effectively dilutes impurity and maintains consistent reduction behavior with the two raw materials, without introducing adverse phase transformations. Following synergistic treatment, the resulting iron-rich concentrates achieve an iron grade of 77.2–98.2 wt%, far exceeding the industrial threshold of >60% Fe for smelting feedstocks. Consequently, blending leverages synergistic effects to drastically reduce both the volume of RM processed per unit of iron produced and the corresponding smelting energy consumption. This approach not only substitutes a portion of primary iron ore to curtail the carbon footprint associated with mining, but also alleviates the ecological pressure of RM disposal at the source. Second, enabling synergistic slag engineering and impurity control. RM typically contains slag-forming components such as CaO , Al_2O_3 , and SiO_2 . In-depth investigations reveal that regulating the basicity of the mixture is crucial: when the CaO content is high, silicon is driven into the calcium aluminate slag phase, thereby producing low-silicon, high-quality ferroalloys; conversely, when CaO is insufficient, silicon reduction into the molten iron is favored, resulting in high-silicon ferroalloys [73].

As sustainable development gains increasing attention, the co-processing strategy of iron-rich wastes and iron-lean RM not only represents an innovative practice in resource recovery and reuse, but also serves as an effective model for promoting the circular economy. Future research should broaden the scope of applicability assessments to include low-grade iron-bearing wastes (such as steel slag, iron tailings), steel scrap, and other metallurgical residues. Developing formulation models based on compositional fluctuations will be key to constructing low-cost, adaptable waste co-processing networks tailored to regional industrial structures.

3.4. Coal-Based Solid Wastes

While introducing iron-rich waste addresses the deficit of iron components, the co-utilization of coal-based solid wastes, such as coal gangue and coal fly ash (CFA), specifically mitigates the high cost and energy intensity of reductants in iron recovery processes. Mechanistic studies indicate that the reducing gases (CO , H_2 , CH_4) and solid carbon generated from gangue pyrolysis are the primary drivers of iron oxide reduction [74]. Yuan et al. utilized a co-pyrolysis–magnetic separation process using coal gangue. Under optimized conditions (750 °C, 50 min, 40% coal gangue ratio), they successfully converted weakly magnetic hematite (Fe_2O_3) into strongly magnetic magnetite (Fe_3O_4), achieving an iron concentrate grade of 55.09% and a recovery of 82.73% [75]. It is noteworthy that Bai et al. utilized coal gangue as a reductant to treat high-iron RM via co-roasting at 850 °C followed by magnetic separation to separate iron and aluminum, achieving an iron recovery of 70.14% [76]. While coal gangue demonstrates excellent reducing performance, the value of CFA as another major coal-based solid waste is increasingly recognized by the academic community. Related studies indicate that co-processing CFA with RM offers a cost-effective route for removing heavy metals (e.g., Pb, Cu, Cd) from aqueous systems, as well as for the efficient recovery of valuable metallic elements [77,78].

Despite demonstrating significant promise in reducing reductant costs and comprehensive utilization, future research on coal-based solid waste co-processing with RM still

requires focus on the following two areas: first, deepening the understanding of reaction mechanisms in multi-waste systems, particularly the interfacial reaction kinetics between gangue/fly ash and RM; and second, exploring low-temperature, low-energy synergistic processes (such as coupling mechanical activation with low-temperature roasting) to reduce processing costs. In summary, by optimizing waste compatibility and integrating advanced processes, the co-processing of coal-based wastes and RM is expected to become a key technology supporting the low-carbon transition of the steel and aluminum industries.

Following the discussion of green low-carbon technologies and synergistic waste-treating-waste strategies, a consolidated comparison of these two groups of approaches is provided in terms of feedstock features, reaction media, operating conditions, iron recovery performance, and representative cases (Table 1).

Table 1. Representative technical categories for iron extraction from red mud and key characteristics.

Technical Category	Red Mud Characteristics	Reaction Medium	Key Operating Parameters	Iron Grade/Iron Recovery	Representative Case	References
Biomass Reduction	TFe 28.69–32.54%, Fe ₂ O ₃ 40.09–46.49%, Al ₂ O ₃ 13.1–26.67%, SiO ₂ 7.80–15.1%, CaO 1.27–5.70%, TiO ₂ 5.05–6.80%, PS 0.034–6.5 µm	Biomass includes banana peel, forest litter, rice husk, tea residue, wheat straw, corn stalk, etc. as reductant, with pulverized coal as a supplementary reductant in some studies	Red mud and biomass are mixed at a preset mass ratio, subjected to reduction roasting at 550–1000 °C for 40–60 min, followed by wet magnetic separation (0.07–0.3 T)	Iron grade approx. 42.0–77.0%, iron recovery approx. 72.0–90.9%	Ref. [42]: TFe 28.69%, RM/wheat straw mass ratio: 1:2.5, 1000 °C, 40 min, 0.15 T, 77% iron grade and 72% iron recovery	[37,42,43]
Hydrogen Metallurgy (Thermal Hydrogen Reduction)	TFe 26.65–30.51%, Fe ₂ O ₃ 38.10–43.59%, Al ₂ O ₃ 18.45–23.60%, SiO ₂ 6.00–7.80%, CaO 7.90–11.38%, TiO ₂ 5.10–5.54%, PS 2.1–400 µm	H ₂ (5–100%) as reductant	Reduction roasting is performed at 480–900 °C for 30–120 min under a H ₂ atmosphere of preset concentration, followed by water leaching and filtration, or wet magnetic separation (0.2–0.3 T)	Iron grade approx. 54.65–69.1%, iron recovery approx. 74.4–88.1%	Ref. [44]: TFe 26.65%, 100% H ₂ , 900 °C, 120 min, 0.29 T, 69.1% iron grade and 88.4% iron recovery	[44–46]
Hydrogen Metallurgy (Plasma Reduction)	TFe 27.80–44.60%, Fe ₂ O ₃ 38.4–63.7%, Al ₂ O ₃ 10.80–11.18%, SiO ₂ 12.90–15.43%, CaO 6.52%, TiO ₂ 10.96%, PS < 2 µm	H ₂ plasma (10% H ₂ , 90% Ar) as reductant	Plasma excitation and reduction roasting are conducted at 900–1850 °C for 10–120 min under an atmosphere of 10% H ₂ and 90% Ar, followed by wet magnetic separation (0.6 T)	Iron grade approx. 71.0–95.0%, iron recovery approx. 62.4–88.1%	Ref. [49]: TFe 44.60%, 10% H ₂ , 90% Ar plasma, 900 °C, 120 min, 0.6 T, 71% iron grade and 88.1% iron recovery	[47,49]
Selective Flocculation (Chemical Flocculation/Bio-flocculation)	TFe 30.90–34.43%, Fe ₂ O ₃ 45.60–49.22%, Al ₂ O ₃ 17.6–31.2%, SiO ₂ 11.5–45.7%, CaO 13.2–28.8%, TiO ₂ 1.5–5.8%, PS 14.8–45 µm	Organic humics, bacterial suspension as flocculant, no reductant input	Red mud slurry with low solid content is prepared, an appropriate amount of flocculant is added under suitable pH, stirring and settling conditions, followed by sedimentation separation	Iron grade approx. 60.06–61.12%, iron recovery approx. 69.34–86.25%	Ref. [52]: TFe 30.90%, 2% solid concentration, 30 mg/L Humics II, pH 10.0, 1000 rpm, 61.12% iron grade and 86.25% iron recovery	[52,53]
Process Intensification (Microwave Heating)	TFe 22.05–24.26%, Fe ₂ O ₃ 31.50–34.68%, Al ₂ O ₃ 19.40–22.26%, SiO ₂ 4.48–13.10%, CaO 5.69–16.70%, TiO ₂ 4.23–7.80%, PS < 74 µm	Activated carbon or rice husk (biomass) as reductant	Red mud and reducing agent are mixed at a preset mass ratio, subjected to microwave reduction roasting at 900–1000 °C for 10–20 min, followed by acid leaching and separation or wet magnetic separation	Iron grade approx. 60.1%, iron recovery approx. 86.3–92.1%	Ref. [56]: TFe 24.26%, rice RM/husk mass ratio: 1:3, 1000 °C, 20 min, iron grade of 60.1% and iron recovery of 86.3%	[54,56]

Table 1. Cont.

Technical Category	Red Mud Characteristics	Reaction Medium	Key Operating Parameters	Iron Grade/Iron Recovery	Representative Case	References
Process Intensification (Flash Joule Heating)	TFe 32.0%, Fe ₂ O ₃ 45.70%, Al ₂ O ₃ 18.7 wt%, SiO ₂ 8.8%, CaO 10.1%, TiO ₂ 6.5%, PS 1–5 µm	Cl ₂ as chlorination medium, no reductant input	The reaction is performed at 1000 °C for 1 min via flash Joule heating in a Cl ₂ atmosphere. After chlorination treatment, iron in red mud is efficiently removed in the form of volatile FeCl ₃	Iron is efficiently removed as volatile FeCl ₃ (recovery > 96%), with iron content in the volatiles reaching 88%	Ref. [58]: TFe 32.00%, FJH-Cl ₂ process, 1000 °C, 1 min, 96.0% iron recovery	[58]
Organic Solid Waste Synergistic Reduction Roasting	TFe 24.20–36.36%, Fe ₂ O ₃ 34.57–51.94%, Al ₂ O ₃ 19.20–39.29%, SiO ₂ 5.89–15.50%, TiO ₂ 4.17–5.10%, PS 10–150 µm	Organic solid waste such as pine sawdust, bamboo, corn cob and other biomass, oily sludge or activated sludge as reductant	Red mud and organic solid waste are mixed at a preset mass ratio, subjected to reduction roasting at 550–1050 °C, synchronous reduction and gasification (SRG) at 900 °C, or catalytic pyrolysis at 600 °C, followed by wet magnetic separation, with co-production of high-value bio-oil, activated carbon and syngas	Iron grade approx. 52.59–66.12%, iron recovery approx. 92.25%, formation of zero-valent iron (ZVI) confirmed in some studies	Ref. [65]: TFe 36.36%, RM/coal mass ratio: 1:0.35, RM pellet/ bamboo mass ratio: 1:0.5, 1050 °C, 90 min, 52.59% iron grade and 84.55% iron metallization degree	[6,64–66]
Phosphogypsum Synergistic Reduction Roasting	TFe 21.97–35.56%, Fe ₂ O ₃ 31.40–50.80%, Al ₂ O ₃ 18.23–19.51%, SiO ₂ 7.13–18.10%, CaO 2.66–13.30%, TiO ₂ 4.80–6.31%, PS < 75 µm	Pulverized coal or coke as reductant; phosphogypsum promotes iron mineral decomposition, with Na ₂ SO ₄ as supplementary synergist for iron reduction and separation in some studies	Red mud and phosphogypsum are mixed at a preset mass ratio, subjected to reduction roasting at 1000–1100 °C for 30–75 min, followed by wet magnetic separation (0.1 T)	Iron grade approx. 75.27–89.02%, iron recovery approx. 78.00–89.88%	Ref. [67]: TFe 35.56%, 6% PG, 50% pulverized coal, 1100 °C, 75 min, 0.1 T, 89.02% iron grade and 87.46% iron recovery	[67–69]
Iron-Containing Waste Synergistic Reduction Roasting	TFe 20.49–34.97%, Fe ₂ O ₃ 29.30–50.00%, Al ₂ O ₃ 22.2%, SiO ₂ 20.0%, CaO 1.2%, TiO ₂ 3.4%, PS < 75 µm	Red mill scale to increase total iron content, graphite as reductant	Red mud and red mill scale are mixed at a preset mass ratio, subjected to reduction roasting at 1600–1650 °C for 30 min with graphite as reductant	Iron-rich aggregate with iron grade of 77.2–98.2%	Ref. [73]: TFe 20.49–34.97%, blended with red mill scale, 1600–1650 °C, 30 min, 77.2–98.2% iron grade	[73]
Coal-Based Solid Waste Synergistic Reduction Roasting	TFe 37.85–47.79%, Fe ₂ O ₃ 54.07–68.27%, Al ₂ O ₃ 11.18–14.90%, SiO ₂ 1.85–10.58%, CaO 0.31–2.45%, TiO ₂ 0.78–4.36%	Coal gangue as reductant	Red mud and coal gangue are mixed at a preset mass ratio, subjected to reduction roasting at 750–850 °C for 30–50 min, followed by wet magnetic separation (0.17 T)	Iron grade approx. 55.09–59.77%, iron recovery approx. 70.14–82.73%	Ref. [76]: TFe 47.79%, 30% coal gangue, 850 °C, 30 min, 0.17 T, 59.77% iron grade and 70.14% iron recovery	[75,76]

Notes: Representative cases were preferentially selected from studies that reported relatively complete datasets and showed balanced performance in terms of iron grade and iron recovery. The listed results reflect the performance reported under specific experimental conditions in the original studies and should not be interpreted as indicating that the corresponding technical route is optimal for all red mud feedstocks or process boundaries.

4. Integrated Strategies for High-Value Cascading Utilization

As research on RM valorization continues to deepen, researchers have gradually recognized that using iron as the sole recovery target not only yields limited economic returns, but also generates large amounts of tailings. Without further utilization pathways, these tailings may still constitute a new environmental burden. Therefore, the concept of “total-component high-value cascading utilization” aims to reconceptualize RM as a complex multi-component resource reservoir rather than merely a waste. This philosophy

emphasizes the stepwise transformation and comprehensive utilization of RM along a cascading pathway of “priority recovery of major components–synergistic extraction of key valuable elements–valorization of final residues”. Specifically, iron-bearing phases are first enriched and efficiently recovered through reduction roasting–magnetic separation, selective separation, or related processes. The remaining enriched phases are then subjected to acid/alkaline leaching, selective precipitation, or solvent extraction to recover valuable components such as Al, Ti, and Sc. Finally, the residues after metal extraction can be converted into cementitious materials, construction materials, or functional materials (Figure 3) [17,79,80]. Such an integrated strategy helps avoid the generation of a new tailings burden after single-target iron recovery and promotes the transition of RM valorization from single-component recovery toward total-component synergistic utilization, thereby maximizing its potential resource value and progressively approaching the goal of “zero-waste” valorization.

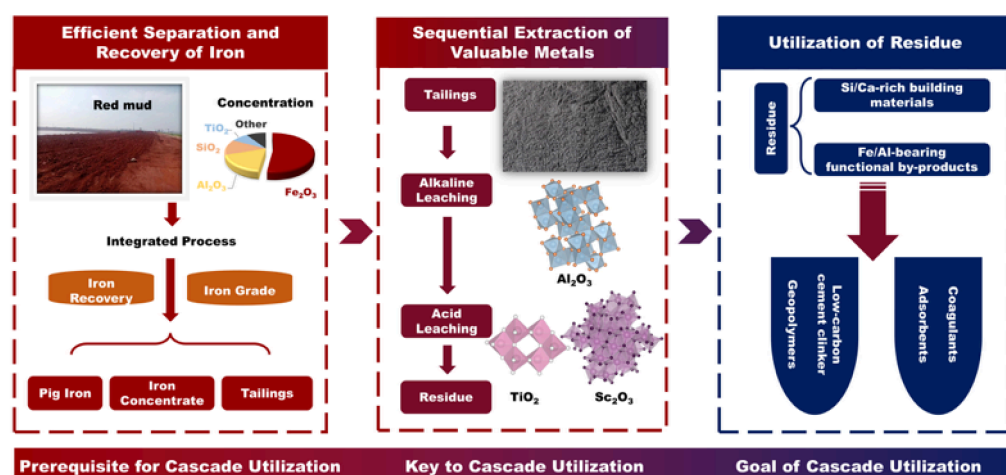


Figure 3. Full-component high-value cascading utilization of red mud, including Fe recovery, extraction of valuable components such as Al/Ti/Sc, and utilization of final residues.

4.1. Efficient Iron Separation and Recovery

Within the macroscopic framework of total-component utilization, the efficient recovery of iron serves as the foundation for the entire process [81–83]. On the one hand, iron is the component with the highest content and the greatest total value by mass in RM, and whether it is recovered directly determines the preliminary economic viability of the entire process; on the other hand, by pre-separating iron in the form of metallic iron or high-grade iron concentrate via pyrometallurgical and other means, it can greatly simplify subsequent hydrometallurgical process flows. This step effectively prevents iron ions in the leaching solution from interfering with the extraction of downstream target elements such as aluminum, titanium, and scandium, while significantly reducing the consumption of chemical reagents such as acids and alkalis.

Various advanced pyrometallurgical technologies have laid a solid foundation for this. For instance, Li et al. employed a pre-reduction smelting process and were able to obtain high-quality pig iron at 1600 °C with a grade of up to 96.55% and a recovery rate of 98.15%, creating extremely favorable conditions for subsequent component separation [84]. Similarly, Xiao et al. utilized calcium-salt roasting followed by magnetic separation technology under relatively mild conditions (1000 °C) and obtained an iron concentrate with a grade of 86.86% and a recovery of 91.48%, likewise achieving the efficient enrichment of iron. These studies indicate that whether through high-temperature roasting or medium-low temperature roasting, iron elements can be stripped as the “first-tier” product from RM, paving the way for subsequent cascading utilization [85].

Although traditional pyrometallurgical technologies have validated the technical feasibility of iron recovery from RM in both laboratory and large-scale production settings, thereby laying a solid foundation for the field, under the current global “dual carbon” strategy background, the high energy consumption and carbon emissions resulting from their reliance on fossil fuels have become the fundamental bottleneck restricting the achievement of large-scale industrial production. Facing future sustainable industrial applications, fundamental innovation and upgrading of traditional pyrometallurgical processes are imperative. Consequently, a technology system centered on low-carbon reduction is emerging as the current research focus, marking a deep evolution of the RM valorization pathway from “technically feasible” to “clean and efficient”.

4.2. Sequential Extraction of Aluminum, Titanium, and Scandium

Following iron removal, the tailings, often termed “high-iron red mud tailings (HRMT)” or “magnetic separation tailings”, see their main composition transform into a silica-aluminate matrix enriched with aluminum, silicon, titanium, calcium, and other elements. The content of these elements is significantly enriched compared to the raw RM, making HRMT an ideal secondary raw material for extracting these valuable metals [86,87].

Aluminum recovery is the critical next link in this cascading chain. Qi et al. developed an alkali-enhanced magnetization reduction process, in which NaOH or Na₂CO₃ and other alkaline additives were pre-added during the magnetization roasting process. These additives not only promote iron reduction, but more importantly, they react with aluminum-bearing minerals in RM (such as aluminosilicates) to transform them into soluble sodium aluminosilicates (e.g., Na_{1.75}Al_{1.75}Si_{0.25}O₄). In this way, after iron extraction, only simple atmospheric alkaline leaching of the tailings is needed to efficiently leach out aluminum, achieving an Al₂O₃ recovery rate of up to 81.56% [88]. Similarly, Wen et al.’s vacuum thermal reduction process, while extracting iron, simultaneously generated easily alkaline-leachable CaO·xAl₂O₃ phases, and subsequent leaching with sodium carbonate solution achieved an even more impressive alumina recovery rate of 95.48% [89]. Building on the foundation of aluminum recovery-centric strategies, researchers have successfully validated a more comprehensive integrated route using sodium salts (Na₂CO₃ and Na₂SO₄) as multifunctional additives. These not only facilitated the recovery of a 90.2% grade iron concentrate, but also activated aluminum and silicon phases, enabling the subsequent sulfuric acid leaching to extract 98.6% of Al and 95.9% of Si while simultaneously enriching TiO₂ to 37.8% in the final tailings, serving as a new paradigm for sequential extraction [16].

The recovery of titanium and rare/rare-earth metals (e.g., scandium) constitutes the higher tier of the value chain. In Li et al.’s integrated process, in the residue remaining after iron and aluminum extraction, the TiO₂ content had been enriched to approximately 20%. Through subsequent hydrochloric acid leaching, aluminum, silicon, and other impurities could be effectively removed, ultimately yielding a perovskite concentrate with a grade of up to 46.44%, and a TiO₂ recovery of 95.53% [84]. As for scandium, a strategic metal of extremely high value, although its initial content in RM was low (approximately 78 ppm), after iron extraction, its concentration in the tailings was significantly elevated. Wei et al.’s research indicated that the Sc₂O₃ content in magnetic separation tailings could be enriched to 0.012%, with scandium recovery exceeding 90%. Subsequently, hydrochloric acid leaching was performed on this Sc-rich tailing, and under optimized conditions, the scandium leaching efficiency could reach 83.94%, realizing the critical leap from trace elements to high-value products [90].

4.3. Valorization of Final Residues into Construction Materials and Functional By-Products

After the sequential extraction of metallic values, the ultimate residue predominantly consists of stable silicates and aluminates. Crucially, hazardous components such as soluble alkalis are substantially removed, and heavy metals are effectively immobilized during preceding steps. These seemingly “spent” final residues actually possess excellent latent cementitious properties, positioning them as ideal precursors for high-performance, low-cost construction materials. Meanwhile, Fe/Al-rich liquors generated during pyro-hydrometallurgical treatment or hydrometallurgical leaching can be further converted into coagulants, adsorbents, or functional oxides, thereby broadening the pathway for the total-component high-value utilization of RM. This stage therefore represents a critical terminal step in closing the loop of RM valorization.

Wu et al. systematically reviewed this pathway, highlighting that the high-temperature reduction process itself serves as an efficient thermal activation mechanism. Under elevated temperatures, the stable, highly polymerized aluminosilicate structures inherent in the RM undergo depolymerization, transforming into more reactive amorphous or low-polymerization phases. This structural evolution significantly activates the residue’s pozzolanic potential [91]. Corroborating this, Wang et al. observed that residues from biomass-assisted magnetization reduction (REIC) exhibited a loose, porous microstructure with increased amorphous content, resulting in markedly enhanced cementitious activity [92].

Leveraging these highly reactive residues enables the fabrication of diverse construction materials [93–97]. For instance, blending them with other industrial wastes like coal fly ash and blast furnace slag yields high-performance geopolymers, with 28-day compressive strengths easily reaching 36–43 MPa [91,92]. Furthermore, scholars have proposed an integrated “calcification–transformation–cyclone reduction–cement preparation” process. Following high-temperature smelting for iron recovery, the liquid low-alkali slag is directly water-quenched to produce a slag with a vitreous content as high as 99%. The reactivity of this material rivals that of S95-grade ground granulated blast-furnace slag, allowing it to be used in substantial proportions (>50%) as a supplementary cementitious material in low-carbon cement production [15,98]. However, when RM residues are used as components of construction materials, their evaluation should not be limited to mechanical strength, cementitious activity, and durability. Environmental safety and long-term service stability must also be considered. In particular, after the co-processing of RM with solid wastes such as PG, rare earth elements, trace heavy metals, and naturally occurring radionuclides such as U, Th, and Ra introduced by PG may be enriched in the residues or construction products. If these components migrate or are released within construction material systems, they may lead to increased leaching toxicity, excessive radioactivity indices, enhanced radon exhalation, and insufficient long-term stability [70–72]. Therefore, the construction-material utilization of such residues has practical significance only when the requirements for material performance, environmental safety, and radiation protection are simultaneously satisfied.

In addition to direct utilization in construction materials, Fe- and Al-bearing leached components generated from RM through hydrometallurgical leaching or pyro-hydrometallurgical treatment can also be further converted into other functional by-products. Conceptual studies on the joint processing of RM with large-tonnage wastes from the oil and petrochemical industries have shown that pyro-hydrometallurgical processes can convert Al-, Fe-, and Ti-bearing components into soluble salt intermediates, providing a potential route for the subsequent preparation of coagulants or inorganic salt by-products [99]. After treatment in acidic or saline media, RM can yield Fe- and Al-rich liquid or solid soluble coagulants, whose phosphorus removal performance can approach

that of commercial aluminum sulfate, ferric sulfate, or ferric chloride coagulants [100]. Recent studies have also prepared polyaluminum ferric sulfate through acid leaching–polymerization and applied it to turbidity removal from coal slurry wastewater [101]. In addition, stepwise leaching of RM can produce functional oxide by-products such as α -Fe₂O₃ and γ -Al₂O₃, which can be used in pigments, adsorbents, catalyst supports, and related fields [102]. Therefore, the preparation of coagulants and functional by-products can serve as an important intermediate link between metal recovery and final residue utilization; however, further attention should be paid to acid consumption, salt consumption, product impurities, leachate recycling, and by-product salt disposal.

In summary, based on the extraction efficiencies reported in the literature, taking 1 ton of typical Bayer process RM (TFe 25–35%, Al₂O₃ 15–20%, TiO₂ 4–8%, Sc 50–100 ppm) as the calculation baseline, an integrated technical route can be constructed covering the cascading extraction of iron, aluminum, titanium, and scandium. For iron recovery, using biomass reduction roasting followed by magnetic separation, with an iron recovery rate of 85%, approximately 354–496 kg of iron concentrate with an iron grade of no less than 60% can be prepared [43]. For aluminum recovery, using alkali roasting and water leaching, with a recovery rate controlled above 75%, approximately 172–230 kg of Al(OH)₃ product can be obtained (equivalent to 112.5–150 kg Al₂O₃, with a grade > 90%) [88]. For titanium recovery, using hydrochloric acid leaching and enrichment to process, with a titanium recovery rate of 90%, approximately 78–157 kg of perovskite concentrates with a TiO₂ grade of 46% can be obtained [84]. For scandium recovery, scandium in the raw RM can be recovered via acid leaching and extraction with a recovery rate exceeding 80%, yielding approximately 0.06–0.12 kg of Sc₂O₃ product [90]. The acid leaching residue is mainly composed of SiO₂ and CaO, with heavy metal leaching concentrations meeting the relevant standard limits, and can be directly used as construction material raw material. Combined with reagent recovery and the total utilization of tailings, this can support a “near-zero waste” process goal. In practical application, targeted optimization is needed according to RM composition fluctuations, equipment efficiency, and operating parameters to approach this theoretical goal. This cascading extraction model, which extracts various valuable elements from RM one by one according to their chemical properties and economic value, not only avoids cross-contamination and loss of components during the processing, but also makes each step of operation more targeted and efficient, achieving the core technology of total-component high-value utilization.

5. Quantitative Evaluation Framework for Green and Low-Carbon Iron Extraction Pathways from Red Mud

Notably, to quantitatively assess the “green and low-carbon” attributes of iron recovery technologies from RM, it is necessary to systematically compare different technical routes under a unified life cycle CO₂e accounting boundary, focusing on unit product energy consumption, energy dependency, reducing agent sources, and environmental sensitivity.

Traditional coal-based pyrometallurgy typically operates at 1000–1200 °C, with high thermal energy demand and significant direct fossil carbon emissions. In contrast, green low-carbon iron extraction pathways show fundamentally different mechanisms, but each is constrained by specific system boundaries: biomass reduction replaces fossil fuels, but its advantage depends on local access to renewable carbon sources; hydrogen metallurgy achieves zero carbon emissions at the reaction stage, but its life cycle low-carbon performance is highly dependent on the green hydrogen supply chain; selective flocculation bypasses high-temperature phase transformations and reaches the theoretical minimum energy consumption, but its application remains limited by reagent stability and slurry conditions; while electrified routes such as microwave and flash Joule heating significantly

improve electro-thermal conversion efficiency, their real environmental benefits are strictly governed by the regional power grid structure. Therefore, although these technologies show clear potential for energy and emission reduction compared to traditional pyrometallurgy, their green and low-carbon nature is not absolute, but dynamically controlled by system boundaries and regional energy structures.

To improve the comparability of different technical routes, future research should aim to establish a unified LCA/TEA evaluation framework, with core elements summarized as a minimum set of key performance indicators (KPIs). For functional unit setting, it is recommended that dual indicators are adopted: “per ton of treated red mud (t-RM)” to characterize solid waste reduction and overall resource recovery efficiency, and “per ton of recovered iron product (t-Fe product)” to compare unit product energy consumption, carbon emissions, and costs. For total-component cascading utilization or multi-source solid-waste co-processing, both t-RM and t-Fe products should be reported to avoid masking the environmental benefits associated with by-product recovery or synergistic waste disposal when using a single functional unit. In terms of system boundaries, it should be clearly stated whether feedstock pretreatment, reductant or additive preparation, electricity and hydrogen supply, main roasting/reduction and separation processes, tailing utilization, wastewater treatment, and off-gas purification are included, so as to avoid distorted comparisons caused by inconsistent boundaries. Regarding allocation rules, the distribution of environmental burdens and costs among co-products should be explicitly described. When iron concentrate, alumina, Ti-rich products, or construction-material residues can replace market products, system expansion should be preferentially adopted to account for substitution benefits. When multiple by-products have clear market values, economic allocation can be applied, with mass allocation used as a sensitivity analysis. For low-abundance but high-value elements such as Sc and Ga, mass allocation alone is inappropriate. For the co-processing of RM with biomass, sludge, coal gangue, PG, or other wastes, it should also be clarified whether the disposal benefits of other solid wastes are included within the system boundary, and the benefits from main products, by-products, and avoided disposal costs should be reported separately.

Alongside environmental and economic boundaries, technology readiness is also an important dimension for judging the industrialization potential of RM iron recovery processes. Since most emerging technologies still lack complete industrial data, order-of-magnitude estimates combined with indicative technology readiness levels (TRLs) can be used for a preliminary comparison of their economic feasibility and scalability. For biomass reduction, the main cost arises from feedstock handling. If a biomass supply cost of several tens to approximately one hundred USD per dry ton and a biomass addition ratio of 0.1–0.3 t biomass per ton RM is assumed, the biomass feedstock cost alone would be on the order of several to several tens of USD per ton RM. The economics of hydrogen metallurgy strongly depend on the hydrogen source and recycling efficiency. From the stoichiometric relationship, the theoretical hydrogen demand for the complete reduction of Fe_2O_3 to Fe is approximately 54 kg H_2 per ton Fe, meaning that the hydrogen cost alone may reach the order of hundreds of USD per ton Fe product. Plasma-enhanced routes further require additional electricity consumption at the level of several MWh per ton product. Although selective flocculation avoids high-temperature reduction, low-solid-content slurries impose a considerable water circulation burden. If the experimental solid concentration is 2–10 g/L, processing 1 t of dry RM would require the formation and circulation of approximately 100–500 m^3 of slurry water. For microwave heating, if the scaled-up specific electricity consumption is on the order of 0.5–2 MWh per ton RM, the electricity cost alone would be approximately 25–200 USD per ton RM at an electricity price of 0.05–0.10 USD/kWh. In comparison, the economics of FJH- Cl_2 are more sensitive to specific electricity consumption

and chlorine circulation. If the specific electricity consumption during scale-up falls within 1–5 MWh per ton RM, the electricity cost alone would reach approximately 50–500 USD per ton RM, with additional costs for Cl₂ replenishment, FeCl₃ condensation and recovery, and corrosion management.

The above order-of-magnitude estimates are not intended to provide definitive process costs, but rather to illustrate that the economic feasibility and environmental performance of different technical routes are highly sensitive to key boundary conditions. In particular, electricity mix, hydrogen source and price, reductant or reagent consumption, roasting intensity, off-gas and wastewater treatment, and the benefits derived from tailings utilization can substantially alter the ranking of different technologies. For example, when the grid carbon emission factor decreases from 0.60 kg CO₂/kWh, which is typical of coal-dominated regional grids, to 0.10 kg CO₂/kWh, which is representative of cleaner grids dominated by hydropower, wind power, or photovoltaics, the indirect carbon emissions of the same electrified process can be reduced by more than 80%. Similarly, switching the hydrogen source from gray hydrogen to green hydrogen can reduce the carbon footprint of hydrogen metallurgy by approximately one order of magnitude. Therefore, establishing a unified evaluation basis is essential for identifying the real environmental performance, economic feasibility, and industrialization potential of different technical routes. By clarifying the above framework elements (Table 2), a unified data-reporting standard can be established for future studies on green and low-carbon RM iron extraction, thereby promoting the evolution of technology assessment from the traditional “grade–recovery” dual-indicator system toward a multidimensional framework covering resource efficiency, energy consumption and carbon emissions, economic boundaries, and technology readiness.

Table 2. Comprehensive evaluation framework for green low-carbon iron extraction technologies from red mud.

Technical Category	Key Performance Indicators	System Boundary Definition	Sensitive Parameters/ Cost Drivers	Major Data Gaps and Scale-Up Barriers	Indicative TRL and Maturity Assessment	Low-Carbon Advantages	References
Biomass Reduction	Iron grade, iron recovery, specific biomass consumption, pyrolysis gas utilization rate, off-gas emissions	Biomass collection and transportation, pretreatment energy consumption, off-gas treatment, and biochar by-product utilization should be clearly defined	Biomass price (0–100 USD/t), transportation radius (50–500 km), pyrolysis temperature (300–800 °C), moisture content, ash composition	Lack of standardized comparison data for different biomass feedstocks, pyrolysis gas recycling rates, tar control, and continuous roasting data	TRL 4–5. Biomass thermochemical conversion also has certain engineering bases. Compared with other technologies, this route is closer to scale-up validation	Replaces coal-based reductants with renewable biomass, reaction temperature generally lower than traditional coal-based roasting	[34–43]
Hydrogen Metallurgy (Thermal Hydrogen Reduction)	Iron grade, iron recovery, unit energy consumption, H ₂ utilization rate, H ₂ recycling rate, waste heat recovery efficiency	H ₂ production, compression, storage and transportation, tail gas dehydration and purification, H ₂ recycling, and waste heat recovery should be clearly defined	H ₂ source (gray hydrogen/ blue hydrogen/ green hydrogen), H ₂ price (1–8 USD/kg), H ₂ concentration (5–100%), reaction temperature, electricity carbon emission factor (0.1–0.6 kg CO ₂ /kWh)	Lack of continuous gas–solid reaction data, as well as energy consumption, carbon emission, and recycling efficiency data under different hydrogen sources	TRL 3–4. Hydrogen metallurgy has a relatively solid foundation in the iron and steel industry, RM systems are mainly at the laboratory validation stage	Avoids direct CO ₂ emissions at the reactor end, possesses deep decarbonization potential	[44–46]

Table 2. Cont.

Technical Category	Key Performance Indicators	System Boundary Definition	Sensitive Parameters/ Cost Drivers	Major Data Gaps and Scale-Up Barriers	Indicative TRL and Maturity Assessment	Low-Carbon Advantages	References
Hydrogen Metallurgy (Plasma Reduction)	Iron grade, iron recovery, unit power consumption, specific hydrogen consumption, hydrogen plasma utilization efficiency, effective reaction-zone volume	In addition to H ₂ supply and tail gas recycling, plasma excitation energy consumption, electrode lifetime, hydrogen-embrittlement-resistant material costs, and corrosion protection measures should be clearly defined	Plasma power (200–800 A), pressure conditions, reaction-zone size, grid structure, electricity carbon emission factor (0.1–0.6 kg CO ₂ /kWh)	Lack of data on plasma-zone scale-up, continuous feeding, long-term hydrogen/corrosion-resistant operation, and energy consumption accounting	TRL 2–3. This route has strong potential in process intensification, RM systems are still at the early laboratory validation stage	Bypasses intermediate phases, reduces activation energy by approximately 45%, and increases reaction rate by 1–2 orders of magnitude	[47–50]
Selective Flocculation	Iron grade, iron recovery, specific reagent consumption, water consumption for slurry dilution, COD/BOD in tailwater, settling/filtration performance	Flocculant preparation, pH adjustment, water reuse, tailwater treatment, and tailing disposal should be clearly defined	Slurry pH (9–11), ionic strength, slurry concentration (2–10 g/L), flocculant stability, tailwater treatment cost	Lack of data on flocculant regeneration and recycling, EPS stability in high-salinity environments, and degradation of organic residues in tailings	TRL 3–4. Selective flocculation has a pilot-scale foundation in fine iron ore separation, RM systems remains mainly at the laboratory validation stage	Avoids high-temperature phase transition and reductant input, giving the theoretically lowest process energy demand	[51–53]
Microwave Heating	Iron grade, iron recovery, unit power consumption, microwave-to-heat conversion efficiency, treatment time	Upstream electricity supply chain, microwave source efficiency, reductant type, off-gas treatment, and equipment lifetime should be clearly defined	Microwave system efficiency (70–85%), dielectric properties of materials, thermal-field uniformity, grid structure, grid carbon emission factor (0.1–0.6 kg CO ₂ /kWh)	Lack of data on thermal-field uniformity after scale-up, continuous processing, and long-term equipment stability	TRL 3–4. Microwave heating equipment has an application basis in mineral processing, RM systems remains at the laboratory validation stage	Selective volume heating directly acts on material, significantly shortened treatment time and improving energy efficiency	[54,56]
Flash Joule Heating	Iron removal rate, iron recovery, unit power consumption, pulse energy consumption, Cl ₂ recycling rate, FeCl ₃ capture rate	Upstream electricity supply chain, Cl ₂ production and recycling, FeCl ₃ condensation and recovery, off-gas alkaline washing, and corrosion protection measures should be clearly defined	Cl ₂ recycling rate, pulse power supply efficiency, grid structure, Grid carbon emission factor (0.1–0.6 kg CO ₂ /kWh)	Lack of data on closed-loop chlorine circulation, corrosion management, and formation and detection of halogenated by-products in off-gas	TRL 2–3. FJH has undergone scale-up exploration in certain carbon material preparation processes, RM systems remains at an early laboratory validation stage	Ultra-fast temperature rise of approximately 200 °C/s enables selective chlorination, with total heat consumption reduced by approximately 80% compared with conventional processes	[57,58]

Notes: TRL denotes technology readiness level. The TRLs listed in this review are indicative judgments based on the experimental scale, degree of continuous operation, level of system integration, and engineering scale-up data reported in the open literature. Overall, biomass reduction and microwave heating are relatively closer to scale-up validation; thermal hydrogen reduction and selective flocculation are between laboratory validation and early scale-up; hydrogen plasma reduction and FJH-Cl₂ remain mainly at the early laboratory validation stage for RM systems.

6. Conclusions and Outlook

Iron recovery from RM has evolved from the traditional energy-intensive, single-target mode to a new phase of comprehensive resource utilization, taking green and low-carbon approaches as the core, multi-technology integration as the means, and high-value utilization of all components as the ultimate goal. Despite substantial progress, achieving its large-scale industrial application still requires systemic breakthroughs to be made at the technical, economic, and industrial levels. Constrained by the current cost and scaling level of clean energy-driven processes, some green and low-carbon iron extraction technologies still face economic constraints when processing conventional iron-rich feedstocks, and their cost advantages are not yet obvious when applied to low-value, complex solid wastes like RM. With the future decline in renewable energy costs, maturity of process intensification technologies, and optimization of system integration, such technologies will have sufficient economic feasibility and application potential in RM resource utilization, but systematic evaluation through LCA and TEA is still required.

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