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Investigation of Rare Earth Elements from Coal-Derived Minerals of Sawahlunto Formation and Leaching Behavior Under NaOH and HCl Washing Treatment

Arif Algifari[1], Fitri Nauli[2], Andri Van Deni[3], Siti Aisyah[4], Dwi Wulan Syakira[5]
[1,2,3,4,5] Mining Engineering, Universitas Negeri Padang, Padang, Indonesia
author emails: [1]a.algifari@ft.unp.ac.id, [2]fitrinauli@ft.unp.ac.id , [3]andrivandeni@unp.ac.id
[4]sitiaisyah032207@gmail.com , [5]dwiwulansyakira@gmail.com

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ABSTRACT

The growing demand for rare earth elements (REE) in modern technological applications has encouraged the exploration of alternative REE sources, including minerals associated with coal. This study aims to evaluate the potential of minerals in the Sawahlunto Formation coal from the Ombilin Basin as a secondary REE source through an alkaline leaching approach. Coal samples from the Sawahlunto Formation were subjected to alkaline leaching using sodium hydroxide solutions of 200–600 g/L at temperatures of 38–78 °C for 0.5–1.5 hours, followed by an acid-washing stage using 14% hydrochloric acid. X-ray fluorescence analysis identified yttrium, lanthanum, and cesium, with a total initial REE content of approximately 181 ppm. The leaching results show that under optimal conditions 400 g/L NaOH, 78 °C, and a particle size of 60/70 mesh, the residual REE content decreased to 2 ppm, indicating effective dissolution of REE-bearing mineral components. Subsequent acid washing further enhanced REE recovery by removing remaining soluble phases. These results demonstrate that coal from the Sawahlunto Formation possesses promising characteristics as a secondary REE source.

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A. INTRODUCTION

Along with the advancement of modern technology, the use of rare earth elements (REE) has increased significantly. This growth is primarily driven by the crucial role of REE in various strategic sectors such as electronics, electric vehicles, wind turbines, defense systems, and renewable energy technologies (Prasodjo, 2024). REE are used as key components in Nd-based permanent magnets (SYAMSUR, 2023) and various industrial catalysts. Catalytic cracking, which generally employs zeolite Y-based catalysts (Algifari et al., 2025), is modified by exchanging with REY ions. Rare Earth Elements plus Yttrium containing lanthanum, cerium, neodymium, praseodymium, and yttrium (Aulia Agus Patria and Ferian Anggara, 2022), as catalyst stabilizers (Martínez et al., 2023). However, despite the continuously growing global demand, the availability of REE remains highly dependent on certain production regions, posing challenges in terms of supply stability and resource security. This condition highlights the urgency of identifying new, locally available REE sources, especially in countries like Indonesia that still rely on imports for strategic mineral supply.

In recent years, scientific and industrial attention has increasingly been directed toward alternative REE sources, including secondary resources such as industrial residues, mine tailings, and even REE-bearing minerals in coal. One region with promising potential is the Sawahlunto Formation, located in the western to central part of the Ombilin Basin, West Sumatra, Indonesia (Algifari et al., 2023). This formation is one of the oldest coal-producing regions in Indonesia, particularly seam C, which has been extensively mined. Geologically, the coal in this formation was deposited in a freshwater environment and contains various inorganic minerals such as quartz, calcite, and kaolinite, which are suspected to be associated with REE enrichment (Agus & Anggara, 2022).

Several previous studies have identified the presence of REE in the mineral fractions of coal from the Sawahlunto Formation and other formations within the Ombilin Basin. Research conducted by Patria and Anggara (Aulia Agus Patria and Ferian Anggara, 2022; Patria & Anggara, 2021), revealed that minerals in seams B and C of the Sawahlunto Formation, as well as in basement and intrusive rocks, including andesite and granitoid, contain the fifteen rare earth elements are La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Y, Ho, Er, Tm, Yb, and Lu. Although the concentrations range between 0 and 100 ppm, these findings demonstrate detectable and consistent REE occurrences across various geological matrices. However, these studies primarily focus on mineral identification and geochemical characteristics, without examining the extractability or leaching behavior of REE from the coal matrix. This represents a clear gap in the current state of the art.

Globally, several researchers have explored REE extraction from coal-related materials, particularly coal ash, using alkaline or acid leaching methods. One notable example is the study by Mei Li et al. (M. Li et al., 2020), who successfully extracted REE through roasting with NaOH at 550 °C for 60 minutes at a NaOH-to-concentrate mass ratio of 0.6:1, followed by leaching with 6.0 mol/L HCl at 90 °C. Their process achieved extraction conversions of up to 92.5%, demonstrating the effectiveness of combined alkaline–acid treatment. Despite these developments, no research has yet applied this combined NaOH–HCl leaching approach directly to raw coal minerals from the Sawahlunto Formation. Likewise, no prior studies have evaluated how operational parameters such as reagent concentration, temperature, reaction time, and particle size, affect REE release from this specific coal type. This establishes the novelty of the present study.

This study focuses on seam C coal from the Sawahlunto Formation with the objectives of (1) investigating the REE content in coal minerals and (2) evaluating the leaching behavior of REE using NaOH and HCl treatments under various operating conditions. The development of REE extraction technologies from coal not only provides an opportunity to utilize local mineral resources more optimally but also supports Indonesia's downstream mineral strategy. Given the distinctive geochemical characteristics of Indonesian coal such as ash composition and associated minerals like kaolinite and silicates, chemical leaching methods offer a promising pathway. Examination of reaction parameters is crucial for understanding the mechanisms of REE release from the coal mineral structure and for determining the feasibility of Sawahlunto coal as a secondary REE resource.

B. METHODS

The research began with a geological survey at an active mining site in the Kandi area of Sawahlunto, West Sumatra. Secondary geological data, including regional geological maps and the stratigraphy of the Sawahlunto Formation, were collected to determine the geological setting and locate the target coal seam C. Representative coal samples were then obtained from the mining site and prepared through drying, crushing, and sieving to achieve a uniform particle size of 60/70 mesh. These samples were used for two main stages: preliminary characterization and leaching experiments.

Preliminary characterization was carried out using X-ray Diffraction and X-ray Fluorescence analysis to quantify the concentration of rare earth elements along with other major elements, providing baseline REE content prior to leaching. The leaching stage involved treating coal samples with NaOH solutions at concentrations of 200 g/L, 400 g/L, and 600 g/L, conducted at reaction temperatures of 38°C, 58°C, and 78°C for durations of 0.5, 1, and 1.5 hours. The leaching experiments were performed using a simple stirred reactor consisting of a heating plate, magnetic stirrer, insulated vessel, reflux system, and thermometer as shown in Figure 1. During operation, the coal–NaOH slurry was heated to the desired temperature while being continuously agitated to enhance solid–liquid interaction, with the insulation minimizing heat loss and the reflux preventing solvent evaporation. Temperature was monitored throughout the reaction to ensure stable operating conditions.

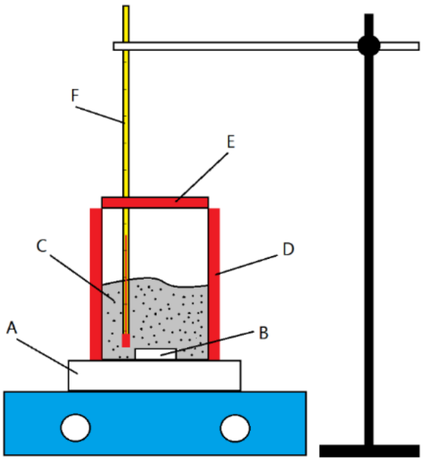

Figure 1. Simple stirred reactor for leaching: (A) Heating plate, (B) Magnetic stirrer, (C) Solid–liquid reactants, (D) Insulation jacket, (E) Simple reflux, (F) Thermometer.

To assess the feasibility of REE extraction, a comparative evaluation was conducted by the measurement REE content in both raw and leached coal samples from the Sawahlunto Formation. This comparison provided an initial indication of the potential for REE recovery and served as a basis for further development, including process optimization, advanced separation methods, and possible integration with other REE resources in Indonesia.

C. RESULT AND DISCUSSION

1. Geological Setting and Genesis of REE in Sawahlunto Formation Coal

The Ombilin Basin in West Sumatra is the result of tectonic dynamics driven by westward subduction, which created a subsidence zone and the accumulation of non-marine sediments since the early Paleogene (Zonneveld et al., 2012). The basin comprises seven Tertiary-aged rock formations, including the Sawahlunto Formation, which contains Eocene coal with a total thickness of more than 8 meters, interbedded with mudstone, siltstone, and quartz sandstone (Belkin et al., 2009). Its formation was influenced by orocline shear faults within a transpressional zone resulting from the subduction of the Indo-Australian Plate, as well as the uplift of the Bukit Barisan Mountains (Patria & Anggara, 2022). The older Sangkarewang Formation indicates a freshwater depositional environment (Algifari et al., 2023), whereas marine conditions first appeared in the early Miocene with the presence of fossiliferous limestone (Zonneveld et al., 2012). Field stratigraphy shows the dominance of reddish claystone, shale, and quartz–olivine sandstone in formations such as Brani and Sangkarewang, indicating basin fill thicknesses of up to 4,600 meters during the Cenozoic (Koesoemadinata, 1981). Structurally, the basin is classified as an intermontane basin with active structural deformation (Algifari et al., 2023).

The Sawahlunto Formation, as shown in Figure 2, is composed of abundant coal seams, shale, siltstone, and sandstone (Algifari et al., 2023). The thickness of this formation ranges from 100 to 200 meters and represents fluvial depositional environments formed during the late Oligocene to early Miocene (Koesoemadinata, 1981). Within this formation, three main coal seams, designated as seams A, B, and C are found, with seam splitting observed in certain locations. Based on the lithological cross-section in Figure 2, the formation consists of repeated sequences of claystone, sandstone, shale, silty shale, and siltstone with quartz sand content, interbedded with thin layers of grayish-brown coal. Carbonaceous components such as coaly shale and underclay dominate the overburden and interburden, imparting a gray coloration to the host rocks (Algifari et al., 2023). The sedimentary features exhibit a fining-upward pattern, with sedimentary structures including low-angle cross bedding, current ripple lamination, and sharp erosional bases, which are characteristic of point bar facies (Algifari et al., 2023).

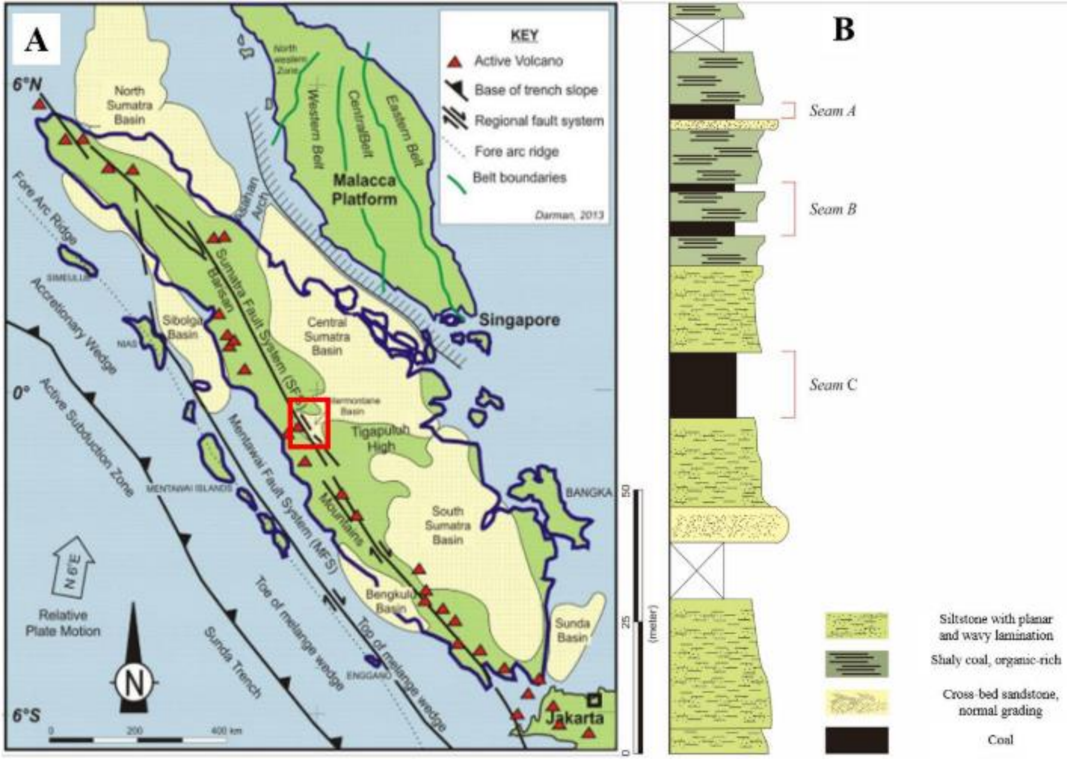

Figure 2. (A) Location of the Sawahlunto Formation on Sumatra Island, (B) Stratigraphy of the Sawahlunto Formation layers in the Ombilin Basin (Aulia Agus Patria and Ferian Anggara, 2022)

The genesis of rare earth elements in the Sawahlunto Formation coal of the Ombilin Basin is classified as a secondary deposit (Vansla et al., 2023). According to Patria and Anggara (Patria & Anggara, 2022), it originates from a combination of primary rock weathering and diagenetic transformation in a reducing swamp environment. Geochemical analyses indicate that REY (rare earth elements and yttrium) are distributed in both organically and inorganically bound forms, primarily associated with clay minerals such as kaolinite and sulfide minerals such as sphalerite. The main source of REY is thought to be the weathering of basement rocks and intrusive bodies comprising granite, basaltic andesite, and surrounding metamorphic rocks, that were transported as detrital material into the peat environment. Geochemical ratios such as Al_2O_3/TiO_2 and the positive anomalies of Eu and La support the interpretation that REY-bearing materials originated from intermediate to felsic igneous rocks.

2. Mineral Composition in the Sawahlunto Formation Coal

The initial stage in characterizing the C-seam coal of the Sawahlunto Formation began with the identification of inorganic minerals using X-ray Diffraction analysis, as shown in

Figure 3, to complement the chemical composition data obtained from the previous X-ray Fluorescence test. This coal is classified as coking coal, making it important to understand its mineral phases, as they influence both coking performance and the potential extraction of associated elements such as REEs. The XRD analysis was conducted by comparing the sample's diffractogram with standard diffractograms of common minerals typically found in coal, such as quartz, pyrite, kaolinite, and calcite. The diffraction pattern shows a strong peak at a 2θ angle of around 26°, indicating the presence of quartz (Sriramoju et al., 2021), as well as peaks at approximately 33°, 37°, and 56°, which are characteristic of pyrite (X. Li et al., 2020). The presence of kaolinite is confirmed by peaks at around 12° and 25° 2θ (Y. Li et al., 2023), while calcite appears at around 29.5° 2θ (Al-Jaroudi et al., 2007). However, it should be noted that XRD generally only identifies major minerals present in significant amounts, such as kaolinite (K) and quartz (Q), and is not sensitive to minor phases or trace elements like REEs. Therefore, further analysis using methods such as XRF is required.

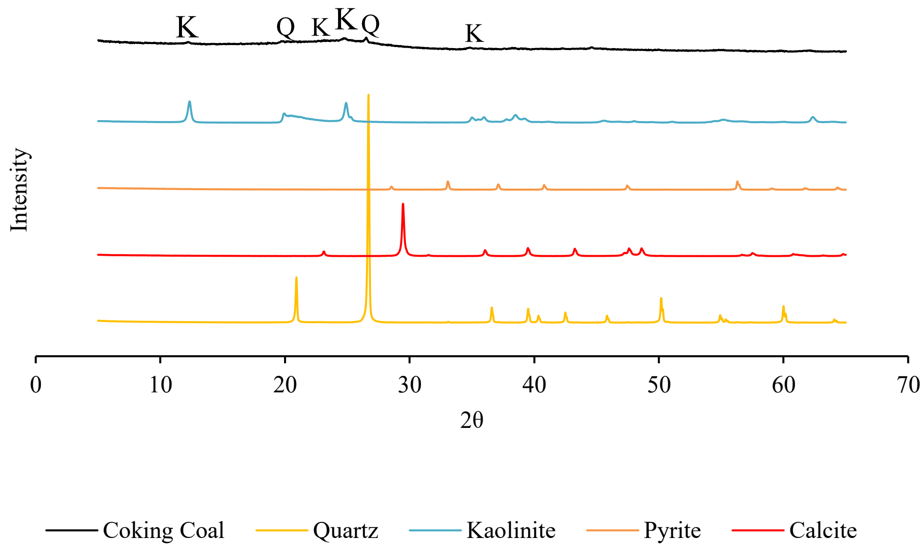

Figure 3. Diffractogram of C-seam coal from the Sawahlunto Formation, labeled as coking coal, along with standard diffractograms for quartz (Q), kaolinite (K), pyrite, and calcite for comparison of 2θ peak positions.

Further testing using X-ray Fluorescence on Sawahlunto Formation coal samples sized 60/70 mesh was presented both qualitatively and quantitatively to describe the potential rare earth element content. Based on the XRF results in Table 1, coal from this formation shows a significant presence of REEs, with a total initial concentration of around 181 ppm. The main REE elements identified include ttrium (Y), lanthanum (La), and cerium (Ce), each serving as an early indicator of the association between the inorganic mineral fraction in coal and REE accumulation. This composition suggests that the C-seam coal from the Sawahlunto Formation possesses not only energy value but also potential as a secondary source of strategic metals. .

Table 1. Rare Earth Element Composition in Sawahlunto Formation Coal

REEs	Minerals and elements	Grades in coal (ppm)	Grades in coal (%)
	Al_2O_3		7.08
	SiO2		16.17
	S		2.06
	CaO	162	
	TiO_2		0.28
	V	93	
	MnO	41	

	Fe_2O_3		0.80
	Co	44	
	Ni	8	
	Cu	38	
	Zn	32	
	As	6	
	Rb	20	
	Sr	25	
Yttrium	Y	6	
	Zr	17	
	Rh	6	
	Sb	19	
	Ba	61	
Lantanum	La	88	
Cerium	Ce	87	
	W	21	
	Pt	17	
	Pb	11	
	Th	45	
	U	8	
Total REE (ppm)		181	

3. Leaching Behavior of REEs from Minerals in Coal

The leaching process in this study was carried out in a simple stirred reactor using NaOH leach solutions with concentrations ranging from 200 g/L to 600 g/L, at temperatures between 38 °C and 78 °C, and reaction times from 0.5 to 1.5 hours. After the leaching stage, the coal solids were washed with 14% HCl solution. The purpose of varying these conditions was to identify the most effective operational parameters for dissolving rare earth elements from the Sawahlunto Formation coal.

a. Effect of NaOH Leachant Concentration

Experimental results show that at an NaOH concentration of 400 g/L, maximum REE dissolution was achieved, as indicated by a significant decrease in REE content in the post-leaching solid residue, only about 2 ppm remained. This suggests that at this concentration, the reaction between the alkaline solution and the coal mineral matrix proceeds efficiently, both in terms of diffusion and dissolution of ionic REE bonds within the mineral structure. In contrast, at 200 g/L, dissolution remained limited, while at 600 g/L no notable improvement was observed, indicating a saturation point or reduced reactivity. A limitation of this study is that it did not analyze Y, La, and Ce cations in the leachate solution. Figure 4 illustrates the relationship between NaOH concentration and residual REE content in the coal.

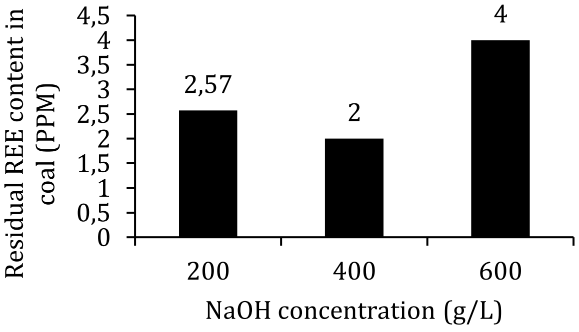

Figure 4. Relationship between NaOH leachant concentration, 78 °C, 1 h reaction time, and residual REE content in coal

This phenomenon aligns with previous findings by Modiga et al. (Modiga et al., 2024), which demonstrated that the effectiveness of REE leaching by caustic solution concentration strongly depends on the specific REE types and the structure of their host minerals. Light rare earth elements (LREEs) tend to form insoluble hydroxides in alkaline media, leading to potential re-precipitation into the residue, whereas heavy rare earth elements (HREEs) and scandium (Sc) exhibit higher solubility and are more likely to remain in solution. Therefore, at high NaOH concentrations, some REEs may precipitate as hydroxides, reducing the overall leaching conversion efficiency.

b. Effect of Coal Particle Size

The results indicate that coal particle size significantly affects the conversion efficiency of REE leaching. Finer particles, specifically 60/70 mesh, produced the most effective leaching, leaving only 2.57 ppm of REE in the solid residue, compared to coarser particles of 30/40 mesh and 10/20 mesh, which retained 74 ppm and 64 ppm of REE, respectively. This demonstrates that smaller particle sizes provide a greater specific surface area for the leaching reaction, thereby accelerating the diffusion process and enhancing contact between the NaOH leachant and REE-bearing minerals. Finer particle size significantly increases REE leaching conversion by expanding the reactive surface area, speeding up RE ion release, and strengthening the diffusion mechanism consistent with the shrinking core model (Ruan et al., 2019). Additionally, increasing the leaching temperature up to 78°C contributes to improved REE solubility, aligning with reaction kinetics principles where higher temperatures accelerate chemical reaction rates. Following the leaching process, washing the residue with 14% HCl significantly enhanced REE recovery. This washing step helps dissolve residual REEs that were not solubilized during the initial leaching, demonstrating a synergistic effect between the two stages. Thus, the combination of finer particle size, elevated temperature, and acid washing is key to optimizing REE extraction from Sawahlunto Formation coal. Figure 5 illustrates the influence of particle size on the residual REE content in coal after leaching.

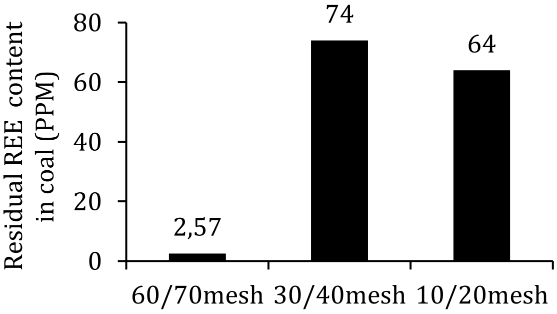

Figure 5. Effect of coal particle size on residual REE content in coal (NaOH leachant 200 g/L, 78 °C, 1 hour)

c. Effect of Leaching Temperature

Increasing the leaching temperature using a 200 g/L NaOH solution for 1 hour with a particle size of 60/70 mesh significantly affects the reduction of residual rare earth element (REE) content in coal. At leaching temperatures of 38°C and 58°C, the residual REE content remains constant at approximately 6 ppm. However, when the temperature is raised to 78°C, the residual REE content drastically decreases to 2.57 ppm. This indicates that leaching at higher temperatures enhances the dissolution conversion of REEs from coal, likely due to increased reaction rates and ion diffusion within the alkaline leaching system. Higher temperatures accelerate the leaching reaction rate and significantly improve REE extraction efficiency, although the effectiveness still depends on sufficient leachant concentration and other reaction conditions (Cao et al., 2018). Figure 6 illustrates the effect of leaching temperature on residual REE content in coal after leaching.

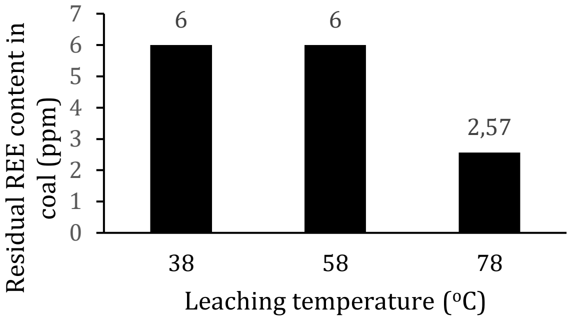

Figure 6. Effect of leaching temperature on residual REE content in coal (NaOH leachant 200 g/L, particle size 60/70 mesh, 1 hour)

d. Effect of Leaching Reaction Time

Leaching time has a significant effect on reducing the residual rare earth element (REE) content in coal. Using a 200 g/L NaOH solution, a particle size of 60/70 mesh, and a temperature of 78°C, the initial REE content of 181 ppm sharply decreased as leaching time increased. After 30 minutes, the REE content dropped to 88 ppm, then drastically fell to 2.57 ppm at 60 minutes, and nearly all REEs were released after 90 minutes, leaving only 0.1 ppm remaining. This trend indicates that the leaching process is highly effective between 60 and 90 minutes, likely because this duration provides sufficient contact time between the solvent and the REE-bearing minerals, thus enhancing the release of REEs from the coal matrix. Reaction time is a crucial factor in the REE leaching process, as adequate duration allows for more effective interaction between the solvent and minerals, supporting increased leaching conversion until an optimum condition is reached (Mousavi, 2025). Figure 7 illustrates the effect of leaching reaction time on residual REE content in coal after leaching.

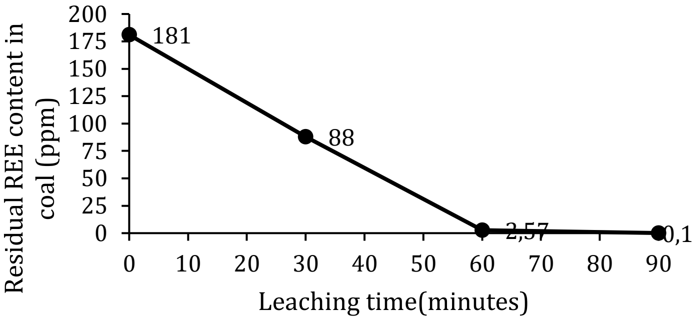

Figure 7. Effect of leaching time on residual REE content in coal (NaOH leachant 200 g/L, particle size 60/70 mesh, 78 °C)

D. CONCLUSION AND SUGGESTIONS

This study successfully achieved its objectives by identifying the rare earth element (REE) content in coal-derived minerals of the Sawahlunto Formation and evaluating their leaching behavior under NaOH and HCl washing treatments. The initial characterization revealed that the coal contains approximately 181 ppm total REEs, indicating its potential as a secondary REE-bearing material. The leaching experiments demonstrated that NaOH treatment, particularly at a concentration of 400 g/L and a temperature of 78°C, was highly effective in dissolving REE-bearing mineral phases, leaving only about 2 ppm of REEs in the solid residue. Subsequent washing with 14% HCl further improved REE mobilization, confirming the complementary nature of alkaline and acid treatments. Overall, the findings highlight that coal from the Sawahlunto Formation, especially Seam C, possesses measurable REE enrichment and responds favorably to combined NaOH–HCl leaching, providing a scientific basis for considering this resource in future REE recovery strategies.

To strengthen the research direction and support potential future development, several recommendations are proposed. Further studies should focus on refining the leaching parameters including reagent concentration, temperature, reaction duration, and particle size, to improve REE recovery efficiency and to better understand the kinetics and mechanisms governing REE release. More detailed geochemical and mineralogical investigations are needed to identify the specific host phases of REEs within the coal matrix, which will aid in selecting more targeted leaching strategies. In addition, exploration of alternative or more environmentally sustainable leaching agents, such as weak acids, organic ligands, or biologically assisted processes, is encouraged to enhance the environmental feasibility of future extraction efforts. Comparative studies involving coal from other formations may also help contextualize the REE prospectivity of Sawahlunto coal within a broader geological framework. Finally, the development of downstream processing and purification schemes is recommended to connect laboratory-scale results with possible industrial applications in REE recovery.

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