

Iron Impurity Removal from Bauxite Ore: A Comprehensive Review of Pyrometallurgical, Hydrometallurgical, and Physical Separation Methods

Raha Rasouli

Department of Materials and Metallurgical Engineering

Tabriz University of Technology, Sahand, Iran

Email: raharasouli98@gmail.com

Abstract

*Bauxite is the world's principal ore for aluminium production. However, its prevalent iron oxide impurities—hematite, goethite, and magnetite—pose critical challenges to the efficiency of the Bayer process, the quality of alumina and high-grade refractory products, and the environmental management of red mud. With global bauxite grades declining and demand for high-purity alumina rising, the development of efficient iron-removal strategies has become a paramount research priority. This paper presents a comprehensive, critically evaluated review of all major iron-removal methodologies: pyrometallurgical routes (classic magnetic roasting, hydrogen-suspension roasting, microwave-assisted roasting, reductive smelting via the Pedersen process, and pyrite-assisted reduction), hydrometallurgical routes (hydrochloric, sulfuric, and organic acid leaching; bioleaching with *Paenibacillus polymyxa* and *Aspergillus niger*; and combined reductive-complexing methods), and physical beneficiation techniques (high-gradient magnetic separation, gravity separation, and flotation). For each method, reaction mechanisms, thermodynamic and kinetic data, optimal parameters, and reported iron-removal efficiencies are discussed. A structured comparative analysis of technical performance, energy consumption, alumina recovery, and environmental footprint is provided, together with selection guidelines for different bauxite types. Particular attention is given to diasporitic karst bauxites of the type found in Iran's Jajarm deposit. The review identifies the hybrid hydrogen-roasting plus magnetic separation route as the most promising technology for low-carbon, high-efficiency iron removal, while organic-acid selective leaching offers a complementary route for moderate-grade ores.*

Keywords: *bauxite; iron removal; magnetic roasting; Bayer process; hydrometallurgy; selective leaching; red mud; bioleaching; refractory grade; diasporitic bauxite.*

1. INTRODUCTION

Aluminium is the most abundant metallic element in Earth's crust (~8.1 wt.%), and bauxite is its only economically viable ore. Approximately 95% of all mined bauxite is first converted to alumina (Al_2O_3) via the Bayer process and subsequently to aluminium metal by the Hall–Héroult electrolysis [1]. Global bauxite production exceeded 390 million tonnes in 2023, driven by the expanding applications of aluminium in transportation, packaging, construction, electrical engineering, and aerospace [2].

Bauxite is a sedimentary rock composed principally of aluminium hydroxide and oxyhydroxide minerals—gibbsite ($\gamma-Al(OH)_3$), boehmite ($\gamma-AlOOH$), and diasporite ($\alpha-AlOOH$)—together with varying quantities of impurity phases. Among these impurities, iron oxides are ubiquitous and by far the most detrimental. Depending on the deposit, Fe_2O_3 contents typically range from 5 to 30 wt.% and may reach 40 wt.% in deeply weathered

lateritic ores [3]. Iron occurs primarily as hematite (Fe_2O_3), goethite (FeOOH), and magnetite (Fe_3O_4), but also as isomorphic substitution of Fe^{3+} for Al^{3+} within the crystal lattice of alumina minerals [4].

The deleterious effects of iron impurities are multifaceted:

(i) In the Bayer process: Iron oxides are essentially insoluble under process conditions ($\text{pH} > 13$, $105\text{--}250^\circ\text{C}$) and accumulate entirely in red mud. Each tonne of alumina produced generates between 0.2 and 8 tonnes of red mud, of which iron oxides constitute 30–55 wt.%. More than 150 million tonnes of red mud are generated annually, of which over 80% are impounded in slurry ponds, occupying thousands of hectares and posing severe leakage and environmental risks [5]. Additionally, goethite-associated alumina (up to 15 wt.% Al_2O_3 isomorphically trapped within the goethite lattice) is irrecoverable by conventional Bayer, reducing overall alumina yield [6].

(ii) In the refractory industry: For high-alumina refractory products, the maximum permissible Fe_2O_3 content is typically below 1.5–2.5 wt.%. At higher levels, iron reacts with alumina to form hercynite (FeAl_2O_3), a spinel phase whose eutectic with corundum melts at $1350\text{--}1450^\circ\text{C}$ —far below the working temperature of high-grade refractories. This generates grain boundary liquid films, promotes creep, and degrades hot mechanical strength [7, 8]. Many Iranian bauxites, such as the Jajarm deposit ($\text{Fe}_2\text{O}_3 = 7\text{--}27$ wt.%), are unsuitable for direct refractory use without prior iron removal [9].

(iii) Environmental and economic context: Every 1% reduction of Fe_2O_3 in Bayer feed saves 5–7 kg NaOH per tonne of bauxite [10]. Recovered iron concentrate can offset up to 20% of processing costs. Hydrogen-based roasting, if fed with green hydrogen, eliminates CO_2 emissions entirely, producing only water as a by-product [11].

Despite extensive laboratory research, a critical and integrated review of all iron-removal routes—covering reaction mechanisms, kinetics, optimal conditions, comparative metrics, and applicability to different bauxite types remains lacking. The present work fills this gap by systematically reviewing pyrometallurgical, hydrometallurgical, and physical separation methods, providing quantitative performance data, and offering evidence-based selection criteria.

2. BAUXITE MINERALOGY AND THE OCCURRENCE OF IRON

2.1 Mineralogical Classification

Bauxites are classified genetically as lateritic (karst-free, formed by in-situ weathering of aluminosilicate rocks such as granite or basalt in tropical climates) and karst (formed on carbonate rocks in sub-tropical and temperate zones). Lateritic deposits, found in Australia, Brazil, Guinea, and India, are gibbsite-dominant and relatively easy to process in the standard Bayer circuit. Karst deposits, prevalent in China, Greece, Hungary, and Iran, are predominantly diaspore or boehmite bearing and require more severe Bayer conditions ($220\text{--}260^\circ\text{C}$, 25–35 bar) [12].

Table 1. Comparative properties of the three principal alumina minerals in bauxite [3, 12].

Mineral	Formula	Hardness (Mohs)	Bayer Temperature (°C)	Dissolution Rate
Gibbsite	$\gamma\text{-Al(OH)}_3$	2.5–3.5	105–145	Fast
Boehmite	$\gamma\text{-AlOOH}$	3.5–4.0	200–230	Moderate
Diaspore	$\alpha\text{-AlOOH}$	6.5–7.0	220–260	Slow

2.2 Forms of Iron in Bauxite

Iron in bauxite occurs in three distinct forms, each with different implications for removal [4, 13]:

(1) Discrete mineral grains: Hematite (Fe_2O_3) and goethite (FeOOH) exist as free particles interspersed with alumina minerals. These are in principle amenable to physical and magnetic separation after liberation by grinding.

(2) Surface coatings and intergrowths: Iron oxides frequently coat the surfaces of gibbsite, boehmite, or diaspore grains, forming intimate intergrowths that resist simple physical separation.

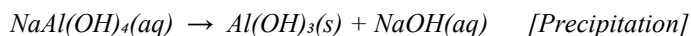
(3) Isomorphic substitution: Fe^{3+} (ionic radius 0.645 Å) readily substitutes for Al^{3+} (ionic radius 0.535 Å) in the aluminium mineral lattice, producing Fe-bearing diaspore and Fe-bearing boehmite. This structurally incorporated iron cannot be removed by any physical method and requires aggressive chemical or thermal treatment [14].

The ratio of structurally incorporated to free iron largely governs the choice of removal strategy. For ores where free hematite dominates (e.g., lateritic gibbsite ores), magnetic separation after roasting is efficient. For diasporitic karst bauxites with predominantly isomorphic iron, stronger methods are required.

3. BEHAVIOUR OF IRON IN THE BAYER PROCESS AND RED MUD

3.1 The Bayer Process Overview

Invented by Carl Josef Bayer in 1887, the Bayer process remains the dominant industrial route for alumina production, consuming approximately 90% of world bauxite [15]. The process relies on the selective dissolution of aluminium hydroxide minerals in hot concentrated NaOH, followed by controlled re-precipitation:



Under standard Bayer conditions ($\text{pH} > 13$, 105–260 °C depending on alumina mineral type), iron oxides are essentially insoluble. Hematite, goethite, and magnetite pass through the circuit unaltered and concentrate in the residue—red mud [16].

3.2 Formation and Composition of Red Mud

Red mud is the alkaline solid waste produced at a rate of 0.2–8 tonnes per tonne of alumina, depending on the ore grade and silica content. Annual global generation exceeds 150 million tonnes [5]. The high pH (10–13) and the presence of heavy metals and radioactive elements render red mud a major environmental hazard. Table 2 summarises its typical composition.

Table 2. Typical chemical composition of red mud from different bauxite types (wt.%) [5, 16].

Oxide	Lateritic (Guinea/Australia)	Karst Diasporic (China/Iran)	Min. (all types)	Max. (all types)
Fe_2O_3	30–50	35–55	25	65
Al_2O_3	15–25	5–15	4	30
SiO_2	3–10	8–20	2	25
TiO_2	4–15	2–8	1	20
Na_2O	2–8	3–10	1	12

3.3 Effects of Iron on Bayer Process Efficiency

Iron impurities affect the Bayer process through several mechanisms [6, 17]:

(1) Alumina entrapment in goethite: Up to 10–15 wt.% of alumina is trapped isomorphically within goethite, rendering it unrecoverable unless a two-stage Bayer process is used.

(2) Sedimentation and filtration: Ultrafine iron oxide particles ($< 2 \mu m$) increase liquor viscosity, impede gravitational settling, and require increased dosages of flocculants (polyacrylamide, 50–200 g/t bauxite), raising operating costs.

(3) Alumina quality: Trace Fe^{3+} ions dissolved at high-temperature Bayer conditions re-precipitate as ultra-fine iron oxide on $Al(OH)_3$ seed crystals, elevating the Fe_2O_3 content of calcined alumina above the ≤ 0.05 wt.% specification required for electrolysis-grade material.

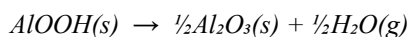
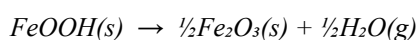
(4) NaOH consumption: Although iron oxides themselves are insoluble, the increased kaolin-type silicate phases that co-exist with iron-rich bauxites consume additional NaOH (approximately 5–7 kg NaOH per percent Fe_2O_3 reduced) [10].

4. PYROMETALLURGICAL METHODS FOR IRON REMOVAL

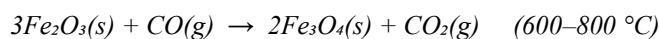
Pyrometallurgical approaches exploit high-temperature reactions to transform non-magnetic iron oxides (hematite and goethite) into strongly magnetic phases (magnetite, wüstite, or metallic iron) that can subsequently be separated by low-intensity magnetic separators. Based on the Ellingham diagram, the partial reduction of hematite to magnetite becomes thermodynamically spontaneous above ~ 550 – $600^\circ C$ for both H_2 and CO reductants. Full reduction to metallic iron requires temperatures above $800^\circ C$ [18].

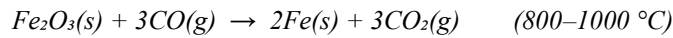
4.1 Classic Magnetic Roasting

Classic magnetic roasting (CMR) is the oldest industrially deployed pyrometallurgical iron-removal route. The process involves mixing crushed bauxite with a carbonaceous reductant (coal, coke, or charcoal at C/bauxite ratios of 0.1–0.2 by weight), followed by roasting in a rotary kiln or muffle furnace under an inert or mildly reducing atmosphere at 650 – $900^\circ C$ for 1–4 hours [19]. A pre-roasting step in air (500 – $600^\circ C$) is often employed to dehydrate goethite to hematite and increase specific surface area:



The principal conversion reactions in the reducing stage are:

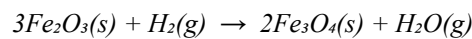




The roasted product is then ground and subjected to low-intensity magnetic separation (LIMS) at field intensities of 235–2400 gauss. Sadler et al. [20] reported 88% iron removal and 85% alumina recovery using 10 wt.% coke at 850 °C for 2 h, reducing total iron from 24 wt.% to 2.8 wt.% in the non-magnetic fraction. A critical constraint is the prevention of hercynite formation (Section 4.6) by maintaining temperatures below 800 °C and avoiding excessive reduction.

4.2 Hydrogen-Suspension Roasting

Hydrogen-suspension roasting (HSR) represents a major advance over CMR. Developed by Yuan et al. [21], a bench-scale fluidised-bed reactor (5 kg/h capacity) suspends crushed bauxite particles (< 100 µm) in a flowing H₂/N₂ atmosphere at 550–700 °C for 4–10 minutes. The extremely short roasting time is enabled by the superior mass and heat transfer in the fluidised bed. The key reduction reaction:



produces only water as a by-product—a decisive environmental advantage over carbon-based methods. Under optimum conditions (600 °C, 25 vol.% H₂, 4 min), iron removal efficiency reached 85.3% with alumina recovery of 80.6%. The Fe₂O₃ content in the magnetic concentrate increased from an initial 0.89 wt.% to 88.61 wt.% [21]. Importantly, temperatures above 750 °C were found to promote hercynite formation, degrading separation performance.

The main parameters are summarised in Table 3.

Table 3. Optimum conditions for hydrogen-suspension roasting [21].

Parameter	Optimum Value
Pre-roasting temperature	750 °C
Pre-roasting time	30 min
Suspension roasting temperature	600 °C
H ₂ concentration	25 vol.%
Roasting time	4 min
Magnetic separation intensity	4000 gauss
Iron removal efficiency	85.3%
Alumina recovery	80.6%

4.3 Microwave-Assisted Roasting

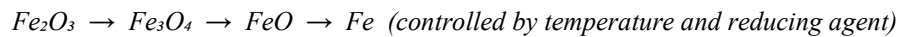
In microwave-assisted roasting (MAR), the selective absorption of microwave radiation by iron oxide minerals (high dielectric loss factor) is exploited. Hematite and goethite heat far more rapidly than the surrounding alumina matrix (which has a low dielectric loss factor), creating localised hot zones that accelerate reduction while keeping the bulk temperature relatively low, reducing overall energy consumption by up to 40% compared to conventional rotary kilns [22].

Agrawal et al. [22] demonstrated that red mud samples reached 1000 °C within 10 minutes of microwave exposure (900 W) while the bulk alumina matrix remained below 600 °C. This selective heating prevented

magnetite grain growth, resulting in fine magnetite crystals that were efficiently separated by LIMS. Iron recovery reached 94–98% under optimum conditions.

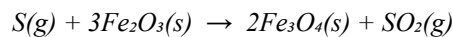
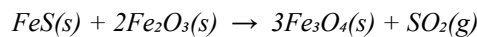
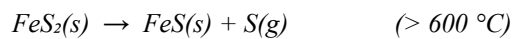
Cardenia et al. [23] investigated the addition of charcoal (carbon-to-bauxite mass ratio $\approx 1:1$) as both a microwave susceptor and reductant. At 900 W for 15 min, Fe_2O_3 was reduced from 15.1 wt.% to 1.7 wt.% in the non-magnetic product. Key advantages include ultrashort processing time (minutes vs. hours), lower capital cost (replacement of large rotary kilns with compact microwave reactors), and reduced CO_2 compared to coal-based methods.

Process schematic:



4.4 Pyrite-Assisted Reduction Roasting

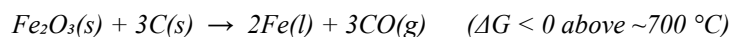
Fu et al. [24] introduced a novel reductant—pyrite (FeS_2)—for selective partial reduction of hematite to magnetite. The thermodynamic advantage of pyrite is that it prevents over-reduction to wüstite (FeO) or metallic iron (Fe), which are poorly magnetic and impair separation. The reactions proceed through:



Under optimum conditions (pyrite-to-hematite molar ratio 1:6, 800 °C, 2 h, N_2 atmosphere, 2400 gauss LIMS), iron recovery reached 91.5% with no hercynite detected by XRD analysis. The SO_2 by-product requires scrubbing, but the process avoids CO_2 emissions. This method is particularly suitable for processing high- Fe_2O_3 red mud.

4.5 Reductive Smelting – The Pedersen Process

The Pedersen process is the most energetically intensive pyrometallurgical route but also the most complete in iron removal. Calcined bauxite, coke (5 wt.%), and flux (lime, $\text{CaO}/\text{SiO}_2 = 1.3$) are melted in an electric arc furnace (EAF) at 1500 °C for 1 hour under argon atmosphere. The key reduction:

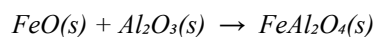


produces a molten pig iron (96–98% Fe purity) that settles to the furnace bottom, while alumina-rich slag ($\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$) floats above. Borra et al. [25] reported >95% iron recovery as cast iron and >90% scandium enrichment in the slag, which can subsequently be leached in NaOH for alumina extraction.

The main disadvantages are very high energy consumption (400–500 kWh/t feed), substantial CO_2 emission, and high capital cost. This process is nonetheless valuable for high-iron red mud valorisation, where the combined iron-REE recovery justifies the economics.

4.6 Thermodynamic Constraint: Hercynite Formation

A critical thermodynamic constraint in all pyrometallurgical routes is the formation of hercynite (FeAl_2O_3), an iron-aluminium spinel phase that is weakly magnetic and thus cannot be separated by LIMS. Pickles et al. [26] calculated the Gibbs energy for hercynite formation:



$$\Delta G^\circ = -26,200 + 7.07T \text{ (J/mol, 298–2100 K)}$$

The increasingly negative ΔG° with rising temperature confirms that hercynite formation is strongly favoured above 1000 °C. Growth of the hercynite layer follows solid-state diffusion kinetics; at 1200 °C for 1 hour the

layer reaches ~0.5 mm, increasing to ~1.3 mm at 1500 °C. Maintaining roasting temperatures below 800 °C and avoiding excess reductant are therefore essential to prevent hercynite formation [27].

Table 4. Comparative performance of major pyrometallurgical iron-removal routes.

Method	Temp. (°C)	Fe Removal (%)	Al ₂ O ₃ Recovery (%)	Energy (kWh/t)	CO ₂ Emission
Classic Magnetic Roasting	650–900	85–88	83–87	80–150	High (C reductant)
H ₂ -Suspension Roasting	550–700	85–92	80–86	50–90	Zero (green H ₂)
Microwave Roasting	800–1000	83–98	80–95	40–80	Low–Moderate
Pyrite Reduction	700–850	88–92	85–90	70–120	Low (SO ₂ risk)
Pedersen Smelting	1450–1550	>95	90–95*	400–500	Very High

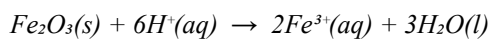
* Alumina recovered from slag via subsequent NaOH leaching.

5. HYDROMETALLURGICAL METHODS FOR IRON REMOVAL

Hydrometallurgical iron removal relies on selective dissolution of iron oxide phases in acidic media at relatively low temperatures (25–100 °C), offering lower energy consumption than pyrometallurgical routes. However, challenges include limited selectivity over alumina minerals, corrosive process conditions, and acid waste management [28].

5.1 Leaching with Hydrochloric Acid (HCl)

Hydrochloric acid leaching is the most effective inorganic acid route for iron dissolution. Dissolution of hematite proceeds by:



Gorai et al. [29] provided the first systematic kinetic study on low-grade gibbsite bauxite. The dissolution rate follows first-order kinetics:

$$-\ln(1 - \alpha) = k \cdot t$$

with an apparent activation energy of 80.1 kJ/mol, indicative of surface chemical reaction control. Under optimum conditions (4 M HCl, 85–90 °C, 120 min, particle size < 74 µm, liquid-to-solid ratio 20:1), iron removal reached 98.2% while alumina losses remained ~10%.

For diasporitic Greek bauxite, Paspaliaris and Tsolakis [30] found that the higher structural stability of diasporite requires temperatures of 90–100 °C and 4 hours to achieve ~90% iron removal with ~5% alumina loss. The comparative leaching velocity order for inorganic acids is HCl > H₂SO₄ > HNO₃ [31].

5.2 Leaching with Sulfuric Acid (H₂SO₄)

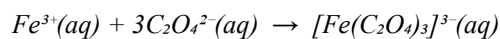
Sulfuric acid is cheaper and more widely available than HCl, but shows lower leaching rate because the rate-controlling step is diffusion of H⁺ through the product layer rather than surface chemical reaction. Activation energy is ~65.7 kJ/mol [32]. Under optimum conditions (2.5 M H₂SO₄, 90 °C, 3 h), iron removal is ~85% with

~12% alumina loss. A notable drawback is the formation of insoluble calcium sulfate if calcium-bearing minerals are present.

5.3 Organic Acid Leaching (Selective Leaching)

Organic acids particularly oxalic acid ($H_2C_2O_4$) and citric acid offer superior selectivity for iron over alumina, making them attractive for high-purity applications. The dissolution mechanism for hematite by oxalic acid involves:

(1) Complexation: Fe^{3+} forms the highly soluble tris-oxalate complex:



(2) Photo-reductive dissolution: Under UV irradiation, Fe^{3+} is photoreduced to Fe^{2+} , which has ~100 times higher solubility in oxalate media:



Cam and Turan [33] reported 97% iron removal with < 5% alumina loss under optimum conditions (oxalate:Fe molar ratio 3:1, 50 °C, 4 h, UV irradiation, pH 2–4). The exceptional selectivity arises from the much greater stability constants of iron-oxalate complexes compared to aluminium-oxalate complexes. For citric acid, Aujla et al. [34] found 72% iron removal from Pakistani bauxite under optimum conditions (5 wt.% citric acid, 70 °C, 2 h)—lower efficiency than oxalic acid, but less corrosive and biodegradable.

5.4 Bioleaching

Bioleaching exploits the metabolic products of microorganisms to dissolve iron from bauxite at near-ambient conditions, offering the lowest environmental impact of all iron-removal methods.

5.4.1 *Paenibacillus polymyxa*

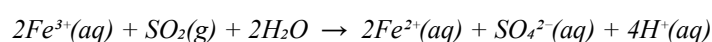
This gram-positive soil bacterium removes iron via two mechanisms: (i) direct contact—cells attach to mineral surfaces and secrete organic acids (oxalic, citric, gluconic) and siderophores (high-affinity iron-chelating molecules); (ii) indirect—metabolites released into solution dissolve iron without cell contact [35]. Under optimum conditions (pH 7, 30 °C, 7 days, 10^8 cells/mL), Anastassakis et al. [35] achieved 75% iron removal and ~8% alumina loss. The main limitation is the long processing time (days to weeks).

5.4.2 *Aspergillus niger*

The filamentous fungus *A. niger* produces large quantities of oxalic acid (up to 100 mM) and citric acid (up to 70 mM) by fermenting sucrose. Under optimum conditions (pH 3, 50 °C, 10 days, anaerobic), iron removal reached 85% [36]. Aerobic conditions lower efficiency because dissolved Fe^{2+} is re-oxidised to Fe^{3+} , which is less soluble in the absence of complexing agents.

5.5 Combined Reductive–Complexing Methods

Mohapatra et al. [37] combined chemical pre-reduction with SO_2 followed by oxalic acid leaching. The reduction step:



converts Fe^{3+} to the more soluble Fe^{2+} , which readily forms the stable bis-oxalate complex $[Fe(C_2O_4)_2]^{2-}$. This combination achieved 99% iron removal in only 30 minutes at room temperature, compared to 4 hours without pre-reduction. The dramatic improvement demonstrates the synergistic benefit of combining reduction and complexation.

Table 5. Comparative performance of hydrometallurgical iron-removal routes.

Method	Temp. (°C)	Fe Removal (%)	Al ₂ O ₃ Loss (%)	Time	Main Drawback
HCl Leaching	85–95	90–98	5–12	2–4 h	Corrosive; acid waste
H ₂ SO ₄ Leaching	80–95	80–88	8–15	2–4 h	CaSO ₂ precipitation
Oxalic Acid	40–60	92–99	< 5	0.5–4 h	UV needed; cost
Citric Acid	60–75	65–75	< 4	2–3 h	Lower efficiency
<i>P. polymyxa</i> Bioleaching	25–35	70–80	5–10	5–10 days	Very slow
<i>A. niger</i> Bioleaching	40–55	80–88	< 8	8–12 days	Very slow
SO ₂ + Oxalic Acid	25–40	97–99	< 3	0.5 h	SO ₂ handling

6. PHYSICAL BENEFICIATION METHODS

Physical methods exploit differences in magnetic susceptibility, density, or surface properties to separate iron-bearing phases without chemical transformation. They are energy-efficient and environmentally benign, but their effectiveness is limited to ores where iron-bearing minerals exist as discrete, liberated grains—not as isomorphic substitutions.

6.1 Magnetic Separation

Direct magnetic separation without prior roasting is applicable only when iron occurs as free hematite or magnetite. Hematite is weakly paramagnetic and requires high-gradient magnetic separators (HGMS) at field intensities of 10–20 kOe. Chang et al. [38] showed that at 15 kOe with 50–100 μm particle fractions, a maximum of 60% iron removal was achievable, but efficacy dropped sharply for particles below 10 μm .

Bolsaitis and Chang [39] achieved up to 80% iron removal from lateritic bauxite at 20 kOe field intensity, though alumina recovery fell below 50% for the sub-20 μm fraction due to entrainment of fine alumina particles in the magnetic product. Magnetic separation is therefore most effective as a downstream polishing step after roasting has converted hematite to the strongly ferromagnetic magnetite.

6.2 Gravity Separation and Selective Comminution

Selective comminution exploits the large hardness difference between iron-bearing silicate clays (kaolinite, Mohs hardness 2–2.5) and diasporite (hardness 6.5–7). In a ball mill, soft clay phases preferentially report to the fine fraction (< 20 μm), which is enriched in iron and silica. Removal of this slime fraction by hydrocyclone increases Al₂O₃/SiO₂ ratios by up to 5% and reduces iron content modestly, with minimal alumina loss [40]. This approach is simple and cheap but limited in iron removal efficiency.

6.3 Flotation

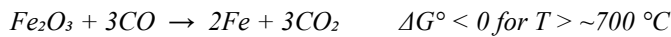
Iron oxide flotation (reverse flotation to float gangue or direct flotation to float iron minerals) has been investigated at laboratory scale. Using anionic collectors (sodium oleate, fatty acids) at pH 6–8, hematite can be selectively floated from alumina minerals. However, the high slime content of many bauxites and the

presence of adsorbing silicate species significantly impair collector performance, limiting iron removal to 50–70% with considerable alumina losses (up to 15%) [41]. Flotation is generally not preferred for bauxite iron removal unless it serves as a pre-concentration step.

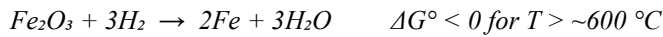
7. THERMODYNAMIC AND KINETIC FRAMEWORK

7.1 Ellingham Diagram Analysis

The Ellingham diagram provides direct thermodynamic guidance for the selection of temperature and reductant. For carbon-based reduction:



For hydrogen reduction:



The lower temperature threshold for H₂ reduction, combined with the absence of CO₂ emissions when green hydrogen is used, underpins the thermodynamic superiority of HSR as a low-carbon process [18].

7.2 Kinetic Models

Two kinetic models are commonly employed to describe iron removal from bauxite:

(1) Shrinking Core Model (SCM): Used for pyrometallurgical solid-state reactions, where the rate-limiting step may be: (a) surface chemical reaction: $-\ln(1 - \alpha) = kt$; (b) product layer diffusion: $1 - (2/3)\alpha - (1 - \alpha)^{2/3} = kt$; or (c) gas-film diffusion: $1 - (1 - \alpha)^{1/3} = kt$. The SCM applies well to carbon-based magnetic roasting, where the reductant gas (CO) must diffuse through the growing magnetite/iron product layer [42].

(2) First-order dissolution model (hydrometallurgy): For acid leaching, where the reaction at the mineral surface is rate-controlling: $-\ln(1 - \alpha) = kt$, with apparent activation energies of 65–80 kJ/mol indicating surface chemical reaction control.

7.3 Activation Energies of Key Processes

Table 6. Apparent activation energies for iron removal by selected methods [21, 26, 29, 33, 37].

Process	E _a (kJ/mol)	Rate-Controlling Step
HCl leaching of hematite	80.1	Surface chemical reaction
H ₂ SO ₄ leaching of hematite	65.7	Product-layer diffusion
H ₂ reduction of hematite (CMR)	40–80	Mixed control
Oxalic acid (photoreductive)	25–40	Photoreduction + complexation
Hercynite formation (solid-state)	180–250	Solid-state diffusion

8. ANALYTICAL AND CHARACTERISATION TECHNIQUES

Reliable characterisation of iron distribution in bauxite and reaction products is essential for process design and optimisation. The main techniques employed are:

- (1) *X-ray diffraction (XRD)*: Identifies mineral phases (hematite, goethite, magnetite, hercynite) and tracks phase transformations during roasting. Rietveld quantitative phase analysis enables determination of mineral abundances to ± 1 wt.% [43].
- (2) *Scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS)*: Reveals morphology, particle size, intergrowth texture, and elemental distribution at the grain scale. Maps of Fe, Al, Si, and Ti provide direct evidence of isomorphic substitution and mineral association.
- (3) *Vibrating-sample magnetometry (VSM)*: Quantifies magnetic saturation (M_s) and coercivity (H_c) to confirm the conversion of hematite to magnetite. Magnetite has $M_s \approx 90\text{--}92$ Am²/kg, while hematite has $M_s \approx 0.4$ Am²/kg.
- (4) *Thermogravimetry and differential thermal analysis (TG-DTA)*: Monitors weight changes (dehydration, reduction) and thermal events during roasting, enabling precise determination of optimal roasting temperatures and times.
- (5) *Mössbauer spectroscopy*: Provides unambiguous identification of iron valence states ($\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios) and coordination environments, making it particularly valuable for detecting the onset of hercynite formation.
- (6) *Inductively coupled plasma–optical emission spectrometry (ICP-OES)*: Quantitative chemical analysis of leach liquors and digested solids for Fe, Al, Si, Ti, and other elements, enabling accurate calculation of iron removal efficiency and alumina loss.

9. INDUSTRIAL APPLICATIONS AND CASE STUDIES

9.1 Chalco (China Aluminium Corporation)

Chalco, the world's largest aluminium producer, has deployed industrial-scale magnetic roasting circuits at several Chinese refineries processing high-iron diasporitic bauxite. A typical circuit comprises a pre-dehydration rotary kiln, a reductive roasting rotary kiln (coal, 700–800 °C, 1–2 h), and a LIMS circuit. Capacity of individual units reaches 500,000 tonnes of red mud per year, with iron recovery of 85–90% at Fe_2O_3 contents of 35–55 wt.% in the feed. The recovered magnetite concentrate (55–60% Fe) is sold to the steel industry, partially offsetting processing costs [44].

9.2 Vaudreuil Refinery, Rio Tinto (Canada)

Rio Tinto's Vaudreuil refinery in Quebec implemented industrial-scale red mud filtration and dry-stacking to reduce the environmental footprint of red mud disposal. The project achieved: red mud moisture content below 30% (vs. 40–50% for conventional pond disposal); geographic footprint reduction of ~70%; economic savings of ~CAD 120 million; and an extension of refinery life by ~18 years [45]. While this represents downstream red mud management rather than pre-Bayer iron removal, it demonstrates the economic incentive for iron valorisation.

9.3 Pilot Projects with Green Hydrogen Roasting (Norway)

A European consortium has operated a 5-tonne/day pilot plant in Norway combining hydrogen-suspension roasting (fed with electrolytic green hydrogen) with high-intensity LIMS. Iron removal of 87–91% was achieved with alumina recovery of 82–88% and zero CO₂ emissions. The process is projected to be commercially competitive once green hydrogen costs fall below €2/kg [46].

10. ECONOMIC AND ENVIRONMENTAL ANALYSIS

10.1 Economic Benefits of Pre-Bayer Iron Removal

A simplified economic analysis for Jajarm-type bauxite (~20 wt.% Fe₂O₃, 1 million t/y processing rate) [47] demonstrates substantial financial incentives:

Table 7. Economic comparison: with and without pre-Bayer iron removal for Jajarm bauxite [10, 47].

Parameter	Without Fe Removal	With Fe Removal (85% eff.)
Bayer feed (t/y)	1,000,000	800,000 (+ 200,000 t Fe conc.)
NaOH consumption (kg/t feed)	150	110
Red mud production (t/y)	700,000	350,000
NaOH saving (USD/y, @600 USD/t)	—	~2,400,000
Revenue from Fe concentrate (USD/y)	—	~12,000,000
Red mud disposal saving (USD/y)	—	~5,250,000

These figures illustrate that iron removal can generate combined annual revenues and savings of ~USD 19.6 million for a 1 million t/y operation, sufficient to justify capital investment in a roasting or leaching circuit (typically USD 50–100 million for a comparable-scale unit) within approximately 5–7 years.

10.2 Environmental Footprint and Life-Cycle Considerations

From a life-cycle assessment (LCA) perspective, the environmental impact order of iron-removal methods is approximately: H₂-suspension roasting (green H₂) ≈ organic acid leaching < bioleaching < microwave roasting < CMR (coal) < HCl/H₂SO₄ leaching < Pedersen smelting [48].

Pre-Bayer iron removal can reduce total CO₂ equivalent emissions of the alumina chain by 15–35%, depending on the method and energy source. For CMR using renewable-powered electric kilns, carbon footprint reductions of 20–30% are achievable relative to conventional Bayer processing of high-iron bauxite [48].

11. SELECTION GUIDELINES FOR DIFFERENT BAUXITE TYPES

The optimal iron-removal strategy depends on a matrix of factors: iron content and mineralogical form; alumina mineral type; required product purity; plant scale; available energy and reductants; and regulatory constraints. Table 8 provides evidence-based selection guidelines.

Table 8. Iron-removal method selection matrix for different bauxite types and objectives.

Bauxite Type	Dominant Iron Form	Best Route	Fe Removal	Notes
Gibbsite lateritic, low Fe (<10%)	Free hematite	HGMS direct	50–80%	Simple; no roasting needed
Gibbsite lateritic, high Fe (>15%)	Free hematite + coatings	CMR + LIMS	85–90%	Industrial proven
Boehmite, medium Fe (10–20%)	Hematite + isomorphic	H ₂ -suspension + LIMS	85–92%	Low CO ₂ ; short time
Diaspore karst, high Fe (>15%)	Mainly isomorphic Fe	H ₂ roasting + HCl polish	>90%	Hybrid recommended
High-purity refractory grade needed	Mixed	Oxalic acid leaching	>95%	< 5% Al ₂ O ₃ loss
Red mud valorisation	Hematite dominant	Pedersen / CMR	>90%	REE co-recovery

For Iranian Jajarm-type diasporitic bauxite ($\text{Fe}_2\text{O}_3 = 7\text{--}27$ wt.%, mainly isomorphic iron within diasporite lattice), a two-stage hybrid process is recommended: (1) hydrogen-suspension roasting at $550\text{--}650^\circ\text{C}$ to partially exsolve and convert iron to magnetite, followed by (2) low-intensity magnetic separation, and optionally (3) mild oxalic acid polish leaching to reach < 1.5 wt.% Fe_2O_3 for refractory-grade applications. This combination balances iron removal efficiency ($> 90\%$), alumina recovery ($> 85\%$), energy consumption, and environmental impact.

12. FUTURE PERSPECTIVES AND EMERGING TECHNOLOGIES

Several emerging directions hold promise for further improvement of bauxite iron removal:

- (1) **Green hydrogen integration:** The declining cost of electrolytic green hydrogen ($< \text{€}2/\text{kg}$ projected by 2030) will make H_2 -suspension roasting the dominant commercial route, especially for low-carbon alumina production targeting the automotive and aerospace sectors.
- (2) **Digital twins and AI-based process optimisation:** Real-time digital twin models of roasting reactors and leaching circuits, trained on sensor data (temperature, gas composition, magnetic susceptibility), can reduce energy consumption and improve iron removal consistency by 10–20% compared to fixed-parameter operation [49].
- (3) **Combined leaching–electrocoagulation systems:** Electrochemical oxidation of Fe^{2+} to Fe^{3+} in situ, combined with selective oxalate leaching, can achieve near-complete iron removal at ambient temperature, eliminating the need for heating [50].
- (4) **Valorisation of recovered iron:** High-purity magnetite concentrate ($\text{Fe} > 65\%$) recovered from bauxite processing is a premium raw material for the direct reduced iron (DRI) route in green steelmaking. Valorising iron as a co-product rather than a waste stream fundamentally changes the economics of iron removal.
- (5) **Biorecovery scale-up:** Continuous bioreactor systems with *P. polymyxa* and *A. niger*, operating at $40\text{--}55^\circ\text{C}$, could reduce processing time from days to hours with concentrated inoculum and controlled oxygenation, making biorecovery competitive with acid leaching for niche high-purity applications.

13. CONCLUSIONS

This review has systematically examined the full spectrum of iron-removal methods for bauxite, from thermodynamic principles through laboratory performance to industrial deployment. The principal conclusions are:

- 1. Iron impurities in bauxite—occurring as free hematite/goethite particles, surface coatings, and isomorphous Fe^{3+} within the alumina mineral lattice—pose cascading problems for the Bayer process, refractory product quality, and red mud disposal. No single parameter describes iron impact; the mineralogical form is as important as total iron content.*
- 2. Pyrometallurgical methods, particularly hydrogen-suspension roasting, achieve 85–92% iron removal with moderate alumina loss (< 20%), in very short processing times (4–10 min), and with zero CO₂ emissions when green hydrogen is used. Classic magnetic roasting remains industrially deployed but has a higher carbon footprint. Pedersen reductive smelting provides the highest iron removal (> 95%) but is energy intensive.*
- 3. Hydrometallurgical methods, particularly selective oxalic acid leaching with photo-reduction, achieve the best combination of high iron removal (> 95%) and very low alumina loss (< 5%), making them ideal for high-purity refractory-grade applications. Combined SO₂ pre-reduction followed by oxalic acid leaching reduces processing time to 30 minutes with 99% iron removal at ambient temperature.*
- 4. Physical separation methods are energy-efficient but limited to ores where iron is present as discrete, liberated grains. HGMS and selective comminution serve best as pre-concentration or polishing steps within hybrid circuits.*
- 5. Hercynite ($FeAl_2O_3$) formation is a critical thermodynamic constraint for all pyrometallurgical routes; maintaining roasting temperatures below 800 °C is essential.*
- 6. For diasporitic karst bauxites (e.g., Jajarm, Iran), a hybrid two-stage process combining hydrogen-suspension roasting with LIMS, optionally followed by mild organic acid polishing, is recommended based on combined technical, economic, and environmental criteria.*
- 7. Economic analysis confirms that pre-Bayer iron removal is profitable for high-iron bauxites at production scales $\geq 500,000$ t/y, with payback periods of 5–7 years driven by NaOH savings, iron concentrate revenues, and reduced red mud disposal costs.*

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