



Recovery of Neodymium from Pelabuhan Ratu Coal-Fired Power Plant: A Comparative Study of Acid Leaching Reagents on Coal Fly Ash

Yasmina Amalia¹, Tri Wahyuningsih^{1*}, Azhar Ramadhan¹, Arya Dwi Fakhor¹,
Dimas Satria Utama¹, Mikhaela Pinanditha¹, Nauval Ilham Firdaus¹, Yazid Muttaqin¹
¹ Metallurgical Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta, Indonesia

Received : September 30,
2025

Revised : October 6,
2025

Accepted : October 7, 2025

Online : October 14, 2025

Abstract

Rare earth elements (REEs) are strategic materials that play a crucial role in high-technology, renewable energy, and defense industries. One alternative source of REEs is fly ash, a solid by-product from coal combustion in coal-fired power plants (CFPPs), which is abundantly available in Indonesia due to the dominance of coal in national electricity generation. This study aims to evaluate the neodymium (Nd) potential in fly ash and the effectiveness of leaching using 0.2 M solutions of HCl, H₂SO₄, and HNO₃. Fly ash samples were collected from the Pelabuhan Ratu CFPP, analyzed for Nd content using ICP-MS, and subjected to leaching tests to determine recovery rates. The analysis revealed an Nd content of 7,920.725 ppb in the solid feed, with a relative standard deviation (RSD) of 3.7%. Leaching experiments showed the highest recovery with HNO₃ (21.366%), followed by HCl (1.819%) and H₂SO₄ (0.315%). The low recovery is likely due to Nd being entrapped within silicate and aluminosilicate matrices, which are resistant to dissolution under dilute acid conditions. These findings indicate the necessity of pretreatment methods such as alkaline fusion to enhance Nd release. The recovery of REEs from fly ash not only has the potential to support the supply chain for high-technology industries but also offers an environmentally aligned solution for waste management.

Keywords *Acid Leaching, Fly Ash, Neodymium, Recovery, Pelabuhan Ratu CFPP*

INTRODUCTION

Rare earth elements (REEs) are widely recognized as critical materials due to their strategic significance in supporting emerging and future technologies (Zhang et al., 2025). Global demand for REEs is projected to rise steadily in parallel with advancements in green energy systems and other high-technology sectors. In the context of mineral resource classification, a substance is considered critical if it possesses substantial economic importance while facing a significant risk of supply disruption. REEs comprise a group of 17 metallic elements within the periodic table, consisting of the 15 lanthanides together with yttrium (Y) and scandium (Sc) (Wang et al., 2020). These elements are indispensable in various applications, including defense technologies, environmentally sustainable systems, and high-performance electronics. Notably, they serve as essential raw materials in the manufacture of advanced metal alloys and high-strength permanent magnets, which are crucial components for electric vehicles, energy-efficient lighting, and wind turbine generators (Sakr et al., 2025).

Commercially, REEs are predominantly traded in the form of rare earth oxides (REOs), with market demand expected to escalate in line with global technological growth. In 2006, worldwide REO production was approximately 133,000 metric tons, with China contributing 97.1% of the total output. Since that period, China has implemented export restrictions, which have significantly influenced the stability of global REE supply chains (Yamaguchi et al., 2018). REE resources are geologically distributed across many regions, with total identified global reserves estimated at 130 million metric tons. China holds the largest reserves, amounting to 44 million metric tons, with

Copyright Holder:

© Yasmina, Tri, Azhar, Arya, Dimas, Mikhaela, Nauval, & Yazid. (2025)
Corresponding author's email: tri.wahyuningsih@upnyk.ac.id

This Article is Licensed Under:



Bayan Obo identified as the most significant mining site. Vietnam and Brazil follow, with estimated reserves of 22 million and 21 million metric tons, respectively. The global distribution of REE reserves is illustrated in Figure 1 (Wu et al., 2023).

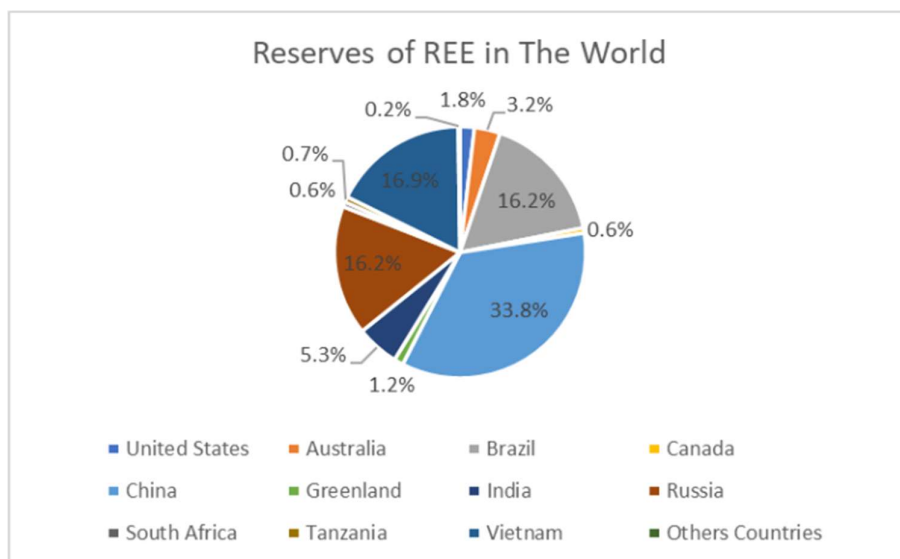


Figure 1. Reserves of REE in The World

Indonesia possesses considerable potential for rare earth element (REE) resources, particularly as by-products associated with the mining of tin, gold, bauxite, and other heavy minerals. Monazite, xenotime, and bastnäsite deposits, which contain REEs such as neodymium, are widely found in regions including Bangka Belitung, Kalimantan, and several coastal areas. In addition, REEs are often present as accessory minerals in alluvial gold and tin deposits. Geologically, REEs are commonly associated with the formation of tin-bearing deposits. The Southeast Asian Tin Belt, which hosts a significant proportion of the world's tin resources, passes through Indonesia, extending from the Karimun and Singkep Islands to the Bangka Belitung archipelago (Rosita et al., 2024).

Fly ash is a combustion by-product generated from coal-fired power plants (CFPPs) and is classified as hazardous and toxic waste (B3) in Indonesia. Its generation increases in parallel with the rising demand for coal-based energy. Coal remains the dominant energy source in Indonesia, accounting for more than 60% of national electricity generation, with dozens of CFPPs producing millions of tons of fly ash annually. This substantial volume poses serious environmental challenges, as fly ash particles are easily dispersed by wind and may contain heavy metals capable of contaminating the environment. Consequently, fly ash management is crucial to prevent environmental damage, and must be conducted in compliance with the provisions of Government Regulation No. 22/2021 and Government Regulation No. 101/2014, which stipulate integrated hazardous waste management, including reuse into economically valuable products. In line with these regulatory frameworks, innovative research has shown that fly ash contains not only silicate and aluminosilicate compounds but also REEs such as Ce, Y, La, Nd, and Sm (Gollakota et al., 2019).

The leaching of REEs from coal fly ash is highly dependent on the selection of suitable acids or reagents, which play a critical role in determining extraction efficiency. Fly ash contains REEs in small quantities, typically trapped within silicate or oxide matrices, requiring a reagent capable of dissolving the target metals without excessively degrading the primary mineral structure. Commonly used mineral acids in REE leaching include sulfuric acid (H_2SO_4), hydrochloric acid

(HCl), and nitric acid (HNO_3) (Aigbe et al., 2021). In an experimental study, Wang et al. (2020) conducted a series of acid leaching tests on three fly ash samples sourced from coal mining regions. The research examined leaching kinetics to evaluate the dissolution behavior of REEs, phosphorus, and other metals such as calcium (Ca), iron (Fe), and aluminum (Al). All tests were performed at 75°C using 1 M solutions of H_2SO_4 , HNO_3 , and HCl. Results indicated that up to 65% of light REEs, including neodymium, were dissolved within the first five minutes of leaching, with extended leaching times of up to 120 minutes increasing the recovery to nearly 75% (Huang et al., 2018).

Therefore, research on REE resources in Indonesia has demonstrated substantial potential to support the clean energy transition (Puspita et al., 2025b). Moreover, it highlights the importance of recovering REEs from contaminated soils through leaching methods, which can enhance extraction efficiency, promote circular economy principles, and strengthen the utilization of REEs in advancing green technology industries and achieving national energy self-sufficiency. Fly Ash from coal-fired power plants is typically a waste product and has been underutilized in Indonesia. This study aims to evaluate the potential of neodymium (Nd) in fly ash and the effectiveness of leaching using 0.2 M HCl, H_2SO_4 , and HNO_3 solutions. This study is expected to utilize fly ash waste for its potential neodymium generation.

LITERATURE REVIEW

Neodymium is a rare earth element that holds high strategic value in various modern technology sectors. One of its primary uses is in the manufacture of neodymium-iron-boron (NdFeB) permanent magnets. These magnets exhibit a remarkably high magnetic strength, considering their relatively small size. Due to these properties, neodymium magnets are widely used in compact electronic devices that require a strong magnetic force, such as speakers, high-quality headphones, hard disk drives, and high-speed electric motors. Even in the electric vehicle and wind turbine industries, neodymium magnets are a vital component due to their high efficiency and lightweight size (Pan et al., 2021).

Neodymium is used in metal alloys to increase strength and corrosion resistance, which is crucial in the aviation and automotive industries. In optics, neodymium is used to produce lasers with medical and industrial applications, including cutting and welding. Finally, neodymium is also used in the manufacture of pigments for paints and glass, providing their distinctive purple and green colors, as well as in some types of batteries and energy storage systems, contributing to the efficiency and durability of these devices (Praneeth et al., 2024; Zhang et al., 2025).

Before chemical extraction, fly ash generally undergoes various pre-treatment stages to improve leaching efficiency (Costa et al., 2020). One frequently used method is particle size classification and density-based separation, which aims to separate certain components based on their physical properties. Furthermore, roasting with the addition of chemicals such as sodium carbonate (Na_2CO_3) or sulfuric acid (H_2SO_4) can change the structure of minerals that are initially difficult to dissolve into more reactive forms, thus facilitating the dissolution of neodymium in acidic solutions (Fu et al., 2022). Thermal activation also plays a role in modifying the crystalline phase of fly ash, making it easier to decompose during leaching. On the other hand, magnetic separation can be applied to remove ferromagnetic components such as iron, which generally does not contain rare earth metals (REEs) but can interfere with the extraction process (Brahim et al., 2022).

The primary method for extracting neodymium from fly ash is through leaching, where the metal is dissolved using an acidic solvent such as HCl, HNO_3 , or H_2SO_4 . The choice of acid significantly impacts the selectivity and efficiency of extraction, depending on operating conditions such as temperature, acid concentration, and contact time. As a more environmentally friendly alternative, several studies have developed the use of organic acids (e.g., citric acid) or bioleaching

techniques utilizing certain microorganisms capable of selectively dissolving metals (Pan et al., 2020). After leaching, a purification step is required to separate the neodymium from impurities, usually through solvent extraction, ion exchange, or selective precipitation. These techniques allow neodymium to be obtained in the form of pure compounds or even pure metal, ready for use in various industrial applications (Traore et al., 2023).

RESEARCH METHOD

This study utilized fly ash samples obtained from the Pelabuhan Ratu coal-fired power plant (CFPP). The samples were first homogenized using a riffle sampler to ensure uniformity. A portion of the homogenized sample was then taken for preliminary analysis using an inductively coupled plasma mass spectrometer (ICP, iCAP RQ, Serial No. RQ02067) and scanning electron microscopy (SEM). These analyses were conducted to determine the distribution of rare earth elements (REEs) within the material.

Following the preliminary characterization, three separate fly ash samples, each weighing 400 g, were prepared for the leaching experiments. Agitation leaching was performed on each sample using three different reagents: sulfuric acid (H_2SO_4), nitric acid (HNO_3), and hydrochloric acid (HCl). The neodymium extraction process was carried out for 4 hours at a controlled temperature of 30°C . After leaching, the slurry was filtered, and aliquots of the resulting solution were collected for further analysis. The filtrates were subjected to ICP measurements to quantify extraction efficiency, while SEM-EDX mapping was conducted to visualize the elemental distribution in the residues from each leaching experiment using the different reagents (Figure 2).

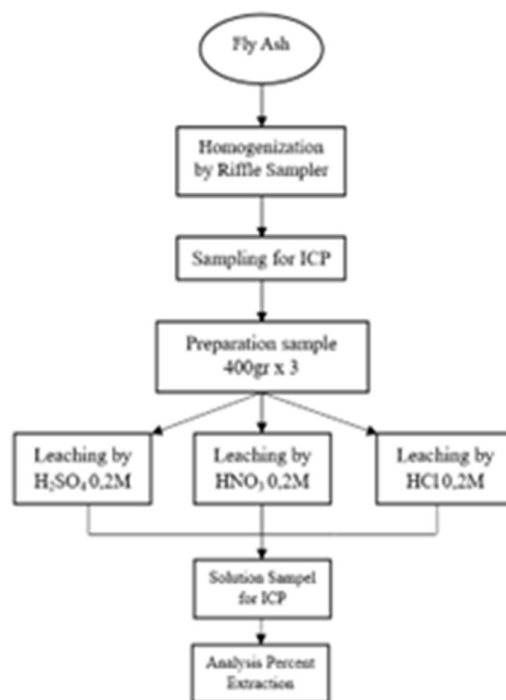


Figure 2. Procedure for Evaluating the Potential of Rare Earth Elements in Fly Ash

The research procedures were as follows:

- a. Homogenization was carried out to obtain samples with relatively similar Nd levels, ensuring representative results. Homogenization was performed using a riffle sampler,

which was then taken for characterization analysis using ICP to determine the elemental composition of the samples.

- b. The leaching process was carried out by creating a 40% solids slurry in a 2L glass beaker for 120 minutes using an agitation speed of 250 rpm. The HCl reagent concentrations were varied in three tanks, each at 0.2, 0.4, and 0.8 M, respectively (Dardona et al., 2023). The leaching process was carried out to obtain the percent recovery of rare earth metals. The second parameter in this study was the variation of the reagents, using HCl, HNO₃, and H₂SO₄ at a concentration of 0.2 M each, to compare the percent recovery levels obtained.
- c. Filtration of the leaching product is performed at the end of the leaching process to separate the solid solution for testing on solution test samples. Testing on solution samples is performed to determine the % recovery from the leaching process.
- d. The filtrate obtained from the filtration stage was placed in 100 mL bottles for further analysis through a series of tests. All filtrate samples were analyzed using Inductively Coupled Plasma (ICP) to determine the levels of rare earth elements (REEs), particularly neodymium (Nd), allowing for the calculation of the recovery percentage. Additionally, Fourier Transform Infrared (FTIR) analysis was conducted on all samples to identify functional groups and interactions between the reagents and minerals. Scanning Electron Microscopy-Energy Dispersive X-ray (SEM-EDX) testing was also applied specifically to samples leached with 0.2 M HCl to visualize the distribution of REEs, particularly Nd, in solution.

FINDINGS AND DISCUSSION

A preliminary analysis was conducted to determine the concentration of rare earth elements (REEs) in the fly ash sample, with a specific focus on quantifying neodymium (Nd) as a basis for assessing the potential of subsequent extraction processes. The analysis was performed using an ICP-MS iCAP RQ instrument. The results indicated that the average Nd concentration detected in the solid feed was 7,920.725 ppb. Furthermore, the Relative Standard Deviation (RSD) was calculated at 3.7%, demonstrating a high degree of consistency and reproducibility among the replicate measurements (Table 1). These findings confirm the reliability of the analytical data and serve as an essential reference for optimizing the leaching process to maximize Nd recovery.

Table 1. ICP result analysis

Category	139La (KED)	146Nd (KED)
Concentration Average	8,642.141 ppb	7,920.725 ppb
Concentration per Run 1	8,014.314 ppb	7,581.239 ppb
Concentration per Run 2	8,558.821 ppb	8,069.751 ppb
Concentration per Run 3	8,723.289 ppb	8,111.185 ppb
Concentration RSD	3.8%	3.7%

Based on the ICP results of the coal fly ash leaching process, the neodymium (Nd) recovery is presented in Figure 3. Leaching with 0.2 M HCl resulted in an Nd recovery of 1.819%, while 0.2 M H₂SO₄ achieved 0.315%, and 0.2 M HNO₃ yielded 21.366% (Figure 3). These results indicate that the leaching process was not fully efficient, which may be attributed to several factors. Further investigations into the mineralogy and structural characteristics of the fly ash are necessary. The presence of Nd in amorphous mineral phases or silicate forms can hinder the leaching process.

Moreover, Nd may also be hosted in inert crystalline phases such as mullite, which require additional processing to enhance Nd release from the fly ash into solution.

The significant difference in performance of HNO_3 compared to other reagents can be attributed to its strong oxidative properties toward metal oxides, which enable it to dissolve and expose the surface of neodymium-bearing minerals. This suggests that Nd in fly ash may also be associated with accessory minerals such as Fe, Mn, Pb, and others, leading to relatively low Nd recovery from PLTU-derived fly ash. Nitric acid is a strong oxidizing agent capable of oxidizing metals into soluble forms in solution, such as Fe^{3+} , Cu^{2+} , Mn^{2+} , and Zn^{2+} , which are commonly present in PLTU fly ash. In contrast, HCl and H_2SO_4 primarily act as proton donors without significant redox effects.

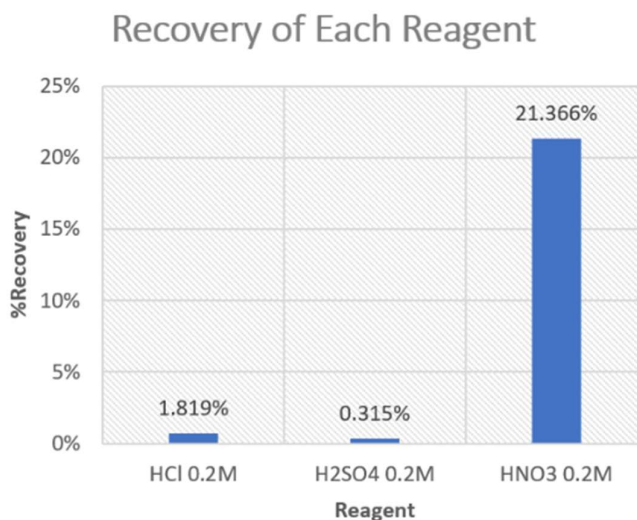


Figure 3. Recovery of Each Reagent

Based on the SEM-EDS analysis shown in Figure 4, the fly ash sample exhibits a dominant distribution of oxygen (O), aluminum (Al), and silicon (Si). The predominance of these three elements suggests the formation of complex aluminosilicate phases, which are known to be highly resistant to leaching processes when using common inorganic reagents, such as the 0.2 M H_2SO_4 , HCl, and HNO_3 employed in this study (Figure 4).

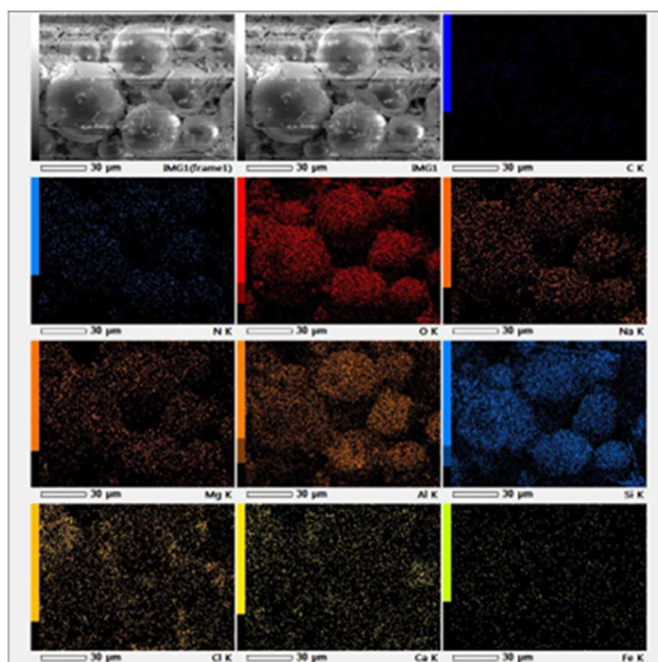


Figure 4. SEM EDX Mapping Result

The presence of such complex phases indicates that rare earth elements (REEs), such as neodymium (Nd), are likely entrapped within silicate or aluminosilicate matrices. These compounds are chemically inert and stable, making them difficult to dissolve under standard leaching conditions. As a result, despite the initial ICP data showing that the fly ash contains a relatively high Nd content, only a small fraction of the total Nd was successfully extracted into solution, reflected in the low recovery values, particularly when using H_2SO_4 and HCl . Morphological analysis of the post-leaching particles using SEM revealed that the fly ash particles largely retained their spherical shape with relatively intact surfaces. No significant degradation or weathering was observed as a result of leaching with dilute acids. This morphology indicates that leaching under the tested conditions, whether with HCl , H_2SO_4 , or HNO_3 at 0.2 M, was insufficient to effectively disrupt or dissolve the primary fly ash matrix. Most crystalline structures, such as mullite or amorphous silica, persisted without significant alteration.

Elemental mapping via EDX of the solid residues confirmed the dominance of oxygen (O), silicon (Si), and aluminum (Al), uniformly distributed across the particle surfaces. Other elements, including calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and iron (Fe), were also detected but at lower intensities. Their presence in the solid residue suggests that most of the metals remain in the form of oxides or silicates, which are insoluble under mild leaching conditions. In contrast, carbon (C) and nitrogen (N) were nearly absent, supporting the conclusion that the fly ash is predominantly inorganic mineral material with very low organic content. The persistence of these elements in the residue directly correlates with the low leaching recovery. HCl and H_2SO_4 were not sufficiently effective at dissolving chemically stable compounds such as aluminosilicates or refractory metal oxides. While HNO_3 achieved higher recovery, EDX mapping still revealed the substantial presence of metallic elements that could potentially dissolve under more aggressive conditions. This suggests that the low efficiency is the result of a combination of factors, including limited reagent reactivity, low acid concentration, and suboptimal thermodynamic conditions for dissolving the major fly ash minerals.

These findings are consistent with the work of Tang et al. (2019), which demonstrated that the presence of silicate and aluminosilicate structures in materials such as fly ash significantly limits the accessibility of REEs during leaching. In their study, an alkaline fusion method using NaOH was applied to break down Si-O and Al-O bonds, making REEs more readily soluble. The significant increase in recovery (from <40% to >80%) after alkaline fusion highlights the importance of such pretreatment for activating REEs trapped in inert matrices. Therefore, the low Nd recovery in this study is likely due to the absence of any pretreatment, such as alkaline fusion, to disrupt the complex silicate structure, thus limiting the reagent's ability to extract the target element efficiently. This observation also provides a clear direction for future research, where the integration of alkaline fusion as a pre-leaching step could substantially improve the recovery of rare earth elements from fly ash.

CONCLUSIONS

This study confirmed the potential of fly ash from the Pelabuhan Ratu coal-fired power plant as a secondary source of rare earth elements (REEs), particularly neodymium (Nd). Nevertheless, the leaching results revealed limited recovery under the tested conditions, emphasizing the need for pretreatment approaches to enhance extraction efficiency. The main conclusions are as follows:

1. REE content: Fly ash contained an average Nd concentration of 7,920.725 ppb, with consistent analytical reproducibility (RSD 3.7%).
2. Leaching performance: Among the tested reagents (0.2 M H₂SO₄, HCl, and HNO₃), nitric acid achieved the highest Nd recovery at 21.366%, significantly outperforming the other acids (HCl: 1.819%; H₂SO₄: 0.315%).
3. Reagent effectiveness: The superior performance of HNO₃ is attributed to its oxidative dissolution of metal oxides, whereas HCl and H₂SO₄ primarily function as proton donors with minimal redox activity.
4. Mineralogical constraints: SEM-EDS mapping revealed that Nd is predominantly entrapped in aluminosilicate matrices and refractory phases such as mullite and amorphous silica, which remain stable under mild acidic leaching.
5. Process implications: The stability of these phases suggests that pretreatment methods, such as alkaline fusion, are essential to disrupt the silicate network and improve REE liberation.

LIMITATIONS & FURTHER RESEARCH

Based on the current findings, this study recommends that future research focus on combining pretreatment techniques with optimized leaching parameters, as this approach is expected to significantly enhance the recovery of rare earth elements (REEs) and promote the valorization of fly ash as a viable source of critical materials for clean energy applications.

REFERENCES

- Aigbe, U. O., Ukhurebor, K. E., Onyancha, R. B., Osibote, O. A., Darmokoesoemo, H., & Kusuma, H. S. (2021). Fly ash-based adsorbent for adsorption of heavy metals and dyes from aqueous solution: a review. *Journal of Materials Research and Technology*, 14, 2751–2774. <https://doi.org/10.1016/J.JMRT.2021.07.140>.
- Brahim, J. A., Hak, S. A., Achiou, B., Boulif, R., Beniazza, R., & Benhida, R. (2022). Kinetics and mechanisms of leaching of rare earth elements from secondary resources. *Minerals Engineering*, 177. <https://doi.org/10.1016/j.mineng.2021.107351>.
- Costa, T. B. da, Silva, M. G. C. da, & Vieira, M. G. A. (2020). Recovery of rare-earth metals from aqueous solutions by bio/adsorption using non-conventional materials: a review with recent studies

- and promising approaches in column applications. *Journal of Rare Earths*, 38(4), 339–355. <https://doi.org/10.1016/J.JRE.2019.06.001>.
- Dardona, M., Mohanty, S. K., Allen, M. J., & Dittrich, T. M. (2023). From ash to oxides: Recovery of rare-earth elements as a step towards valorization of coal fly ash waste. *Separation and Purification Technology*, 314, 123532. <https://doi.org/10.1016/J.SEPPUR.2023.123532>.
- Fu, B., Hower, J. C., Zhang, W., Luo, G., Hu, H., & Yao, H. (2022). A review of rare earth elements and yttrium in coal ash: content, modes of occurrences, combustion behavior, and extraction methods. *Progress in Energy and Combustion Science*, 88. <https://doi.org/10.1016/j.pecs.2021.100954>.
- Gollakota, A. R. K., Volli, V., & Shu, C. M. (2019). Progressive utilisation prospects of coal fly ash: A review. *Science of The Total Environment*, 672, 951–989. <https://doi.org/10.1016/J.SCITOTENV.2019.03.337>.
- Huang, Z., Fan, M., & Tiand, H. (2018). Coal and coal byproducts: A large and developable unconventional resource for critical materials – Rare earth elements. *Journal of Rare Earths*, 36(4), 337–338. <https://doi.org/10.1016/J.JRE.2018.01.002>.
- Pan, J., Hassas, B. V., Rezaee, M., Zhou, C., & Pisupati, S. V. (2021). Recovery of rare earth elements from coal fly ash through sequential chemical roasting, water leaching, and acid leaching processes. *Journal of Cleaner Production*, 284. <https://doi.org/10.1016/j.jclepro.2020.124725>.
- Pan, J., Nie, T., Vaziri Hassas, B., Rezaee, M., Wen, Z., & Zhou, C. (2020). Recovery of rare earth elements from coal fly ash by integrated physical separation and acid leaching. *Chemosphere*, 248, 126112. <https://doi.org/10.1016/J.CHEMOSPHERE.2020.126112>.
- Praneeth, S., Sakr, A. K., Dardona, M., Tummala, C. M., Roy, P. K., & Dittrich, T. M. (2024). Selective separation and recovery of rare-earth elements (REEs) from acidic solutions and coal fly ash leachate by novel TODGA-Impregnated organosilica media. *Chemical Engineering Journal*, 500. <https://doi.org/10.1016/j.cej.2024.156849>.
- Rosita, W., Perdana, I., Bendiyasa, I. M., Anggara, F., Petrus, H. T. B. M., Prasetya, A., & Rodliyah, I. (2024). Sequential alkaline-organic acid leaching process to enhance the recovery of rare earth elements from Indonesian coal fly ash. *Journal of Rare Earths*, 42(7), 1366–1374. <https://doi.org/10.1016/J.JRE.2023.09.001>.
- Sakr, A. K., Praneeth, S., Dardona, M., Kakaris Porter, D., Tummala, C. M., Roy, P. K., & Dittrich, T. M. (2025). Potential for eco-friendly recovery of rare earth elements from fly ash using carboxylic acids: A comparative study with mineral acids and environmental risk assessment for sustainable fly ash reuse. *Chemical Engineering Journal*, 503. <https://doi.org/10.1016/j.cej.2024.158355>.
- Traore, M., Gong, A., Wang, Y., Qiu, L., Bai, Y., Zhao, W., Liu, Y., Chen, Y., Liu, Y., Wu, H., Li, S., & You, Y. (2023). Research progress of rare earth separation methods and technologies. *Journal of Rare Earths*, 41(2), 182–189. <https://doi.org/10.1016/j.jre.2022.04.009>.
- Wang, Z. Y., Fan, H. R., Zhou, L., Yang, K. F., & She, H. D. (2020). Carbonatite-related REE deposits: An overview. *Minerals*, 10(11), 1–26. <https://doi.org/10.3390/MIN10110965>.
- Wu, Z., Chen, Y., Wang, Y., Xu, Y., Lin, Z., Liang, X., & Cheng, H. (2023). Review of rare earth element (REE) adsorption on and desorption from clay minerals: Application to formation and mining of ion-adsorption REE deposits. *Ore Geology Reviews*, 157, 105446. <https://doi.org/10.1016/J.OREGEOREV.2023.105446>.
- Yamaguchi, A., Honda, T., Tanaka, M., Tanaka, K., & Takahashi, Y. (2018). Discovery of ion-adsorption type deposits of rare earth elements (REE) in southwest Japan with speciation of REE by extended X-ray absorption fine structure spectroscopy. *Geochemical Journal*, 52(5), 415–425. <https://doi.org/10.2343/GEOCHEMJ.2.0531>.
- Zhang, L., Chen, H., Pan, J., Yang, F., Long, X., Yang, Y., & Zhou, C. (2025). Rare earth elements recovery

and mechanisms from coal fly ash by column leaching using citric acid. *Separation and Purification Technology*, 353, 128471. <https://doi.org/10.1016/j.SEPPUR.2024.128471>.