Harnessing Indian Coal Fly Ashes for Rare Earth Elements Recovery: A Review

Akanksha Aggarwal[1*], Raj K Tripathi[1], A Lakshman Kumar[2], Pranay Sharma[3], Anil Kumar Das[4]

[1] Analytical Lab, NTPC Energy Technology Research Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.

[2] Corrosion & Research Analysis Lab, NTPC Energy Technology Research Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.

[3] Coal Lab, NTPC Energy Technology Research Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.

[4] NDE, Imaging and Life Management Lab, NTPC Energy Technology Research Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.

akankshaaggarwal@ntpc.co.in

Abstract. Coal fly ash (CFA), produced in large quantities by thermal power plants in coal-dependent India, has emerged as a potential source for extracting Rare Earth Elements (REEs). Given the increasing demand for REEs in high-tech and green technologies, exploring alternative sources like CFA is vital. This review evaluates the composition and variability of REE content in fly ash from various Indian power plants. It examines extraction methods such as acid leaching, solvent extraction, and ion exchange, assessing their efficiency, feasibility, and associated environmental and economic implications. The necessity for innovative and sustainable sources of REEs is pressing. India produces approximately 140 million tons of CFA yearly, yet a substantial portion remains underutilized or is directed to landfills. The recovery of REEs from CFA represents a sustainable alternative that addresses the scarcity of essential materials and the environmental challenges of coal ash disposal. Emerging extraction methods, which are still primarily in the laboratory phase, offer significant promise for commercial applicability, highlighting the urgent need for effective strategies to recover valuable components. This review accentuates the significance of sustainable practices in recovering REEs, promoting a circular economy within India's energy sector.

Keywords: Thermal Power Plants, Coal Fly Ash, Utilization, Rare Earth Elements, Recovery.

1. Introduction

Coal plays a crucial role as a fuel source for electricity generation, accounting for more than 39 percent of global energy production [1, 2]. Beyond its use in generating electricity, coal is also important in metallurgical processes and cement production, as well as a precursor for activated carbon and various industrial chemicals. The

© The Author(s) 2025

S. Shaswattam et al. (eds.), *NTPC Transactions on Energy Research (NTER 2025)*,
https://doi.org/10.2991/978-94-6463-849-3_16

traditional burning of coal produces significant amounts of coal ash, which can cause environmental and economic issues if not managed properly.

Coal ash mainly consists of three components: fly ash, bottom ash, and slag. While bottom ash and slag are usually removed from the furnace, fly ash is made up of finer particles that are carried away with flue gas during combustion. The mineral makeup of coal ash often contains various rare earth elements (REEs) in concentrations that can be much higher than in the original coal. Research has shown that fly ash may have REE levels that are eight to ten times greater than those found in source coal, with concentrations reported to reach up to 1.85% on an oxide basis.

Globally, copious amounts of coal ash are produced; for example, India produces approximately 140 million tons of coal fly ash (CFA) per annum from thermal power plants, with 78.14 % of it being effectively utilized [3]. Despite its potential as a resource, a significant quantity of CFA is commonly sent to landfills. The rising production of CFA emphasizes the need for recycling and repurposing, particularly for the extraction of REEs, which could provide a sustainable domestic supply of these essential materials. Simultaneously, the demand for REEs has experienced a notable increase, driven by their critical applications in emerging technologies. This juxtaposition presents an opportunity to explore CFA not just as a waste but as a resource for REE recovery.

1.1 Overview of Coal Fly Ashes

CFA is a lightweight material composed of fine particles produced from coal combusted in thermal power plants. India is one of the leading producers of CFA worldwide, with thermal power plants generating millions of tons each year. Currently, much of this fly ash is either landfilled or used for low-value applications like cement production, leading to environmental concerns and resource wastage.

CFA is composed predominantly of calcium oxide (CaO), alumina (Al_2O_3), iron oxide (Fe_2O_3), and silica (SiO_2), alongside traces of other metals, including REEs. The mineralogical composition differs depending on the origin of coal, combustion conditions, and the specific processing of the ash [4]. REEs are typically found in lower concentrations but can be recovered using specialized extraction techniques. Notably, CFA from certain thermal power plants in India can have REEs concentrations sufficient to make their recovery economically viable.

Indian coal, particularly from significant mining regions such as Chhattisgarh, Jharkhand, Madhya Pradesh, Odisha, West Bengal, and Telangana, contains a variety of trace elements, including valuable REEs such as lanthanum (La), cerium (Ce), and neodymium (Nd). The concentration of these elements in fly ash can be influenced by the coal seams' geological characteristics and the power plants' combustion efficiency [5].

1.1.1 Rare Earth Elements. REEs comprise a set of 17 chemical elements that majorly consist of lanthanides, along with scandium and yttrium [6]. Typically, classified into three main categories: light (LREE– Sc, La, Ce, Pr, Nd, and Sm), medium (MREE – Eu, Gd, Tb, Dy, and Y), and heavy (HREE– Ho, Er, Tm, Yb, and Lu) [7–9]. Based on market demand and significant applications across numerous sectors, REEs have been divided into three more categories: critical (Nd, Eu, Tb, Dy, Y, and Er), excessive (Ce, Ho, Tm, Yb, and Lu and uncritical (La, Pr, Sm, and Gd) [5, 9, 10]. These metals, characterized by their unique physical and chemical properties,

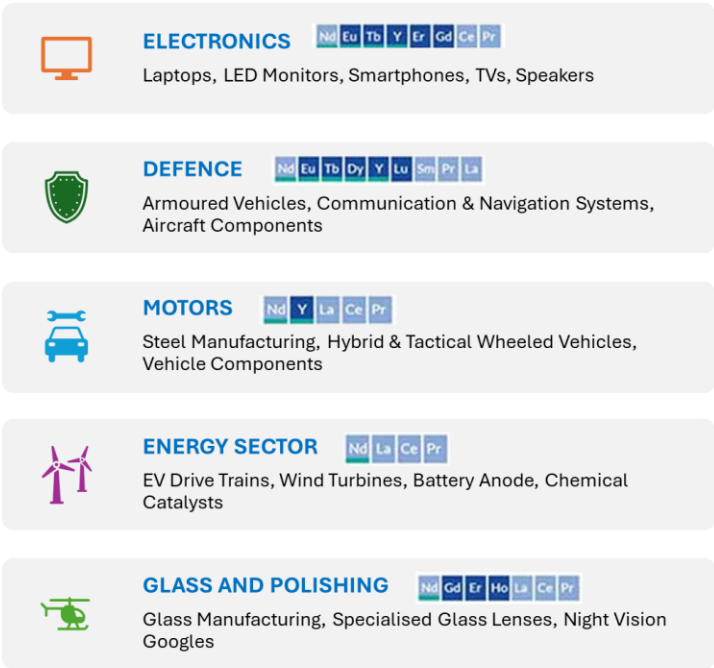

Fig. 1: Schematic representing the utilization of REEs for specific products

play a crucial part in several applications, including electronics, green or renewable energy technologies, and defense systems. In the Indian context, the usability of REEs is specified by the Ministry of Mines. The Ministry has declared REEs as critical minerals with a value chain in zero-emission vehicles, defense, and security technologies. These materials are vital for numerous applications across various industries, as represented in Fig. 1. They serve in the production of permanent magnets for electricity generators and motors, enhance catalysts and polishing agents,

and contribute to the development of batteries and electronics. These materials are also critical in defense technologies and play a key role in the wind energy sector, as well as in aviation and space exploration. Their diverse applications highlight their importance in driving innovation and efficiency across multiple fields. The worldwide need for REEs has increased significantly, fueled by technological progress and the shift toward sustainable energy options [11]. Currently, a considerable volume of CFA is disposed of in landfills, which contributes to both air and soil contamination, as well as the leaching of hazardous metals into groundwater sources. Figure 2 displays the overall generation, utilization, and accumulation of CFA between 1996 - 2019 in India [12]. Currently, the production of CFA in India is 142.07 million tons, while ~78% is being utilized. Thermal power plants like NTPC have been using CFA in the production of construction materials such as cement, bricks, and tiles. This helps reduce the environmental impact caused by fly ash disposal and offers a sustainable alternative to traditional building materials [4]. Fly ash is also being used in road construction, which enhances the durability and strength of roads while reducing the cost and environmental footprint. Utilizing CFA for the recovery of REEs can reduce these environmental risks while simultaneously addressing the scarcity of these materials [13]. While some CFA is employed in construction (e.g., concrete and cement) and agriculture (as a soil amendment), the potential for improved resource recovery through REE extraction remains largely untapped. This paper aims to investigate the feasibility of CFA as a resource for the recovery of REEs in India, advocating for sustainable practices that can contribute to both environmental protection and resource recovery.

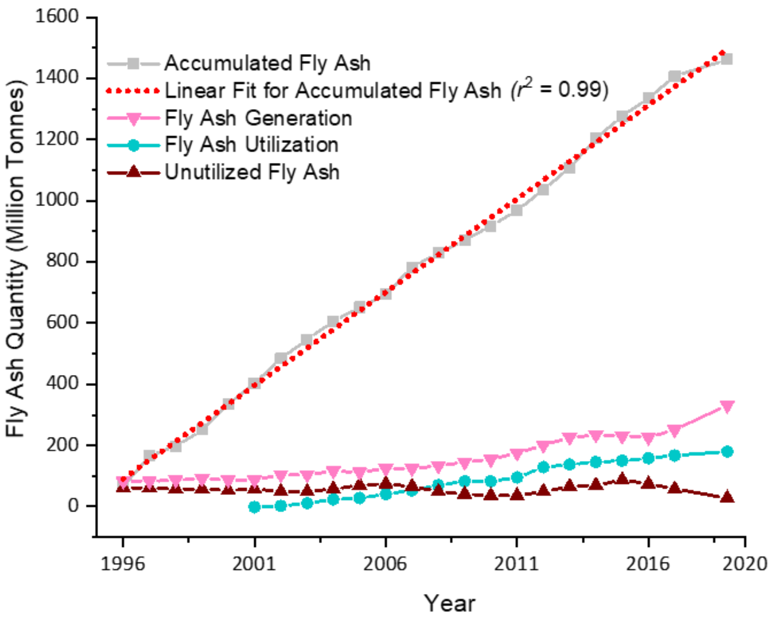

Fig. 2. Represents the overall utilization, generation, and accumulation of CFA from 1996 to 2019 in India [27]. Accumulated fly ash inclination with time (in years) shows a linear trend (r^2 = 0.99) which suggests that by 2030 the accumulated fly ash reaches around 2400 million tons.

2. REEs Recovery from Coal Fly Ash

The extraction of REEs from typical ores involves a complex, multi-stage process that demands significant financial investment, consumes a considerable amount of energy, produces large quantities of undesired tailings, and leads to negative environmental impacts. Moreover, since REEs are seldom found in substantial concentrations, standard mining techniques are often insufficient. Given the unique characteristics of REE-containing ores and their increasing demand, it has become essential to develop innovative methods for extracting REEs from both conventional and alternative sources [1].

Various techniques have been proposed for extracting REEs from minerals such as monazite, bastnäsite, and xenotime. These methods include gravity separation and flotation, among others. Additionally, techniques like supercritical extraction, solid-liquid extraction, electro-winning, precipitation, liquid-liquid extraction, and electrorefining have been documented for concentrating REEs from relatively low-grade ores. More recent approaches include (1) microwave irradiation combined with the addition of powdered carbon, subsequently followed by physical separation processes, and (2) roasting in conjunction with pretreatment using an aqueous NaOH solution, among others. Traditional separation processes such as gravity separation, flotation, electrostatic techniques, and magnetic separation are generally employed to process industrial rare earth minerals, including monazite, bastnäsite, and xenotime. [1, 14].

Examination of the current and emerging technologies used for extracting REEs from Indian CFA, involving hydro- and pyro-metallurgy, is ongoing. Hydrometallurgical methods, such as acid leaching, solvent extraction, and precipitation, were extensively employed for extracting REEs from CFA. Acid leaching using sulfuric or hydrochloric acid has shown promising results for extracting REEs from ash matrices [15, 16]. High-temperature processing techniques, including smelting and calcination, offer alternative methods for concentrating and extracting REEs [16]. Technologies such as bioleaching and the use of ionic liquids (ILs) are gaining traction as more sustainable and efficient methods for REEs extraction [4]. Research is ongoing to develop greener methodologies that minimize waste and energy consumption. However, these methods typically require significant energy input, raising concerns about their sustainability.

3. Extraction Methodologies

The process of extracting REEs from CFA after characterization typically includes numerous steps:

1. Leaching: Various leaching agents, such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), or ammonium sulphate $(NH_4)_2SO_4$), are employed to solubilize REEs from CFA.
2. Purification and Separation: Methods such as ion-exchange, solvent extraction, and precipitation are being utilized to separate specific REEs from the leachate.
3. Recovery: Finally, REEs can be recovered in high purity through crystallization or other suitable processes.

Rao et al. (2022) established a two-phase solvent extraction method to recover REEs from sulphuric acid leachate attained in Indian CFA containing REEs with ~2160 mg/kg concentration. They discovered that using 12% (v/v) and 40% (v/v) concentrations of D2EHPA solvent allowed for the recovery of ~ 94% of HREE in the initial stages and ~ 86% of LREE in subsequent stages of the extraction process. Following this, the concentrated organic streams underwent treatment with a 6M HCl solution to remove REEs values. The resulting acidic liquors were then effectively neutralized using NaOH and treated further with oxalic acid dihydrate to precipitate LREE oxalate, which contained 17.5% LREE, along with HREE [1, 15].

CFA samples collected from various power plants across India were analyzed by Rao and colleagues [15, 16]. In their work REEs were extracted using different solvents i.e. water, buffer solution of ammonium acetate (at pH of 8.3 and 5), hydrochloric acid, a strong oxidizing combination of nitric acid and hydrogen peroxide, hydrofluoric and nitric acid combination, dissolution in strong basic sodium peroxide followed by dissolution in strong acidic HCl. All the above solvents were used to evaluate the type of REEs present in the fly ash samples. Apart from understanding the appropriate solvent for extraction of REEs, authors also optimized the leaching parameters like rotating speed (varied b/w 100 - 700), acidic strength (varied b/n 0.5M to 3M), leaching period (0 - 12 h), solid content (varied b/w 10 - 40% solid by weight), and temperature (25 - 90 ºC) [16]. In addition, using X-ray techniques (XRD and XRF), authors reported that the chief elements in fly ash are silicon, aluminum, iron, and calcium. The mineral composition of fly ash includes Quartz (36-61%), Alumina (10-30%), Iron oxide (3 to 10% as magnetite and hematite), and killalaite mineral, along with gypsum (constituting 9–30% CaO). Quartz is the major mineral (36-61%) found in fly ash. Quartz structure lacks lattice sites to accommodate REEs, and this statement is further strengthened by established scientific agreement that quartz is deficient in REEs [15, 16]. The authors also concluded that ~ 55% of REEs were ion-exchangeable and that ~ 38% were linked to the Fe phase. However, the results reported by Pan et al. [17] exhibited notable discrepancies, which can be attributed to the differing sources and ranks of coal examined. Pan et al. [17] analyzed fly ash from low-volatile bituminous coal, while Rao et al. studied fly ash from lignite coal. Further, a comparison of these two studies reveals that leaching REEs from low-rank CFA (where REEs are 55% ion-exchangeable) is easier and economically viable than extracting REEs from bituminous CFA, which contains REEs in their alumina silicate phase (requires strong aggressive acids for their extraction) [16].

Ionic solvents, often known as ILs or room-temperature molten salts, belong to a category of solvents that remain in the liquid state at or around ambient temperature. Recently, ionic and deep-eutectic solvents (DESs) have gained significant attention as effective alternatives to traditional methods of metal recovery. Their unique properties and capabilities position them as promising options in the field of metal extraction. These systems operate as responsive agents in leaching and extraction procedures. Karan et al. used two varieties of DESs, i.e., choline chloride (ChCl) with lactic acid and ChCl with para-toluene sulphonic acid monohydrate (pTSA), to extract REEs from CFA [1, 4]. Further, the REEs in the extract were precipitated by using a cocktail of different chemicals and further diluted with DM water [1]. DES systems achieved a recovery of 85–95% of REEs from the CFA. Moreover, research has been conducted on rare earth oxides' dissolution processes from bauxite residue utilizing the IL betainium bis(trifluoromethyl sulfonyl)imide (HbetTf2N). The findings indicated that temperature and retention time are crucial factors, with elevated temperatures and prolonged retention times resulting in increased REEs extraction, reaching up to 70–85% [1].

Kumari et al. investigated geographically varied coal samples and found 0.5 to 1.5 kg/ton of REEs in a specific coal seam located in eastern India. To this end, systematic leaching experiments were conducted to extract REEs from Indian coal ash samples through hydrometallurgy. The highest dissolution of REEs from these samples was observed when HCl concentrations in the range of 2 to 6 M were used at higher temperatures. More than 90% of the REEs were recovered from the leachate through oxalate precipitation. The developed process holds significant promise for commercialization following feasibility assessments [18].

Mondal et al. utilized the HNO_3 acid-digestion method to dissolve various CFA samples from multiple power plants and fused the resulting material in a NaOH + $NaNO_3$ mixture at 600 °C, subsequently treating it with hydrothermal processes. The overall concentration of REEs was found to be between 300 and 500 mg/kg. The extraction of REEs from the matrix utilized XAD-7 resin that had been treated with N, N, N′, N′-tetrakis-2-ethyldiglycolamide (TEHDGA). The REEs that had been loaded were subsequently eluted using 0.01 M HNO_3 [1, 19].

Extraction through acid leaching has shown to be one of the most effective methods of extracting REEs from CFA. Research indicates that acid leaching can achieve recovery rates of approximately 70-90% for specific REEs like lanthanum and cerium. However, the concentration of acids used can pose environmental hazards, necessitating thorough management strategies post-extraction. With its selective separation capabilities, solvent extraction has demonstrated the potential to recover up to 80% of REEs from CFA. It operates on the principle of using organic solvents to extract specific REEs based on their chemical properties. While the process is highly efficient, challenges remain concerning the disposal of used solvents and the economic viability of the process when scaled for larger operations. Although the Ion Exchange method has lower recovery rates, generally in the range of 50-70%, it offers advantages in selectivity and the potential for the regeneration of ion-exchange materials. The ability to utilize fewer caustic chemicals makes it more environmentally friendly, which can be a significant factor in terms of sustainability.

Some of the extraction methods that have shown promise for retrieving REEs from CFA, particularly for industrial applications, are being worked upon in India, such as:

- Ionic Liquids: This method has shown promising results, and its research is currently underway in India [20]. The use of ILs like HbetTf2N has demonstrated high efficiency in extracting REEs due to their ability to be tailored for specific element affinities. However, the scalability and cost-effectiveness of this method for large-scale industrial applications are still under evaluation [21].
- Sequential Extraction Techniques: These techniques have proven to be effective in selectively extracting REEs from CFA. The multi-step process helps in reducing reagent consumption and process complexity, making it more environmentally friendly and cost-effective. Studies have shown that sequential extraction can achieve high recovery rates of REEs, but the method's efficiency can vary depending on the specific composition of the fly ash.
- Improved Ambient Temperature Extraction: This method, developed by the U.S. Department of Energy’s National Energy Technology Laboratory, has shown high levels of extraction efficiency (ranging from 80-100%) using mild inorganic acids at ambient temperatures. This approach is particularly advantageous as it reduces energy costs and environmental impact [22]. While this method is promising, its application in India is still in the early stages, and further research is needed to optimize it for local CFA compositions.

Research in India has been increasingly focused on optimizing the extraction process of REEs from CFA. Various studies have acknowledged effective leaching methods and have developed optimized protocols for the separation and purification of these elements. However, challenges remain in improving the efficiency and economic viability of these processes to ensure commercial scalability.

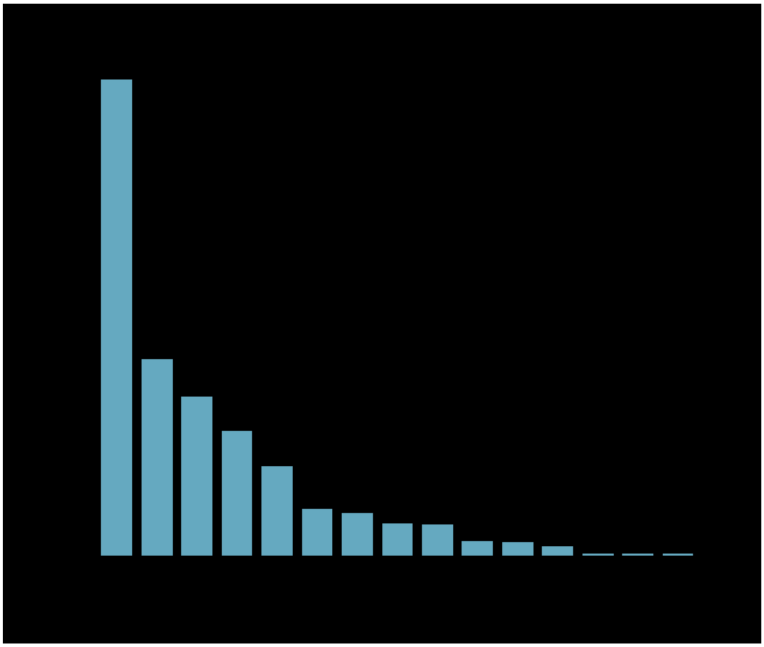

Fig. 3. Average proportion of individual REEs to total REEs (%) in CFA samples [5].

4. Characterization of REEs

A thorough analysis of the ash is conducted to quantify and identify the specific REEs present. Various analytical techniques, viz. Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) [5, 23, 24], X-ray fluorescence (XRF) [25, 26], X-ray diffraction (XRD) [25], Neutron Activation Analysis (NAA) [27], Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) [19, 25, 28], Laser-Induced Breakdown Spectroscopy (LIBS) [29], and Microscopy techniques [25] have been used for REEs analysis in diverse matrices comprising of coal and CFA samples [5].

Gautam et al. (2021) and Sandeep et al. (2023) quantified rare earths in Indian CFA using ICP-MS. Results from chemical analysis indicate that Ce is the most abundant among the REEs, whereas Lu demonstrates the lowest concentration [5, 30]. Figure 3 presents the average proportion of each REEs to the total REEs (∑REE) concentrations (%). The contribution of Ce to the ∑REE ranges from 36% to 40%, with a mean value of 37.5%. Conversely, the contribution of Lu is notably minimal, ranging from 0.15% to 0.23%. Among the more significant REEs—including Eu, Nd, Dy, Tb, Y, and Er—neodymium reflects a significant contribution, ranging from 12% to 13.1%, followed by yttrium, which contributes between 9.9% and 10.8%, and dysprosium with a contribution of 2.3% to 3.2% within Indian CFA samples [5].

Rao et al. (2020) used various techniques (XRF, XRD, ICP-OES, Optical microscopy, and SEM-EDX) for the characterization of the fly ash samples. The authors reported a feasible concentration of ∑REE (~ 2100 mg/kg), out of which 20% are HREE. Optical microscopy demonstrated that the LREE are found as Zircon and Monazite minerals [25].

Mondal et al. analyzed elements (major and trace) by ICP-OES and observed that all the samples had analogous element distribution with ∑REE ranging from 300-500 mg/kg. The major elements present were Al, Si, Ca, Fe, and Mg [19] while in the case of Maity et al., the ∑REE ranged from 51-66 mg/kg, with Pr having the highest concentration [28].
Table 1 shows comparative data of the average concentrations of REE in Indian CFA published by various authors [5, 19, 25, 27, 28, 30, 31]. The present work compared these data using the criteria outlined by the authors [10, 23], which include the outlook coefficient (C_{out}), ∑REE, uncritical percentage (U_p), critical percentage (C_p), and excessive percentage (E_p). The formulas used for these calculations are provided below [10, 23]:

$$C_{out} = \sum CREE \,/ \sum EREE \tag{1}$$

$$C_P = \frac{\sum CREE}{\sum REE} \times 100 \tag{2}$$

$$\mathrm{U_P} = \frac{\sum \mathrm{UREE}}{\sum \mathrm{REE}} \times 100 \tag{3}$$

$$\mathrm{E_P} = \frac{\sum \mathrm{EREE}}{\sum \mathrm{REE}} \times 100 \tag{4}$$

As the name implies, critical minerals are in extreme demand. Therefore, the parameters $\mathrm{C_p}$ and C_{out} are particularly important, as they determine the economic viability of extracting the given samples. Authors [32, 33] described that a C_p value above 30% and a C_{out} value greater than 1 are considered favourable [32, 33]. However, as indicated in Equation 1, C_{out} is influenced by both C_p and E_p. A $\mathrm{C_{out}}$ value of less than 1 can still indicate the sample's utility as a viable secondary source for REEs, highlighting its potential for further evaluation and application. Therefore, all major parameters mentioned in eq. (1-4) must be analyzed to assess the economic potential of the source effectively.

Table 1: Data Comparison of Average Concentration of REEs in Indian CFA published by several authors

Element	Chand et al. (2024)	Banerjee et al. (2024)	Sandeep et al. (2023)	Maity et al. (2022)	Pooja et al. (2021)	Rao et al. 2020)	Mondal et al. (2019)	Average (ppm)
La	120.0	91.6	57.1	1.0	123.1	253.0	62.4	101.2
Ce	208.0	166.9	136.9	BDL**	265.6	580.0	137.4	249.1
Pr	29.0	19.9	13.3	54.0	36.9	85.0	20.2	36.9
Nd	68.2	71.2	45.7	BDL	166.9	508.0	45.9	151.0
Sm	20.3	13.3	12.5	BDL	33.4	95.0	5.9	30.1
Eu	4.3	2.9	2.1	0.1	7.9	23.0	2.3	6.1
Gd	9.9	16.1	9.6	BDL	30.3	96.0	5.7	27.9
Tb	2.5	2.1	1.5	BDL	3.3	8.0	1.2	3.1
Dy	14.0	11.2	9.5	BDL	22.4	61.0	4.9	20.5
Y	NA*	59.6	36.4	0.8	123.6	300.0	34.5	92.5
Ho	2.5	2.2	1.7	0.5	1.5	1.0	0.9	1.5
Er	5.1	6.0	4.6	BDL	9.6	28.0	0.9	9.0
Tm	2.5	0.9	0.6	BDL	1.2	1.0	0.6	1.1
Yb	8.9	5.2	4.6	0.2	9.3	20.0	3.8	7.4
Lu	1.4	0.8	0.7	0.6	1.1	1.0	1.4	1.0
∑REE	496.6	469.8	336.7	57.2	836.2	2060.0	328.0	654.9
LREE (%)	89.7	77.3	78.8	96.1	74.9	73.8	82.9	81.9
MREE (%)	6.2	19.5	17.6	1.6	22.4	23.7	14.8	15.1
HREE (%)	4.1	3.2	3.6	2.3	2.7	2.5	2.3	3.0
CREE (ppm)	94.1	152.9	99.8	0.9	333.8	928.0	89.7	242.7
UREE (ppm)	179.2	140.9	92.5	55.0	223.7	529.0	94.2	187.8
EREE (ppm)	223.3	176.0	144.5	1.3	278.7	603.0	144.1	224.4
C_{out}	0.4	0.9	0.7	0.7	1.2	1.5	0.6	0.9
C_p	18.9	32.5	29.6	1.6	39.9	45.0	27.3	27.9
U_p	36.1	30.0	27.5	96.1	26.8	25.7	28.7	38.7
E_p	45.0	37.5	42.9	2.3	33.3	29.3	43.9	33.5

*NA – Not Available; **BDL- Below Determination Limit

5. Environmental and Economic Implications

5.1 Environmental Considerations

Recovering REEs from CFA can significantly mitigate the environmental impacts associated with ash disposal. By converting waste into value-added products, the process can contribute to reduced landfill use. However, potential ecological risks associated with leaching agents and chemical processes must be carefully managed to prevent secondary pollution [31]. Recycling waste aligns with the principles of sustainable development and the circular economy. Apart from waste reduction and environmental pollution mitigation, fly ash utilization could be beneficial in the reduction of the carbon footprint associated with mining and processing virgin materials [18]. Thus, extracting REEs from fly ash provides an alternative source of these critical materials, thereby increasing the efficacy of resource utilization.

5.2 Economic Viability

The economic aspects of REEs recovery from CFA hinge upon factors such as the concentration of the elements within the ash, the cost of extraction processes, and market prices for REEs. Given the fluctuating nature of REE prices globally and the competitive landscape of extraction, robust economic models need to be established to assess the viability of large-scale operations. While initial extraction costs may be high, the growing demand for REEs can potentially make this process economically viable. Investment in research and development, coupled with supportive government policies, can further enhance the viability of REEs recovery from CFA. Thus, there is a need for an assessment of the cost-effectiveness of rare earth extraction from CFA compared to traditional mining methods [31, 32].

With only 6.9 million metric tons of reserves, India is ranked fifth in the world for REEs. Figure 4 lists the major nations and their global reservoirs of REEs as of 2023 (in 1,000 metric tons of rare earth oxides) [34]. An estimated 11.93 Mt of monazite with 55%–65% rare earth oxides can be found in beach sand in India [11]. Although India holds 35% of the world's coastal sand mineral resources, it relies entirely on imports for its REEs. India's supply chain is more vulnerable because of its heavy reliance on imports of REEs from China. As observed from Table 1, the $C_{out} > 1$ accounts for the viability of Indian CFA as a promising alternative for REE resources and harnessing CFA for REEs recovery.

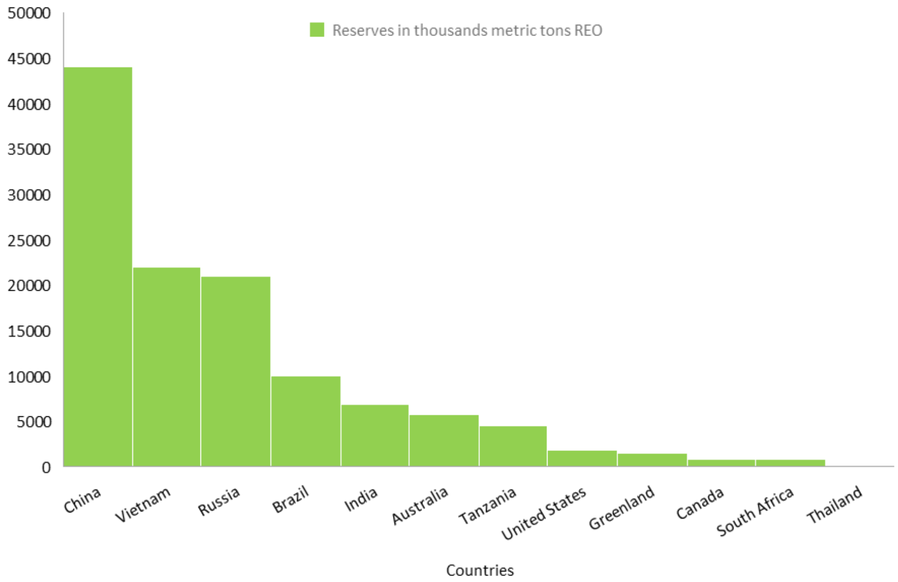

Fig. 4: REEs reserves worldwide (in thousand metric tons rare earth oxides) [34]

6. Conclusion and Recommendations

CFA represents a significant and underutilized resource in India, offering a dual solution to waste management and resource scarcity, particularly in recovering REEs. This paper highlights the considerable potential of CFA in the recovery of REE, advocating for sustainable practices that support both environmental conservation and resource recovery. By adopting innovative extraction techniques and sustainable practices, India can transition from a conventional coal economy to a more circular and resource-efficient model. A concerted effort is needed to explore future research directions, challenges, and opportunities to escalate the REEs' extraction efficiency from CFA. Collaborative research initiatives should optimize extraction processes, minimize environmental impacts, and explore economic models that incentivize recycling efforts. Cooperative efforts between academia, industry, and government are critical to unlocking CFA's potential and addressing energy and environmental challenges in the country.

Acknowledgments. The authors are thankful to Shri S. Shaswattam, ED-NETRA, for their continuous support and guidance towards the exploration of modern condition monitoring techniques for the sustainable development of the Power sector. The authors are thankful to Smt. Kiran Diwakar for her extreme lab support in conducting the present study.

Disclosure of Interests. The authors hereby declare that there are no competing interests relevant to the content of this article.

References

1. Dodbiba, G., & Fujita, T.: Trends in Extraction of Rare Earth Elements from Coal Ashes: A Review. Recycling, 8 (1), 17 (2023)
2. Dai, S., Finkelman, R.B.: Coal as a promising source of critical elements: Progress and future prospects. Int. J. Coal Geol., 186, 155–164 (2018)
3. Central Electricity Authority. Report On Fly Ash Generation at Coal/Lignite Based Thermal Power Stations and it's Utilization in the Country for the 1st half of the Year 2022–2023 (April 2022 to September 2022), https://cea.nic.in/wp-content/uploads/tcd/2023/05/Half_Yearly_Ash_Report_2022_23.pdf, last accessed on 2024/10/25
4. Karan, K. K., Masto, R. E., Agarwalla, H., Bari, S., Kumar, M., Gopinathan, P., Hazra, B., Saha, S., & Maity, S.: Separation of coal combustion residue for critical element extraction and other bulk uses. Environmental Science Advances, 3(1), 109–118 (2023)
5. Sandeep, P., Maity, S., Mishra, S., Chaudhary, D. K., Dusane, C., Pillai, A. S., & Kumar, A. V.: Estimation of rare earth elements in Indian coal fly ashes for recovery feasibility as a secondary source. Journal of Hazardous Materials Advances, 10, 100257 (2023)
6. Yuksekdag, A., Kose-Mutlu, B., Kaya, B., Kumral, M., Wiesner, M. R., Koyuncu, I.: Comprehensive characterization of secondary sources originating from Turkey in terms of rare earth elements and scandium. Science of The Total Environment, 777, 146033 (2021)
7. Dai, S., Zhou, Y., Ren, D., Wang, X., Li, D., & Zhao, L.: Geochemistry and mineralogy of the Late Permian coals from the Songzo Coalfield, Chongqing, southwestern China. Science in China Series D Earth Sciences, 50(5), 678–688 (2007)
8. Palozzi, J., Bailey, J. G., Tran, Q. A., Stanger, R.: A characterization of rare earth elements in coal ash generated during the utilization of Australian coals. International Journal of Coal Preparation and Utilization, 43, 2106–2135 (2023)
9. Wang, Z., Dai, S., Zou, J., French, D., Graham, I. T., Rare earth elements and yttrium in coal ash from the Luzhou power plant in Sichuan, Southwest China: Concentration, characterization and optimized extraction. Int J Coal Geol, 203, 1–14 (2019)
10. Seredin, V.: A new method for primary evaluation of the outlook for rare earth element ores. Geology of Ore Deposits, 52(5), 428–433 (2010)
11. Report of the Committee on Identification of Critical Minerals. (2023). In Ministry of Mines, https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf, last accessed on 2024/10/25Banerjee, R., Chakladar, S., Chattopadhyay, S. K., & Chakravarty, S.: A comparative study on the association and extractability of rare earth elements from laboratory ash, bottom ash, fly ash: A perspective on Indian coals. Minerals Engineering, 213, 108745 (2024)
12. Coal ash in India: A Compendium of Disasters, Environmental and Health risks. (2020). Health Energy Initiative, https://unesdoc.org/ark:/48223/pf0000139578, last accessed on 2024/10/25
13. Liu, P., Zhao, S., Xie, N., Yang, L., Wang, Q., Wen, Y., Chen, H., & Tang, Y.: Green Approach for Rare Earth Element (REE) Recovery from Coal Fly Ash. Environmental Science & Technology, 57, 5414−5423 (2023)
14. Jordens, A., Cheng, P. Y., & Waters, E. K.: A review of the beneficiation of rare earth element bearing minerals. Minerals Engineering, 41, 97-114 (2013)
15. K, A. R., Karan, R., J, M. B., G, R. D., & T, S.: Development of process scheme for recovery of rare earths from leachate of coal flyash. Cleaner Chemical Engineering, 4, 100078 (2022)
16. Thomas, B. S., Dimitriadis, P., Kundu, C., Vuppaladadiyam, S. S. V., Raman, R. S., & Bhattacharya, S.: Extraction and Separation of Rare Earth Elements from coal and coal fly ash: A review on fundamental understanding and on-going engineering advancements. Journal of Environmental Chemical Engineering, 12(3), 112769 (2024)

17. Pan, J., Nie, T., Hassas, B. V., Rezaee, M., Wen, Z., & Zhou, C.: Recovery of rare earth elements from coal fly ash by integrated physical separation and acid leaching. Chemosphere, 248, 126112 (2020)
18. Kumari, A., Jha, M., Chakravarty, S., & Pathak, D.: Indian Coal Ash: A Potential Alternative Resource for Rare Earth Metals (REMs). In the minerals, metals & materials series, 265–273 (2020)
19. Mondal, S., Ghar, A., Satpati, A., Sinharoy, P., Singh, D., Sharma, J., Sreenivas, T., & Kain, V.: Recovery of rare earth elements from coal fly ash using TEHDGA impregnated resin. Hydrometallurgy, 185, 93–101 (2019)
20. India Science, Technology & Innovation - ISTI Portal, https://www.indiascienceandtechnology.gov.in/research/extraction-and-separation-rare-earth-elements-coal-fly-ash-using-ionic-liquids-multifunctional, last accessed on 2025/02/19
21. Wang, K., Adidharma, H., Radosz, M., Wan, P., Xu, X., Russell, C., Tian, H., Fan, M., & Yu, J.: Recovery of rare earth elements with ionic liquids. Green Chem., 19, 4469-4493 (2017)
22. TECHBRIEF_Improved REE Extraction, https://netl.doe.gov/sites/default/files/2020-11/TECHBRIEF20-004_20N-12_Improved%20REE%20Extraction.pdf, last accessed on 2025/02/19
23. Blissett, R., Smalley, N., & Rowson, N.: An investigation into six coal fly ashes from the United Kingdom and Poland to evaluate rare earth element content. Fuel, 119, 236–239 (2013)
24. Lin, R., Howard, B. H., Roth, E. A., Bank, T. L., Granite, E. J., & Soong, Y.: Enrichment of rare earth elements from coal and coal by-products by physical separations. Fuel, 200, 506–520 (2017)
25. K, A. R., Md, S., RamaDevi, G., Thakurta, S. G., & T, S.: On the characterization and leaching of rare earths from a coal fly ash of Indian origin. Separation Science and Technology, 56(3), 541–557 (2020)
26. Nakayama, K., & Nakamura, T.: X-ray Fluorescence Analysis of Rare Earth Elements in Rocks Using Low Dilution Glass Beads. Analytical Sciences, 21(7), 815–822 (2005)
27. Chand, M., Bagchi, S., & Khan, B. H.: Assessing rare earth elements in Indian coal ash using Westcott formalism in NAA and leaching studies. RSC Advances, 14(35), 25820–25829 (2024)
28. Maity, S., Choudhary, A. K. S., Kumar, S., & Gupta, P. K.: Partitioning of Rare Earth Elements (REEs) from Coal-to-Coal Fly Ash in Different Thermal Power Stations (TPSs) of India. Journal of the Geological Society of India, 98(4), 460–466 (2022)
29. Phuoc, T., Wang, P., & Mcintyre, D.: Detection of rare earth elements in Powder River Basin sub-bituminous coal ash using laser-induced breakdown spectroscopy (LIBS). Fuel, 163, 129–132 (2015)
30. Gautam, P., Sharma, P., & Satyakam, R.: Determination of rare earth elements in NTPC coal fly ash through ICPMS Technique. NETRA Journal, 26, 55-59 (2019)
31. Banerjee, R., Chakladar, S., Chattopadhyay, S. K., & Chakravarty, S.: A comparative study on the association and extractability of rare earth elements from laboratory ash, bottom ash, fly ash: A perspective on Indian coals. Minerals Engineering, 213, 108745 (2024)
32. Seredin, V., & Dai, S.: Coal deposits as potential alternative sources for lanthanides and yttrium. International Journal of Coal Geology, 94, 67–93 (2012)
33. Franus, W., Wiatros-Motyka, M. M., & Wdowin, M.: Coal fly ash as a resource for rare earth elements. Environmental Science and Pollution Research, 22(12), 9464–9474(2015)
34. Statista 2024, https://www.statista.com/statistics/277268/rare-earth-reserves-by-country/, last accessed on 2024/10/25

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this chapter or parts of it.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.