



Hydrometallurgical Extraction of Aluminum and Rare-Earth Elements (REEs) from REE-Bearing Bauxite Ores: Recent Advances

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Rare-earth elements (REEs) are geologically widespread, but their mining and especially processing are concentrated in a small number of countries; as demand grows, some specific REEs may face supply shortages in the near future. Consequently, owing to their economic potential even at low concentrations, ability to provide alternative supply opportunities, and process development potential, various countries are conducting studies on REE production from secondary geological sources such as high-silica bauxite ore. This study provides a detailed examination of aluminum (Al) and REE recovery from bauxite ore, emphasizing sustainable utilization of these resources. In this context, the study presents the technological evaluation potential of these deposits in the context of modern demands, the acquisition process, and an analysis of the main technical difficulties in this process. Furthermore, the application of both mechanical and thermal activation methods in conjunction may prove more economically viable and environmentally sustainable by reducing the temperature requirements of fossil fuel-consuming heat treatment. The development of sustainable Al and REE recovery technology from bauxite ore is of significant importance, not only in terms of mitigating supply risk but also as an alternative source for REE production.

INTRODUCTION

In the report published by organizations such as the European Commission and the US Department of Energy in 2023, considering global commodity supply and demand, 30 raw materials were identified as critical in terms of supply risk, with rare-earth elements ranked among the most critical.¹ REEs are indispensable to modern materials and energy technologies; although their usage by weight is relatively low, they impart superior mechanical, magnetic, electrical, and optical properties to materials.² Accordingly, REEs are widely used in advanced technological applications such as permanent magnets (electric vehicles, wind turbines,

aircraft), electrical and electronic devices (mobile phones, computers, TVs), rechargeable batteries, medical imaging systems (e.g., magnetic resonance imaging), catalytic converters, ceramics, oil refining, and solar panels.^{3–5} Based on their atomic number, ionic radius, and geochemical behavior, REEs are generally classified into light REEs (LREEs; La–Gd) and heavy REEs (HREEs; Tb–Lu).⁶ While LREEs are typically supplied from primary geological sources such as carbonatites, HREEs are mainly produced from secondary geological sources, including ion-adsorption clays and lateritic deposits.^{7,8} Despite their lower crustal abundance and reserves compared to LREEs, HREEs are particularly critical for defense, renewable energy, and high-tech industries.⁹

Rare-earth permanent magnets (NdPrFeB and SmCo) are so strong that they are at the heart of modern efficient engines that power electric

vehicles, wind turbines, and aircraft. They are highly preferred because they reduce power consumption and greenhouse gas emissions. In addition, with the widespread use of hybrid electric vehicles, wind turbines, and solar panels, the demand for REEs is increasing. According to the U.S. Geological Survey (USGS) data for 2025, global mine production of rare-earth oxides (REOs) equivalent was estimated at about 390,000 tonnes in 2024.¹⁰ It is predicted that the demand for neodymium in electric vehicles will increase 11-fold by 2032. The annual growth in NdFeB magnet consumption across different sectors is projected to increase steadily. The global consumption of sintered NdFeB magnets was 184,000 tons in 2022 and is expected to grow at an average annual rate of 5.8% in the coming years. Based on this trend, total demand is forecast to reach approximately 322,000 tons by 2032. From a sectoral perspective, electric vehicles are anticipated to account for around 32% of the total NdFeB magnet demand by 2032.¹¹

According to 2024 data, China accounts for approximately 69.23% of total REE mine production, followed by the United States (11.54%), Myanmar (7.95%), and Australia (3.33%).¹⁰ China holds a dominant position in the production of intermediate and end products, with an approximate share of 80%. This position has enabled China to utilize its REE reserves as a significant instrument in commercial, political, and strategic contexts. Today, the United States, Japan, and European Union member states remain largely dependent on China for REE supply due to limited domestic resources and challenges in competing with China in terms of production costs. For this reason, countries have begun to seek REE production from secondary geological sources with low U and Th contents. Among the secondary geological sources that can be used for REE production, red mud,¹² bauxite, related shale ores,^{13,14} and ionic clays,^{15,16} are remarkable. REE production from ionic clays outside China has been established at Serra Verde (Brazil), Liberty Hill (USA), and Zandskopdrift (South Africa) deposits. In addition, studies are ongoing in the Makuutu (Uganda), Koppamurra (Australia), Caldeira (Brazil), Brazilian rare earth (Brazil), and Ambasindava (Madagascar) deposits, which are known to be in the project phase.

Alumina (Al_2O_3) is commonly produced from bauxite ore using the Bayer process. High-silica bauxite is a type of bauxite characterized by a relatively high total SiO_2 content (typically > 8–10 wt.% SiO_2), in particular containing reactive silica phases such as kaolinite and halloysite. High-silica bauxites cannot be directly processed using the Bayer process because of their high caustic soda consumption, low alumina recovery, and increased red mud (RM) generation. Reactive silica is converted into insoluble sodium aluminosilicate hydrate, leading to substantial losses of both alumina and caustic soda.^{17,18} Bauxite deposits

suitable for the conventional Bayer process are limited on a global scale, and the reserves of such deposits are gradually declining. In contrast, high-silica bauxites are more widely distributed across many countries and constitute a significant proportion of total bauxite reserves. This situation necessitates the evaluation of high-silica bauxites as an alternative raw material source through the sustainable production of alumina and critical by-products. Several researchers have proposed methods to mitigate the issues associated with high-silica bauxites; however, due to certain technological and economic limitations, the silica challenge has not been fully resolved.

REE-bearing bauxites are considered a potential secondary geological source of REEs due to their enrichment in REEs. However, the use of bauxite as an REE source is limited due to geological, mineralogical, and process-related constraints. This limitation becomes evident when compared with bastnäsite ore. Bastnäsite $[(\text{Ce}, \text{La})(\text{CO}_3)\text{F}]$ typically contains a high total REO grade, ranging from approximately 3 wt.% to 15 wt.%, in which REEs are concentrated within a distinct mineral phase and can be processed using well-established hydrometallurgical routes on an industrial scale. In contrast, the total REE content of high-silica bauxites is generally low, typically at the ppm level. Moreover, REEs in these materials do not form a discrete mineral phase but are instead dispersed within clay minerals, Fe oxides, or various secondary phases. This dispersed occurrence significantly complicates the selective enrichment of REEs, leading to high acid consumption and complex solution chemistry issues. In addition, the high silica content adversely affects leaching kinetics and increases operational risks such as gel formation and precipitation. For these reasons, high-silica bauxite cannot technically or economically compete directly with primary REE ores. Nevertheless, this does not imply that high-silica bauxite is entirely insignificant in the context of global REE supply. On the contrary, when integrated into large-scale, existing processes such as alumina production, REE recovery from intermediate products and process residues may become feasible. Under this integrated processing approach, high-silica bauxites can be considered as a secondary strategic REE resource with meaningful potential.

Numerous studies have focused on the geochemical aspects, formation, and economic potential of REE-bearing bauxite.^{19–22} However, research on the sustainable production of REEs from REE-bearing bauxite ores, along with Al as a byproduct, is limited. Therefore, the primary objective of this study was to assess the potential for Al and REE recovery from bauxite. In this scope, the review focuses on pyrometallurgical (e.g., alkaline roasting) and hydrometallurgical (e.g., leaching) techniques but also include studies combining these two methods (roasting–leaching). A further aim of this review

is to comprehensively present and summarize the findings of recent research. Thus, current trends, research gaps, and potential directions for future studies are highlighted, aiming to provide a valuable resource for researchers in this field.

REE-BEARING BAUXITE ORE FORMATIONS

Karst bauxite is a type of bauxite deposit formed on carbonate rocks (particularly limestone and dolomite) or within their cavities and doline systems as a result of karstic weathering and residual enrichment processes. It is not directly classified within high-silica bauxites but is considered a distinct bauxite type. These deposits commonly contain REEs and are therefore regarded as a potential source. Representing approximately 14% of the world's bauxite resources,¹⁹ karst bauxites have recently attracted increasing attention due to their REE potential.^{20,22} Karst bauxite deposits of the Pedernales Peninsula (Dominican Republic) have high REE (La-Lu) contents ranging from ~ 500 ppm to ~ 14000 ppm. Two deposits in the Bahoruco area, Aceitillar and El Turco, stand out with average REE contents of ~ 1200 and ~ 7600 ppm and Y contents of ~ 700 ppm and ~ 8800 ppm, respectively. In these deposits, REE host minerals mainly consist of relict monazite, authigenic Y-dominant phosphates, and hydroxylbastnäsite.²³ Similar REE enrichments have been reported in karst-type bauxite mineralization in Mediterranean countries (such as Greece, Montenegro, Hungary, and Bosnia Herzegovina).²⁴ Karst bauxite deposits in the Southern Chongqing bauxite belt of China are rich in REEs. It has been determined that the source of REEs in these bauxite ores are bedrock host.

In karst-type bauxite formation processes, Al, Fe, and Ti are dissolved from source rocks during extremely acidic weathering and are deposited on karst surfaces. In the following process, it is formed by in-situ leaching, silicification, and enrichment of element concentrations in the karst drainage system.^{25,26} As a result of this process, bauxite deposits are enriched in relatively immobile elements such as Al, Ti, Zr, Nb, and REE in karst cavities.^{27,28} REE minerals such as monazite, xenotime and hydroxylbastnäsite are widely found in low concentrations in bauxite deposits.^{28–31} The most common REE-bearing minerals are hydroxylbastnäsite ($\text{Ce}(\text{CO}_3)(\text{OH})$) and detrital monazite, xenotime (YPO_4) and florensite type supergene phosphate ($(\text{REE})\text{Al}_3(\text{PO}_4)_2(\text{OH})_6$) minerals formed by the weathering of monazite ($(\text{Ce,La,Nd,Th})\text{PO}_4$).³² Normalized diagrams of Italy, Türkiye, Greece, the Balkan countries, and Mediterranean bauxites are shown in Fig. 1. Major oxide and REE contents of some REE-bearing bauxite deposits are given in Table I.

According to Fig. 1 and Table I, the geochemical trends of karst bauxites in different countries are similar. Table I shows that karst bauxites are rich in Ce and La relative to other REEs. The REE content in bauxite ores varies widely from 17 ppm to 3610 ppm, and most ores show an obvious positive Ce anomaly.³⁵ Researchers have stated that there is geochemical similarity between the bauxite deposits in the Bolkardağı region (Türkiye) and the ion adsorption clay deposits in China (Fig. 2). Considering the REE production from clays in the ion adsorption deposits of China, it is predicted that the Kızıldağ bauxite-associated shale and Kemiklitepe bauxite deposits in the Bolkardağı region may be potential sources.³¹

Greek bauxites formed during the Late Jurassic paleo relief in the Parnassos-Ghiona geotectonic zone have the highest average REE content of approximately 1280 ppm. This is followed by Jurassic bauxites from the Vojnik-Maganik and Prekorinica regions of Montenegro, with an average of approximately 1000 ppm, and Turkish bauxites from the Bolkardağı tectonic unit, with an average of approximately 950 ppm. The lowest average content is observed in Jurassic bauxites from the Čevo region of Montenegro, with an average of approximately 550 ppm, and in Greek bauxites from the Parnassos-Ghiona geotectonic zone, with an average of approximately 390 ppm. Regarding Cretaceous bauxites, the highest contents are found in the Caserta bauxites of Italy and the Provence and Languedoc bauxites of France, which exceed 700 ppm. In contrast, the lowest contents were recorded in Montenegro (~ 310 ppm), Greece (~ 420 ppm), and Spain (~ 440 ppm). Despite the uneven level of exploration and the average values obtained from the analyses of different numbers of samples, it can be concluded, based on the average REE contents, that the Jurassic bauxite formations have the highest potential for REE extraction.³⁶ Bauxite deposits are enriched in LREEs compared to HREEs. It has been stated that the preferential adsorption of LREE by kaolinite, illite, boehmite, diasporite and anatase results in separation from HREE.³⁶ The adsorption of REE on kaolinite and the REE adsorption model associated with the Al-octahedral layers of kaolinite are shown in Fig. 3.

REE EXTRACTION PROCESS FROM BAUXITE ORE

High-silica bauxite cannot be processed in the conventional Bayer process due to technological limitations. A high reactive silica content adversely affects process efficiency, especially during the Bayer process, as it leads to sodium losses and the formation of desilication products. Therefore, alternative methods such as direct acid leaching, flotation–Bayer, sintering, lime–soda, and alkaline roasting–leaching are applied for the recovery of aluminum from high-silica bauxite. The direct

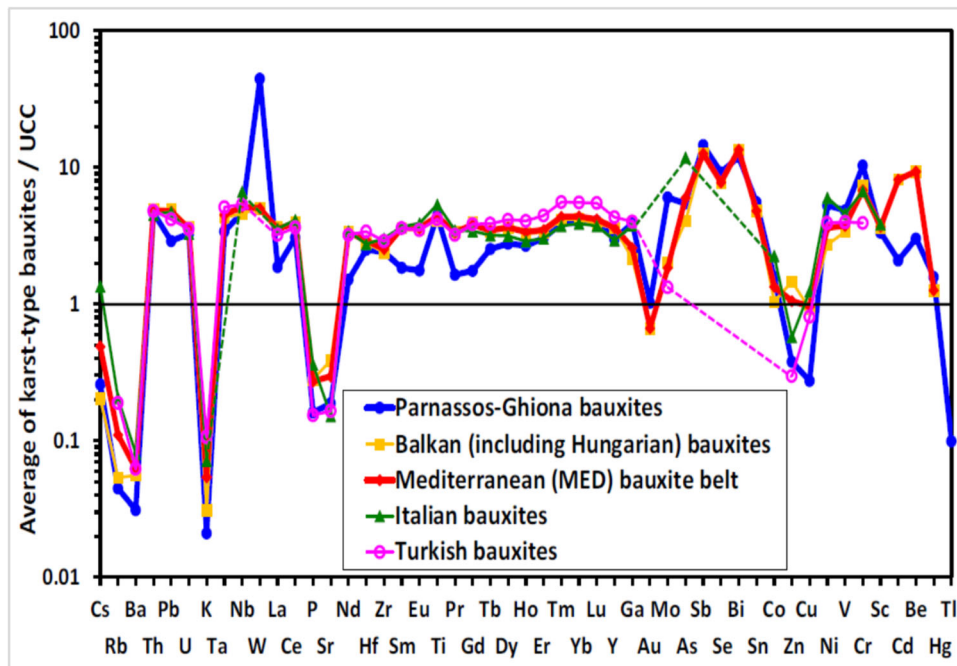


Fig. 1. Chondrite-normalized diagrams of karst bauxites of Italy, Türkiye, Greece (Parnassos), Balkan and Mediterranean bauxites belt (partially reprinted from Ref. 33, Copyright © 2018, The Minerals, Metals & Materials Society).

Table I. Major oxide and REE contents of some REE-rich bauxite deposits^{21,26,32–34}

Location	Al ₂ O ₃ (%)	SiO ₂ (%)	Fe ₂ O ₃ (%)	TiO ₂ (%)	Ce (ppm)	La (ppm)	Nd (ppm)	Y (ppm)	Ga (ppm)
Muğla, Türkiye	53	9.0	22	2.7	273	150	100	82	59
Jajce, Bosnia-Herzegovina	59	1.0	25	2.7	287	121	108	53	45
Halimba, Hungary	53	5.8	22	2.6	126	78	49	55	52
Nikšić, Montenegro	57	6.4	20	2.8	331	153	117	100	48
Parnassos, Greece	55	5.0	23	2.7	258	87	65	75	58
Suhodoll, Kosovo	56	4.2	27	2.8	310	165	120	92	63
Guangxi, China	58	3.5	24	3.0	340	180	135	65	75
Weipa, Australia	61	6.2	19	2.2	210	95	78	48	52
Odisha, India	49	7.5	28	3.5	380	170	142	105	69
Poços de Caldas, Brazil	54	5.8	23	2.9	320	155	118	88	60
Penjikent, Tajikistan	57	4.7	26	2.6	360	165	128	95	72

leaching method is considered an alternative approach for ores that are not amenable to processing by the conventional Bayer process. In this method, the ore is directly dissolved using acidic solutions, enabling the transfer of aluminum along with associated valuable elements into the solution phase. However, high reagent consumption, equipment corrosion, limited selectivity, and challenges related to waste management constitute the main disadvantages of this method. The sinter and Bayer–sinter processes are environmentally disadvantageous due to their high energy requirements and associated carbon emissions. The lime–soda method refers to an alkaline pretreatment (digestion) process carried out using lime (CaO/Ca(OH)₂)

and sodium carbonate (Na₂CO₃), facilitating the stabilization and/or removal of impurity phases prior to subsequent processing steps. This method exhibits an unfavorable environmental profile due to its high chemical consumption and significant waste generation potential. Although the alkaline roasting–leaching process produces acidic waste solutions, these can be effectively managed through neutralization and sulfate recovery. In the alkaline roasting–leaching process, the ore is roasted with alkaline (Na₂CO₃) at approximately 900°C, after which the resulting sodium aluminate phases are dissolved through water leaching. REEs and major elements (Al, Fe, Na, etc.) concentrated in the water leach residue are subsequently recovered via

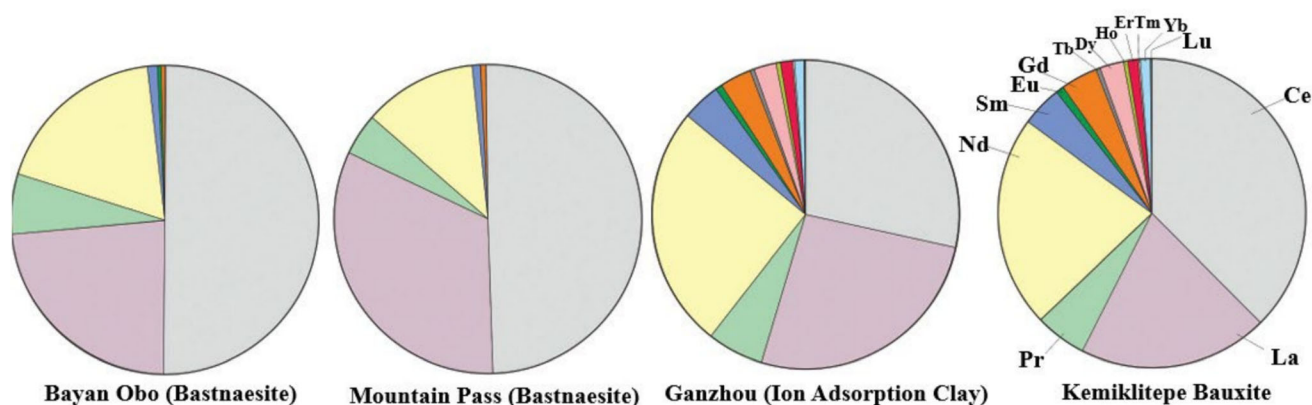


Fig. 2. Comparison of REE distribution of Bayan Obo (China), Mountain Pass (USA), Ganzhou ionic clay (China) and Kemiklitepe (Türkiye) bauxite deposits associated with carbonatite–alkaline igneous rocks (adapted from Ref. 34).

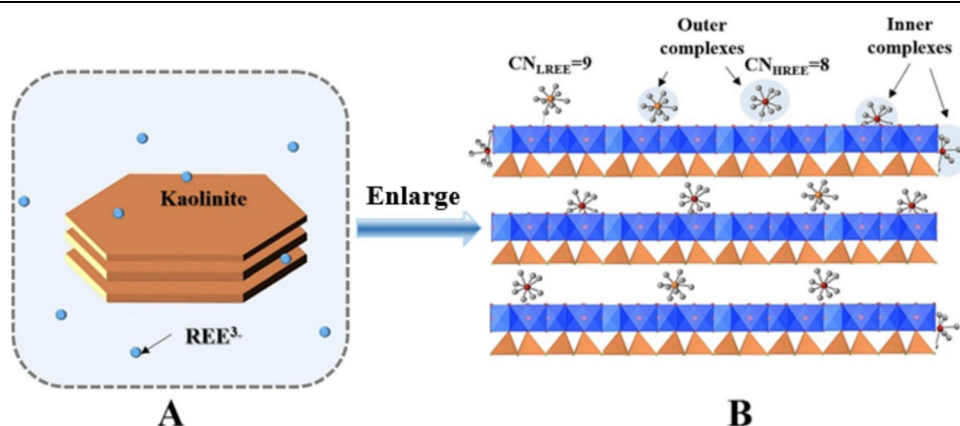


Fig. 3. Adsorption model of REE on kaolinite (a) and REE adsorption model associated with Al-octahedral layers of kaolinite (b) (reprinted from Ref. 37, under the terms of the Creative Commons CC BY 4.0 license).

sulfuric acid leaching, and the pregnant leach solution is purified by solvent extraction (SX). In contrast, the flotation–Bayer process is characterized by lower soda consumption and reduced RM generation due to pre-enrichment, and is therefore considered to have the most balanced environmental profile among the alternative methods.¹⁸ The purpose of the flotation process applied here is to reduce the silica content in bauxite, thereby serving as an important beneficiation step aimed at enhancing the efficiency of alumina production. However, despite these advantages, the flotation–Bayer process becomes economically inefficient for bauxites with a very low silica modulus, as high reactive silica contents lead to excessive caustic soda consumption and significant alumina losses during the Bayer process.^{38,39} Among these, the most feasible approaches are flotation–Bayer and alkaline roasting–leaching. In this study, the alkaline roasting–leaching–SX technology, as an ideal method for the simultaneous recovery of Al and REEs from high-silica bauxite, is examined in detail.

Due to the complex mineralogical composition of certain ores and their low beneficiation efficiency, direct leaching approaches may be preferred

without applying conventional mineral processing methods such as flotation.^{40–42} In such cases, thermal pretreatment steps, including alkaline roasting, can be employed to induce structural transformation of the ore and enhance leaching efficiency. For example, the flow chart suggested for REO production from Kemiklitepe (Türkiye) bauxite ore is given in Fig. 4. The comparison of REE production parameters from bastnäsite, ionic clay, and bauxite, which are the main minerals of REEs, is summarized in Table II. Borra et al.¹³ conducted a study to recover alumina, Fe, and Sc separately from Greek RM by combining of alkaline roasting with sodium carbonate (Na_2CO_3), followed by water leaching, smelting and acid leaching (Fig. 5). RM was alkaline roasted with Na_2CO_3 at 950°C , followed by water leaching, which dissolved approximately 75% of the alumina. The undissolved residue was smelted to recover over 98% of Fe, while about 80% of Sc was subsequently extracted from the slag by acid leaching. The authors highlighted that the process is nearly zero-waste, enabling the recovery of most major metals and REEs.

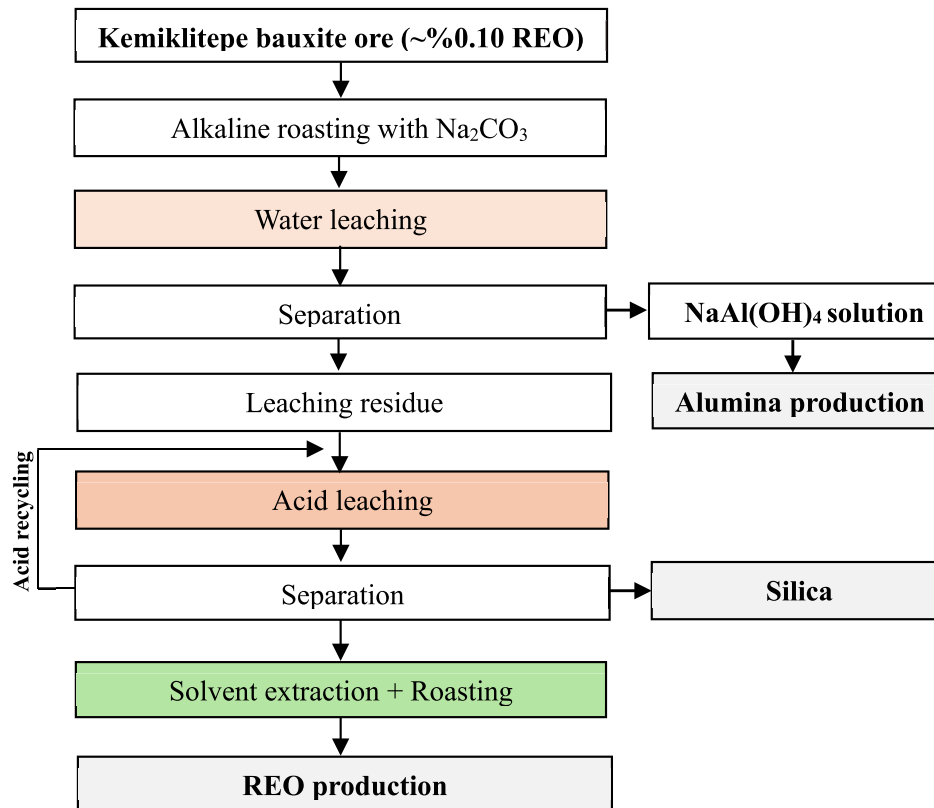


Fig. 4. Proposed process flowsheet for REO production from Kemiklitepe (Türkiye) bauxite ore.

Table II. Comparison between REE production from bastnäsite, ionic clay, and bauxite^{44,45}

Parameters	Bastnäsite	Ionic clay	Bauxite
REE content	7–10%	0.05–0.3%	0.05–0.3%
REE composition	50% Ce, 30% La, 15% Nd, 5% etc.	20 La%, 20 Nd%, 20 Y%, 10% Ce, 30% etc.	40% Ce, 30% La, 15% Nd, 10% Y, 5% etc.
Production method	Mineral processing, enrichment, acidic leaching	In situ leaching by ion exchange	Mineral processing, alkali roasting, acidic leaching
Solvent type	HCl and H ₂ SO ₄	NH ₄ -Mg-Al-SO ₄	HCl and H ₂ SO ₄

The recycling and reuse of leach solutions emerge as a critical parameter for process economics and sustainability, particularly in the evaluation of low-grade and secondary REE resources. Within the scope of this study, the process flowsheet proposed in Fig. 4 has been designed to integrate acid recovery and its recirculation to the leaching stage. Provided that appropriate pH regulation and impurity control are maintained, the residual acid content and the major ionic composition of the raffinate offer a recirculation potential capable of reducing additional reagent consumption. Nevertheless, the long-term effects of this approach, especially with respect to the accumulation of Al, Fe, and Si, phase stability, and leaching kinetics, need to be investigated in detail using pilot-scale or continuous systems. Accordingly, the recycling/recovery of

leach solutions and SX reagents, together with mass balance and economic analyses, are considered an integral component of advanced process development studies.

Thermal Activation via Alkaline Roasting

Prior to this section, different recovery methods for the utilization of high-silica bauxites were presented in general terms. In this section, alkaline roasting, which is considered the most suitable and necessary pretreatment method for REE recovery from high-silica bauxites, is discussed in greater detail. Alkaline roasting is an important pre-activation step that enhances the reactivity of bauxite, thereby reducing the high temperature requirements of subsequent hydrometallurgical processes.

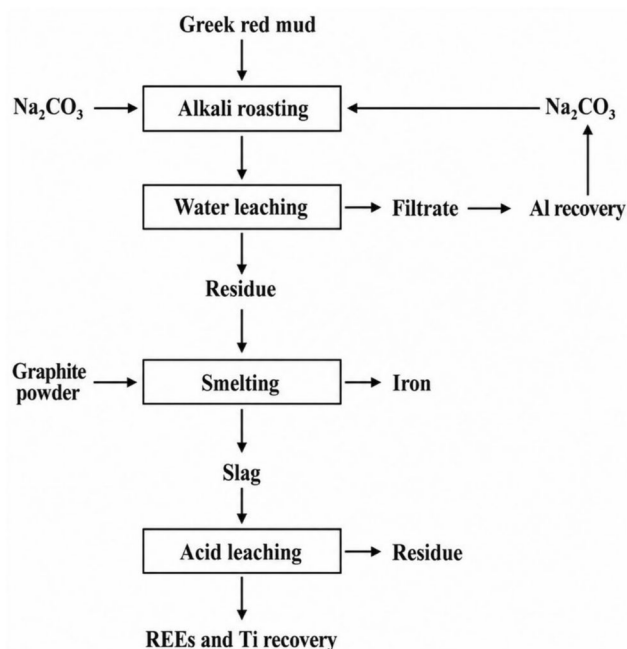
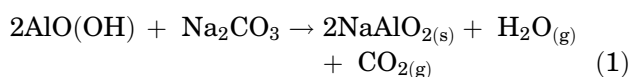


Fig. 5. Flow sheet for recovery of metals from Greek red mud (reprinted from Ref. 12, Copyright © 2016, The Minerals, Metals & Materials Society).

In this approach, sodium carbonate (Na_2CO_3) is the most commonly employed reagent due to its economic viability and widespread industrial use. However, alkaline roasting is not limited to Na_2CO_3 alone; in certain cases, the addition of CaO can provide a synergistic effect. In this context, the lime-soda sintering process can be considered a specific application of alkaline roasting. In this process, bauxite is mixed with CaO and Na_2CO_3 and heated at high temperatures to form a porous sintered structure. During this treatment, aluminum-bearing phases are converted into soluble sodium aluminate (NaAlO_2), while the primary role of CaO is to react with silica to form insoluble calcium silicate (Ca_2SiO_4), thereby suppressing silica dissolution into the solution phase. This enhances selectivity and improves the efficiency of the subsequent leaching stage. In the conventional lime-soda sintering process, the dosages of Na_2CO_3 and CaO are typically controlled based on molar ratios of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3 \approx 1$ and $\text{CaO}/\text{SiO}_2 \approx 2$.^{46,47} The dosage of alkaline additives is generally determined based on the content of the main components in the bauxite. In this study, since both Al_2O_3 and SiO_2 reacted with Na_2CO_3 during roasting, the $\text{Na}_2\text{O}/(\text{Al}_2\text{O}_3 + \text{SiO}_2)$ molar ratio was used as an indicator to control the Na_2CO_3 dosage. According to a previous study, the mixture was prepared with a $\text{Na}_2\text{O}/(\text{Al}_2\text{O}_3 + \text{SiO}_2)$ molar ratio of 1.⁴⁸ The reaction resulting from alkaline roasting is described as:



Literature studies on the effect of thermal activation on REE extraction are given in this section. Ji and Zhang⁴⁹ reported that REE recovery was less than 20% as a result of 1.2 M HCl leaching of kaolinite ore containing 245 ppm REE, while, after calcining the ore at 600°C , a recovery of over 80% was obtained in 0.01 M HCl . After REE recovery, porous silica with a specific surface area of $336.95 \text{ m}^2/\text{g}$ was produced as a result of H_2SO_4 leaching. In a different study, Ji et al.⁵⁰ investigated the effect of thermal activation on REE recovery from two natural kaolinite samples. While the leaching recovery of the samples without pretreatment was 10% and 56% in 1.2 M HCl , the leaching recovery in the samples calcined between 500°C and 900°C increased significantly and reached 93%. As a result, it was explained that calcination has positive effects on REE recovery. Accordingly, it was stated that encapsulated REE-containing minerals are released by the expansion of kaolinite aggregates and that REE-containing minerals are transformed into more soluble forms. Uysal⁴⁰ investigated the REE recoverability from Kemiklitepe bauxite ore (Türkiye). The milled bauxite ore was alkaline-roasted with Na_2CO_3 at 950°C , and then the roasted bauxite ore was subjected to water leaching. The total REE recovery from the ore was 89% as a result of H_2SO_4 leaching of the remaining leach waste after water leaching.

Mechanical Activation via Intensive Milling

Mechanical activation is defined as the “increase” in the ability of a solid whose chemical structure remains unchanged during the milling process in which mechanical energy transfer occurs. During mechanical activation, while the particle size of the mineral decreases with milling, defects occur in the crystal structure depending on the mechanical energy density.⁵¹ Thus, fresh, clean surfaces and metastable species are formed.⁵² Mechanical activation of minerals increases the selective dissolution efficiency and solvent efficiency during leaching, leading to an increase in the reaction rate.⁵³ This increase occurs as a result of an increase in specific surface area and structural disorder, an increase in microstress, amorphization of mineral crystals,⁵⁴ microtopographic changes,⁵⁵ and formation of new phases more susceptible to dissolution.⁵⁶ In the case of mechanical activation, the mineral will now behave more actively during a metallurgical process such as calcination,⁵⁷ sintering,^{58,59} or leaching,^{60,61} where it will be processed, and this will reduce the temperature of the process or increase its speed.

The mechanical activation method can be considered an alternative to thermal pretreatment, as it enhances leaching efficiency while offering lower

energy consumption and a more environmentally friendly process option. Mechanical activation can be realized at lower energy costs than thermal processing. In addition, it is known that in facilities where mechanical activation is applied, reactions occur in shorter times, and simpler and cheaper reactors or furnaces are used.⁶² While many studies have examined the effects of intensive milling on minerals, studies on the effect of mechanical activation on REE recovery are limited. Kato et al.⁶³ mechanically activated a decomposed residual ore containing britolite, cerianite, serite, and monazite by intensive milling to increase the solubility of cerium. The mechanical activation process reduced tetravalent (Ce^{+4}) cerium to trivalent (Ce^{+3}) and increased the solubility of cerium. According to the results of the leaching experiments with H_2SO_4 , it was emphasized that the Ce solubility increased not only because of the increase in the surface area of the ore but also by the mechanochemical reaction. In addition, it was determined that the main mechanism of the increase in Ce solubility with mechanical activation was not the increase in the leaching rate but the reduction of the insoluble tetravalent cerium in the cerianite component to the soluble +3 valence. The crystal lattice defects, oxygen vacancies, and locally reducing environments generated during mechanical activation render the reduction of Ce(IV) to Ce(III) in CeO_2 -like phases thermodynamically and kinetically feasible.⁶⁴ Notably, cerium is the only REE that can stably exist in the +4 oxidation state, which explains why the redox behavior observed during mechanochemical processing is largely confined to Ce. In contrast, because Pr, Nd, and the majority of other lanthanides predominantly occur in the stable +3 oxidation state under natural and processing conditions, there is no generalization that mechanical activation induces a similar reduction behavior for these elements. Instead, the literature indicates that the primary effect of mechanical activation on these REEs is an enhancement of leaching reactivity through phase disordering, amorphization, and increased solubility, rather than a change in valence state.^{65,66}

The effect of mechanical activation is generally applicable to bauxites with varying SiO_2 contents; however, this effect is strongly dependent on both the SiO_2 level and the mineralogical mode of silicon occurrence. Mechanical activation can enhance the leaching reactivity of Al-bearing phases (gibbsite, boehmite, and diaspore) as well as secondary mineral phases hosting REEs through structural modifications such as increased specific surface area, lattice distortion, amorphization, and increased dislocation density. Nevertheless, the presence of kaolinite and reactive silica phases may, particularly after mechanical activation, lead to gel formation during leaching, increased acid consumption, and challenges in solution management.⁴⁸ Within the scope of this study, the beneficial effect of

mechanical activation was therefore not treated as a general assumption but was evaluated by explicitly considering potential limitations associated with SiO_2 content. Accordingly, mechanical activation is not regarded as a universal solution for bauxites, but rather as an auxiliary pretreatment that can enhance Al and REE recovery under controlled conditions.

Leaching of Bauxite Ores

It is important to understand the binding mechanisms that dissolve REEs. REEs bound to clays consist of three main binding phases in terms of their leaching mechanisms,⁴³ which consist of water-soluble and ion-exchangeable phases, colloid precipitate phases, and mineral phases. A visual summary of these bonding phases is shown in Fig. 6.

In the water-soluble phase, REEs exhibit high solubility in water, whereas in the ion-exchangeable phase they can be efficiently recovered via ion exchange using monovalent salt solutions. The colloidal precipitate phase hosts REEs primarily as insoluble oxides, hydroxides, or as constituents of colloidal polymeric organometallic complexes, which generally require acid leaching for effective recovery. In contrast, REEs in the mineral-bound phase are structurally incorporated into crystal lattices and can only be liberated through combined calcination and subsequent acid leaching. In bauxites, REEs predominantly occur in ion-exchangeable, colloidal, and mineral-bound phases. Although the ion-exchangeable fraction is typically limited in abundance, it represents the most readily recoverable phase from a processing perspective. Consequently, bauxites should not be directly compared with ion-adsorption-type REE deposits. Within the ion-exchangeable phase, REEs are electrostatically adsorbed onto clay mineral surfaces or retained by weak, labile bonds. An increase in clay mineral content promotes REE adsorption onto these surfaces, thereby increasing the relative contribution of

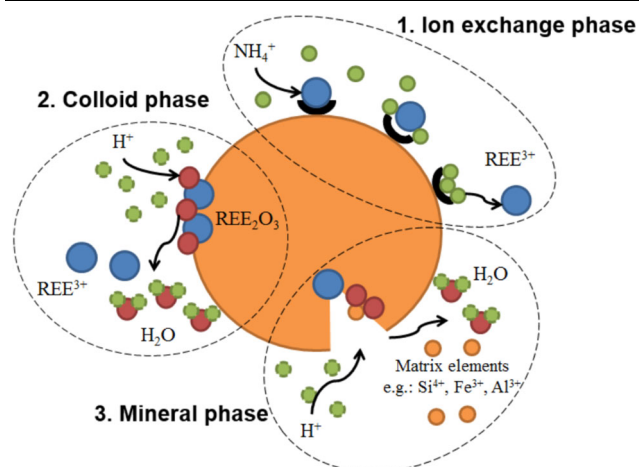
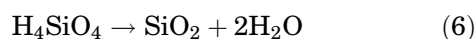
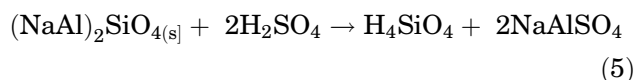
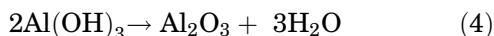
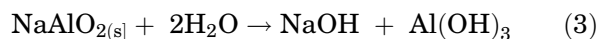


Fig. 6. Binding phases of REEs: 1 ion exchangeable phase, 2 colloid phase, 3 mineral phase (adapted from Ref. 67).

this fraction. The colloidal phase in bauxites is generally co-dominant. Elevated contents of low-crystallinity goethite and hematite enhance the proportion of colloidally-bound REEs due to their strong affinity for Fe-oxide surfaces. The mineral-bound phase constitutes the most chemically stable and strongly bound form of REEs and may occur in higher proportions relative to the other phases. The leaching reactions corresponding to these phases are presented in:



The bauxite ore was mixed with Na_2CO_3 and calcined at approximately 900°C , and the resulting calcined product was dissolved in hot pure water (Eq. 3). NaAlO_2 , which passes into the solution phase, is filtered and separated from the insoluble waste. Insoluble REE, Al, and Fe silicates ($(\text{REE,Al,Fe})_2\text{SiO}_4$) remained in the cake, which was dissolved with H_2SO_4 , resulting in the formation of silicic acid (H_4SiO_4) and sodium aluminum sulfate (Eqs. 4 and 5). Silica was obtained by removing water from the silicic acid structure (Eq. 6).

Kusrini et al.⁶⁸ the recovery of lanthanides from low-grade bauxite using the acid-leaching method was investigated. The effects of leaching parameters, including temperature, oxalic acid concentration, and leaching duration, were examined. The results showed that although the leaching efficiency was temperature-dependent, increasing the temperature from 45°C to 85°C did not improve lanthanide recovery. The optimum leaching conditions were determined to be 1 M oxalic acid, a temperature of 40°C , and a leaching time of 2 h. The findings demonstrate that oxalic acid is an effective reagent for the dissolution of lanthanides from low-grade bauxite. Uysal et al.¹⁵ investigated the usability of REE-bearing bauxite-associated shale ore in Kızıldağ (Türkiye) for REE production. HCl leaching was performed under different leaching conditions to determine the leaching optimization conditions for the raw ore. The modeling and optimization parameters for leaching recovery were investigated using response surface methodology. Accordingly, the optimum leaching parameters were determined as 1 M HCl concentration, leaching temperature of 98°C , leaching time of 3 h, and solution-to-ore ratio of 8.75 l/kg. The REE leaching recovery corresponding to the determined optimum values was 49.13%. Because leaching optimization

was performed on raw ore in this study, the obtained leaching recoveries were low. To increase the leaching ability, ore activation by calcination and/or intensive milling before leaching is recommended.

Alkaline methods are generally not suitable for alumina production from bauxites with a low silica modulus. In contrast, acid-based processes offer significant advantages, including the reduction of bauxite waste and the potential for waste recycling. In this context, Sun et al.⁴⁸ achieved zero-waste Al extraction from high-silica bauxite using a hybrid processing strategy. According to their study, sodium aluminate solution was obtained by water leaching of bauxite ore that had been alkaline-roasted with Na_2CO_3 , from which alumina was subsequently recovered. The solid residue remaining after water leaching was then subjected to sulfuric acid leaching, enabling the recovery of the remaining critical elements. The advantages and disadvantages of the main alumina extraction methods for high-silica bauxites are summarized in Table III. In the study conducted by Valeev et al.⁷³ boehmitic bauxite ore with high silica content in Severoonezhsk (Russia) could not be used in the Bayer process. To evaluate this ore, the bisulfate method (H_2SO_4 and NH_4HSO_4), which combines the advantages of acidic and alkaline methods, was tested. Accordingly, it was determined that the solubilities of Al, Fe, and Ga were greater than 90%, and that most of the silica and titania remained in the cake. In addition, an REE leaching efficiency of 70–80% was achieved. According to the results obtained, it was stated that it could be an effective technology for the processing of high-silica bauxites. Alkaline roasting and acid leaching are promising and suitable methods for evaluating high-silica bauxite ores. Thus, it is an alternative source that will meet the REE demand by ensuring the sustainable production of Al together with REEs, can be obtained from these karstic bauxite deposits that are REE-bearing. The utilization of sulfuric acid as a leaching reagent results in significant environmental pollution. Excessive acid is detrimental to soil and water ecosystems, subsequently affecting flora and fauna. In summary, the selection of leaching agents should consider environmental sustainability, leaching efficiency, and commercial availability.

Solution Purification

In the pregnant leach solution where the acidic leaching process lacks selectivity, impurities such as Al, Fe, and Na will be present in the solution. These impurities are anticipated to adversely affect the quality of the REE and by-products to be obtained. Consequently, there is a risk of decreased selectivity. As the leaching process conducted in short durations increases selectivity, it may be performed gradually in brief intervals. The removal

Table III. Advantages and disadvantages of alumina production methods for high-silica bauxite ores

Process	Advantages	Disadvantages	References
Sinter process	Lower competition with silica; generally lower red mud volume	High energy cost due to elevated temperatures; complex phase equilibria	69
Bayer–sinter process	Potential to reduce sodium loss; possibility of increasing overall alumina recovery	High energy consumption; operational complexity due to dual-process management	70
Lime–soda process	Silica can be immobilized by binding to Ca phases; potential for lower operating costs	Low solubility of Ca–aluminate phases; difficult phase control; limited commercial maturity	71
Flotation–Bayer process	Provides Bayer-compatible ore feed; reduced sodium loss.	High chemical cost; flotation efficiency depends strongly on ore mineralogy.	72
Alkali roasting–leaching process	Silica is bound to more inert phases; reduced Na loss; high alumina solubility; lower waste volume.	Corrosion and cost issues; technology is not yet fully commercialized.	48, 73

of dissolved metal ions such as Al, Fe, and Na in the leach solution containing predominantly REE ions is typically accomplished through selective precipitation at varying pH levels and/or SX methods.

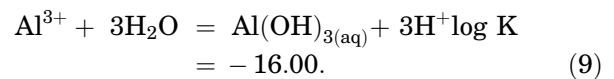
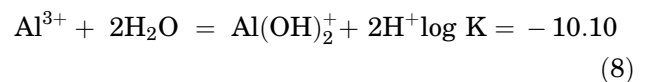
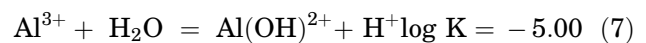
Precipitation

Precipitation is a process wherein a precipitant is introduced to the pregnant solution, resulting in the acquisition of metal ions as precipitates.⁷⁴ Common precipitants include oxalates, carbonates, sulfates, phosphates, and hydroxides. In the study conducted by Han,⁷⁴ oxalate was identified as the most effective precipitant, exhibiting superior precipitation behavior for REEs even at low pH levels. This is attributed to the generally high affinity of oxalic acid for REEs.^{75,76} The order of precipitation efficacy was determined to be oxalate > phosphate > fluoride > sulfate > carbonate. Nawab et al.⁷⁷ investigated the experimental parameters and morphology of oxalate precipitations in chlorinated rare-earth solutions in the presence of contaminant elements such as Al, Fe, and Na. Their findings indicated that the quantity of precipitant and solution pH were the most significant factors influencing the reaction. Under specific conditions, the precipitation rate of REEs reached 98.9%.

The general objective of precipitation in this context is either the removal of Al, Fe, and Na from the solution prior to REE recovery or the direct precipitation of REEs while allowing these elements to remain in the solution. In the selective precipitation process, the removal of impurities can be effectively achieved through controlled precipitation conditions, often guided by Eh–pH diagrams to optimize phase stability and separation efficiency. For instance, the Eh–pH diagram of the La–Ce–Al–H₂O system based on fundamental thermodynamic data is presented in Fig. 7.

According to Fig. 7, it can be observed from the Eh–pH diagram that Al³⁺ exhibits stability when the pH value is below 3.8, and the stable region for La³⁺

and Ce³⁺ in the solution is below pH 6.2. Based on this diagram, the theoretical leaching pH value at which both aluminum and REEs demonstrate stability should be below 3.8. Furthermore, REE–Al separation can be achieved through gradual precipitation of Al at approximately pH 4, and La and Ce at pH 7. The extraction rate of Al increases slowly with the pH values in the range 1.5–3.0 and increases quickly in the range 3–4. This is attributed to the formation of transient or metastable-state mononuclear and multinuclear compounds by hydrolysis, polymerization, flocculation, and precipitation with increasing pH value. The most common hydroxyl polymeric aluminum ions include Al(OH)²⁺, Al(OH)₂⁺, Al(OH)_{3(aq)}, Al(OH)₄[–], Al₂(OH)₂⁴⁺, Al₃(OH)₄⁵⁺, Al₆(OH)₁₅³⁺, Al₇(OH)₁₇⁴⁺, Al₈(OH)₂₀⁴⁺, and Al₁₃O₄(OH)₂₄⁷⁺. The equilibrium reactions are presented in:⁸⁰



Solvent Extraction

SX is a hydrometallurgical separation technique used to selectively transfer metal ions from an aqueous phase into an immiscible organic phase using specific extractants. In this context, the SX process is applied to separate impurities such as REEs, Al, and Fe from the pregnant leach solution. In the SX process, the optimal conditions should be determined by considering multiple critical parameters, including the types of reagents to be employed

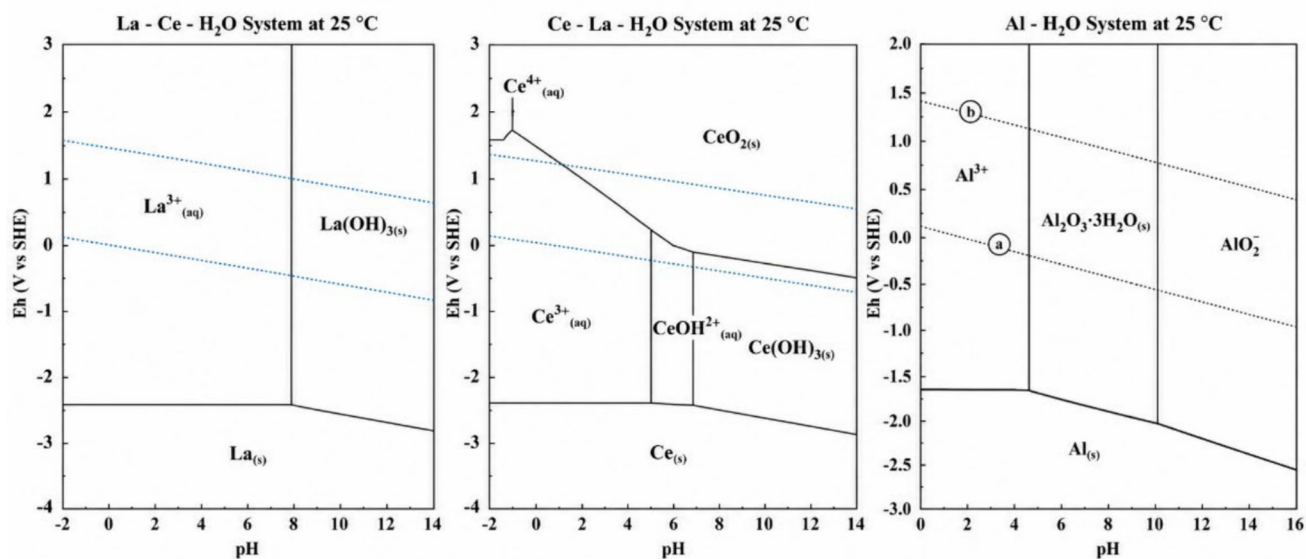
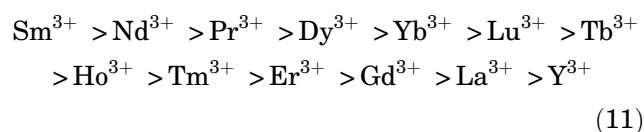
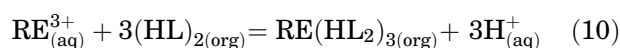


Fig. 7. Eh–pH diagram of the La–Ce–Al–H₂O system at 25 °C, 10^{−3} M and 1 bar pressure (adapted from Ref. 78, under the terms of the Creative Commons CC BY 4.0 license, and from Ref. 79, Copyright © 2020, Springer Nature).

for impurity removal, their quantities, reaction duration, organic/aqueous phase ratio, selective or batch SX feasibility, and the characteristics of the medium in which the loading and stripping processes will occur. In recent years, researchers have identified various types of extractants. However, a limited number of extractants are employed in industrial applications. For an extractant to be utilized industrially, it must exhibit low operating costs and provide effective separation. Di-2-ethyl-hexyl-phosphoric acid (D2EHPA), 2-ethyl-hexyl-2-ethyl-hexyl-phosphonic acid (EHEHPA), versatic acid, and Aliquat 336 (C₂₅H₅₄ClN) are reagents that are generally used in hydrometallurgical systems for solvent extraction.^{81,82} In this study, the main extractants specifically applied in the solvent extraction of REEs are considered. For the selective removal of impurities such as Al and Fe from REE-bearing solutions, more selective extractants such as D2EHPA,^{83,84} saponified naphthenic acid,^{85,86} and tri-*n*-butyl phosphate, are preferentially used. In the stripping stage, the type of acid utilized in the leaching stage is generally employed.

At present, D2EHPA, and naphthenic acid are the most widely used extractants in REE extraction process. Naphthenic acid (NA) is produced from petroleum or crude oil and are mainly composed of cyclic aliphatic monocarboxylic acids with varying composition. The major advantages of NA are low cost, high loading capacity in regard to REEs and easy stripping.⁸⁷ NA as a weak organic acid can be denoted by HL. The extraction of RE³⁺ by naphthenic acid is a cation-exchange mechanism (Eq. 10). The rare-earth extraction sequence in naphthenic acid–mixed alcohol–kerosene–HCl system at pH 4.8–5.1 follows⁸⁸ Eq. 11:



To evaluate the effect of pH on the separation of REEs and Al, experiments were conducted at room temperature using a 1.5 M extractant concentration and a fixed saponification value at different pH levels. The results, as shown in Fig. 8, indicate that an increase in pH leads to a significant enhancement in REE extraction efficiency.

D2EHPA is one of the most widely used REE extractants from the organophosphorus group.

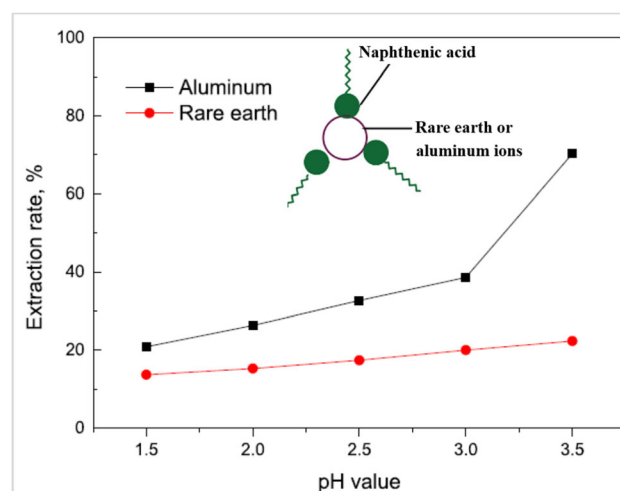


Fig. 8. Effect of pH value on the extraction rate of REE and Al (adapted from Ref. 85).

Peppard et al.⁸⁹ studied the properties and application of D2EHPA as an extractant for the separation of REEs. D2EHPA has the ability to reduce the total number of extraction steps required for REE separation. They also discovered that D2EHPA, which is mostly in dimer form, has a high affinity for REE³⁺ ions, indicating that pH has a significant effect on the reaction.^{89,90} Sato⁹¹ studied the behavior of REEs in HCl with D2EHPA and EHEHPA. The study concluded that REEs follow the cation exchange mechanism at low acidity and the solvent mechanism at high acidity. Both extractants showed higher extraction efficiency for metals with larger atomic numbers in the lanthanide series. The extraction efficiency was found to be La < Ce < Pr < Nd < Sm < Eu < Gd < Tb < Dy (~Y) < Ho < Er < Tm < Yb < Lu. The possible explanation for this is the attraction effect of the extractant anion and the increase in electrostatic force causes the size of the cation to decrease.⁸¹

Following the selective separation of metal ions from the pregnant leach solution, REEs are typically precipitated selectively using oxalic acid. The resulting REE oxalate hydrates (REE₂(C₂O₄)₃ · nH₂O) are subsequently converted into REO by calcination in the temperature range of 800–1000°C. The oxalate precipitation method is widely recommended in the literature, particularly due to its ability to limit the co-precipitation of Fe and other base metals.^{92,93} Chen et al.⁹³ compared the effects of calcination after precipitation with oxalic acid, sodium carbonate, and bisulfate for the preparation of REOs. The REE recoveries in the three processes were 99.44%, 97.95%, and 99.12%, respectively. Among these, precipitation with oxalic acid recovered the highest purity but at a higher cost. Xu et al.⁹⁴ implemented a stepwise precipitation process utilizing NaOH as a pH adjuster to recover REEs and Al. By adjusting the pH value of the pregnant leach solution to 4.5, 99% of the Al and < 1% of the REEs were precipitated. Subsequently, by adjusting the pH value in the pregnant leach solution to 8.5, 99% of the REEs were precipitated. As a result of this precipitation process, the purity of Al(OH)₃ was determined to be 82% Al₂O₃, with the total content of metal impurities being less than 5%. The purity of RE(OH)₃ was determined to be 93% REO, with other base metals comprising less than 2%. Erust and Uysal⁹⁵ demonstrated that aluminum can be selectively purified from REEs in the pregnant leaching solution obtained after acid leaching of bauxite-related shale ore using the SX method. Under optimized SX conditions (1.5 M D2EHPA, 50% O/A ratio, pH 1.5, and 15-min mixing time), the total REE extraction efficiency reached 95%, with the element-specific extraction order determined as Pr > La > Nd > Ce > Dy > Y > Sc. Furthermore, following REE separation, Al(OH)₃ was precipitated with an efficiency of 97.16% at pH 5 by electrolysis from the Al- and Fe-enriched solution. The resulting

precipitate was subsequently roasted at 1100°C to produce coarse-purity α -alumina containing approximately 75% Al₂O₃.

CURRENT ASSESSMENT AND FUTURE PERSPECTIVES

In recent years, significant progress has been made in the recovery of Al and REEs from bauxite. Hybrid processes, such as alkaline roasting-leaching, and environmentally friendly biosorption-based approaches, have attracted increasing attention due to their technical feasibility and sustainability potential. In particular, deep eutectic solvents, considered as alternatives to conventional mineral acids, offer environmentally benign leaching media and can provide both technical and economic advantages. Therefore, parameters such as energy consumption, CO₂ emissions, chemical usage, waste disposal costs, process efficiency, and investment requirements should be comprehensively evaluated. Moreover, sustainability is not limited to technical performance but also encompasses social and environmental aspects. In this context, water usage, waste disposal, generation of hazardous by-products, and overall environmental impacts should be assessed within a life cycle assessment framework.

Hybrid processes, such as integrated multi-step approaches combining biological pre-treatment, alkaline roasting, leaching, and solvent extraction, have the potential to combine the advantages of individual methods while minimizing their respective drawbacks. In addition, the development of processes aimed at the simultaneous recovery of not only the primary product (Al) but also critical by-products such as REEs is considered an ideal approach for sustainable mining.

Manfredi et al.⁹⁶ reported that the use of the microalga, *Galdieria sulphuraria*, in repeated adsorption-desorption cycles enabled the recovery of REEs from bauxite suspensions at 5–30% (w/w). This approach combines biological and chemical processes to enhance recovery efficiency while potentially reducing environmental impacts. However, biosorption processes generally exhibit low REE yields, while chemical methods are constrained by high energy requirements, intensive reagent consumption, and waste generation. Therefore, the development of biotechnology-based methods and environmentally friendly leaching processes to mitigate these limitations is of great importance. Bacteria- and microalgae-based biosorption methods are still at the developmental stage. In particular, more comprehensive research is needed on the selective recovery of REEs, optimization of adsorption-desorption cycles, and the reuse of biosorbents. These biotechnological and hybrid approaches can reduce chemical consumption and energy requirements in conventional leaching processes, thereby minimizing environmental burdens and waste generation.

CONCLUSION

REE mining globally is derived from primary geological sources like carbonatite and alkaline complexes, as well as secondary sources such as ionic clays, RM, and bauxite ores. It is evaluated that REE recovery directly with Al from bauxite ore is easier than REE recovery from RM. This study details the process of producing REEs, aluminum, and silica from bauxite ore using a sustainable, zero-waste technology. Karst bauxites are considered a potential REE source due to their high REE content worldwide. Research is ongoing regarding the feasibility of REE production from these sources. In this context, for REE production from bauxites, it is crucial to thoroughly define the mineralogy and geochemistry of the ore and to develop the recovery method accordingly. Since REEs are typically bound to the crystal lattice structure in bauxite ore, they require thermal and/or mechanical activation before leaching to enhance solubility. The thermal activation process poses an environmental challenge due to the costs associated with roasting and fossil fuel consumption. To mitigate fossil fuel use and improve energy efficiency, it has been suggested that incorporating mechanical activator mills before roasting could be a more economical and environmentally friendly approach. It is anticipated that future research on REE production will concentrate on scaling the process to industrial conditions, conducting techno-economic evaluations, and focusing on reactive recycling and energy efficiency.

The process of REE recovery from RM is quite difficult. It has been stated in some studies that direct REE recovery with Al from bauxite ore is easier. Consequently, REE-bearing bauxite ores hold potential for use in REO production. The development of REE production technology from alternative sources such as bauxite can reduce the global REE supply risk. Utilizing this REE-bearing bauxite ore in environmentally friendly and zero-waste critical REE production is crucial for sustainable raw material use. Although the simultaneous recovery of Al and REEs from bauxite still presents several challenges, significant scientific advances have been achieved in recent years. It is considered that future progress will depend on the transfer of these approaches to industrial scale, the optimization of process parameters, effective waste management, and the development of techno-economic and circular economy based integrated methods.

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Turan Uysal: Investigation, Methodology, Writing—original draft. Yayat Iman Supriyatna: Investigation, Validation, Writing—review and editing, Supervision.

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CONFLICT OF INTEREST

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

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