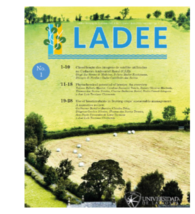

Importance of Rare Earth Elements in Modern Society and their Potential Source in Coal Ashes

Importancia de los Elementos de Tierras Raras en la Sociedad Moderna y su Potencial Fuente en las Cenizas de Carbón

Importância dos Elementos de Terras Raras na Sociedade Moderna e sua Potencial Fonte nas Cinzas de Carvão

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Abstract

Introduction: Rare Earth Elements (REEs) are crucial for advanced technologies in modern society, ranging from electronics to renewable energy and defense. Their increasing demand in critical industries underscores the need for a consistent and sustainable supply. Historically extracted from REE-rich minerals such as bastnäsite and monazite, the search for alternative sources has gained prominence, among these, coal ashes stand out, produced by burning coal to generate energy, ashes contain REEs in relatively low concentrations but with significant potential due to their massive global volume. The importance of ensuring the resilience of the REE supply chain has driven research to extract these elements from coal ashes, diversifying sources and reducing reliance on specific minerals. As technologies advance and REE applications expand, the ability to recover them from unconventional sources like coal ashes could have a sustainable impact on our societies. Research into the extraction and utilization of REEs from ashes is in progress and may enhance supply security. This study highlights the global importance of finding alternative sources of REE, such as coal ash, emphasizing the need to ensure a consistent and sustainable supply of these essential elements.

Keywords: Advanced technologies; minerals; unconventional sources

Resumen

Introducción: Los Elementos de Tierras Raras (ETR) son vitales para tecnologías avanzadas en la sociedad actual, desde electrónica hasta energía renovable y defensa. Su demanda creciente en industrias clave subraya la necesidad de un suministro constante y sostenible. Históricamente extraídos de minerales ricos en ETR, como bastnasita y monazite, la búsqueda de fuentes alternativas ha cobrado relevancia, entre estas, las cenizas de carbón se destacan, producidas al quemar carbón para generar energía, las cenizas contienen ETR en concentraciones relativamente bajas pero con un potencial significativo debido a su gran volumen global. La importancia de garantizar la resiliencia de la cadena de suministro de ETR ha impulsado la investigación para extraer estos elementos de las cenizas de carbón, diversificando fuentes y reduciendo la dependencia de minerales específicos. A medida que las tecnologías avanzan y las aplicaciones de ETR se expanden, la capacidad de recuperarlos de fuentes no convencionales como las cenizas de carbón podría tener un impacto sostenible en nuestras sociedades. La investigación en la extracción y uso de ETR de cenizas está en desarrollo y puede aumentar la seguridad en su suministro. Este estudio destaca la importancia global de encontrar fuentes alternativas de REE, como las cenizas de carbón, enfatizando la necesidad de garantizar un suministro constante y sostenible de estos elementos esenciales.

Palabras clave: Tecnologías avanzadas; minerales; fuentes no convencionales

Resumo

Introdução: Os Elementos de Terras Raras (ETRs) são vitais para as tecnologias avançadas na sociedade moderna, desde a eletrônica até a energia renovável e a defesa. Sua demanda crescente em indústrias-chave sublinha a necessidade de um suprimento constante e sustentável. Historicamente extraídos de minerais ricos em ETRs, como bastnasita e monazita, a busca por fontes alternativas tem ganhado relevância, entre essas fontes, as cinzas de carvão se destacam, produzidas pela queima de carvão para gerar energia, as cinzas contêm ETRs em concentrações relativamente baixas, mas com potencial significativo devido ao seu grande volume global. A importância de garantir a resiliência da cadeia de suprimentos de ETRs impulsionou a pesquisa para extrair esses elementos das cinzas de carvão, diversificando as fontes e reduzindo a dependência de minerais específicos. À medida que as tecnologias avançam e as aplicações de ETRs se expandem, a capacidade de recuperá-los de fontes não convencionais, como as cinzas de carvão, poderia ter um impacto sustentável em nossas sociedades. A pesquisa sobre a extração e utilização de ETRs das cinzas está em andamento e pode melhorar a segurança no fornecimento. Este estudo destaca a importância global de encontrar fontes alternativas de REE, como as cinzas de carvão, enfatizando a necessidade de garantir um fornecimento consistente e sustentável destes elementos essenciais.

Palavras-chave: Tecnologias avançadas; minerais; fontes não convencionais

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1. Introduction

In the contemporary era, Rare Earth Elements (REEs) have emerged with unprecedented prominence, establishing themselves as vital components in a wide array of innovative and strategic technologies. These REEs, a distinguished group of seventeen chemical elements, have evolved to become the invisible yet invaluable foundation of diverse applications, spanning from advanced electronics to renewable energy solutions and military defense capabilities (Alonso et al., 2012).

In the realm of modern electronics, REEs have infiltrated our everyday devices, from smartphones and televisions to satellite navigation systems. Their capacity to enhance efficiency and processing speed has been pivotal in driving the digital revolution. In the renewable energy sector, REEs play a leading role in the manufacture of crucial technologies such as wind turbines, solar panels, and energy storage batteries, proving indispensable for advancing toward a more sustainable energy matrix (Pagano, 2016; Islam, Sohag et al., 2022).

The significance of REEs extends beyond consumer devices and clean energy. In defense applications, REEs are tactical necessities, utilized in the production of communication systems, advanced radars, and precision weaponry. Their availability ensures technological superiority in strategic and competitive environments (Dobransky, 2012).

Despite their escalating demand, the supply of REEs remains vulnerable and susceptible to geopolitical disruptions. Most of these elements are extracted in their primary form from specific mineral deposits, granting countries with such reserves considerable control over the global supply. This vulnerability has underscored the importance of securing the resilience of the REE supply chain, driving the quest for alternative and sustainable sources (Binnemans et al., 2013).

It is within this context that the innovative perspective of coal ashes as an alternative source of REEs emerges. These ashes, inevitable byproducts of coal combustion in power plants, have been underestimated in terms of their potential REE content. While the concentration of REEs in ashes tends to be low compared to primary mineral deposits, their global abundance and the lack of alternatives make this resource highly intriguing for researchers and materials experts (Eterigho-Ikelegbe et al., 2021). The pursuit of more diverse and sustainable REE sources could significantly impact the security and sustainability of our modern societies.

This article aims to delve into the possibility of extracting REEs from coal ashes, highlighting their advantages and challenges. Through an examination of ash composition, extraction techniques, environmental impacts, and economic feasibility, this study seeks to shed light on the viability of harnessing this secondary resource for the sake of a more sustainable and resilient society. With a focus on innovation, science, and the constant pursuit of solutions, this research embarks on a journey to understand the full potential of REEs in coal ashes and their ability to transform our technological and environmental outlooks. Furthermore, it is important to emphasize that the study can significantly contribute to the global supply of REEs, promoting source diversification and reducing dependence on specific mineral deposits, which is essential for the security and stability of technologies and industries that rely on these valuable elements.

2. Composition and Formation of Coal Ashes: Exploring the Interaction of REEs in the Combustion Process

Coal ashes, as an inevitable byproduct of coal combustion in power plants and other industrial facilities, present an intriguing starting point for the exploration of REEs. These ashes, although often considered waste, represent potential reservoirs of REEs that warrant closer attention due to their implication in the search for alternative sources of these vital elements (Binnemans et al., 2013).

The composition of coal ashes is a fundamental topic in REE research. Comprising a complex mixture of inorganic materials generated by coal incineration, their composition can vary based on the source and combustion conditions. Ashes contain metal oxides, silicon, and aluminum oxides, as well as trace elements, including REEs (Dardona et al., 2023).

During combustion, REEs present in coal are released and dispersed in the ashes. Factors such as the type of coal used, combustion conditions, and the efficiency of emissions capture systems influence the form and concentration of REEs in the ashes. Variability in the concentration of REEs in ashes is a point of interest. Although their concentration tends to be low compared to primary mineral deposits, this variation can be significant among different ash samples. The presence of additives or adjuvants in the combustion process can also influence REE content, adding complexity to the characterization and recovery of these elements (Stuckman et al., 2018).

Research focuses on identifying patterns in the incorporation of REEs in coal ashes. Analytical techniques such as X-ray spectroscopy and scanning electron microscopy allow the observation of the distribution and association of REEs in the ashes. These methods help identify minerals and phases containing REEs and understand how they are bonded with other ash components.

The composition and formation of coal ashes are crucial in exploring REEs as potential resources. Understanding how REEs interact in combustion and distribution within ashes lays the foundation for effective extraction strategies and the viability of using these byproducts as sustainable sources of essential elements in modern society.

3. Characterization of Rare Earth Elements in Coal Ashes: Unveiling Their Distribution and Association through Advanced Analytical

Techniques Accurate characterization of REEs in coal ashes is essential for understanding their behavior and potential for recovery. Given the complexity of ash matrices and the relatively low concentrations of REEs, advanced analytical techniques are required to identify, quantify, and map the distribution of these elements in samples (Thompson et al., 2018).

X-ray spectroscopy, a fundamental technique, plays a crucial role in this characterization. X-ray Fluorescence Spectroscopy (XRF) detects elements over a wide range of concentrations, invaluable for determining the presence of REEs. Energy-Dispersive Spectroscopy (EDS) in Scanning Electron Microscopy (SEM) provides detailed characterization on a micrometer scale, revealing the point elemental composition and distribution of REEs within ash structures (Silva et al., 2020).

Transmission Electron Microscopy (TEM) offers an even more detailed view at the nanometer level, allowing direct observation of the phases and minerals hosting REEs. This technique provides insights into the morphology and association of REEs with other ash components, essential for understanding the capture and retention mechanisms of these elements (Silva et al., 2020).

X-ray Absorption Spectroscopy (XAS) is valuable for investigating the chemical speciation of REEs in ashes. It enables the determination of the specific chemical form in which REEs are present and how they are bonded to other elements in the ash matrix, essential for designing effective recovery strategies (Stuckman et al., 2018).

X-ray Diffraction (XRD) also plays an important role by providing information about the crystal structure of minerals present in the ashes. This helps identify minerals that host REEs and understand how REEs are incorporated into the crystal structure of materials (Silva et al., 2020).

These advanced techniques are vital for unraveling the distribution, association, and speciation of REEs in coal ashes. This understanding not only informs the feasibility of REE recovery but also sheds light on the physical and chemical processes during the formation and incineration of ashes.

Ketris and Yudovich (2009) estimated that coal fly ashes contain an average of 445 ppm of REEs on a global scale. In addition to the cumulative REE content within fly ash, the proportion of critical elements within this content and the ratio of critical to excessive elements, expressed as an outlook coefficient, as highlighted in the evaluation by Seredin and Dai (2012), is of paramount importance.

Several studies have documented the presence of REEs in coal ash. Bielowicz (2020) reported a gallium content of 110.4 ppm in coal ashes from the Bogdanka deposit in Poland. In China, approximately 140 ppm of vanadium is extracted from coal ash (Ketris & Yudovich, 2009). Scandium, although naturally occurring in the Earth's crust at a concentration of approximately 22 ppm (Rudnick & Gao, 2022), is widely dispersed. However, it reaches 24 ppm in coal ashes. Franus et al. (2015) investigated fly ashes and identified critical element contents ranging from 30.46% to 38.26% and outlook coefficients ranging from 0.78 to 1.07. Therefore, it can be considered a promising source of REEs for economic development (Seredin & Dai 2012).

4. Methods REE Extraction from Coal Ashes: Exploring Techniques for Separation and Concentration

The successful recovery of REEs from coal ashes requires efficient and selective extraction methods that allow for the separation and concentration of these elements from the ash matrix.

Given the complexity of ashes and the low concentrations of REEs, various extraction techniques have been developed to address this challenge.

4.1. *Chemical Leaching*

Chemical leaching is one of the most common and widely investigated methods for extracting REEs from coal ashes. This process involves the use of acidic or basic solutions to selectively dissolve REEs and other soluble components present in the ash matrix. The choice of leaching agent and reaction conditions are critical factors influencing the efficiency of extraction (Wen et al., 2022).

The appropriate selection of the leaching agent is essential to ensure efficient and selective extraction of REEs. Acids and bases are the most used agents in the chemical leaching of coal ashes. Acids such as hydrochloric acid (HCl) or nitric acid (HNO_3) can dissolve REEs by forming soluble complexes (Arrachart et al., 2021). On the other hand, bases like sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH) can dissolve REEs by forming complex ions (Islam, Wagh et al., 2022).

In addition to the leaching agent, reaction conditions such as temperature, leaching time, and solid-liquid ratio are also crucial in determining extraction efficiency. Optimizing these conditions can improve the solubility of REEs and minimize the leaching of other unwanted components (Gergoric et al., 2019).

One challenge in chemical leaching is achieving high extraction efficiency of REEs without negatively affecting selectivity. Selectivity refers to the ability to selectively dissolve REEs without excessive dissolution of other components present in the ashes, which could result in contamination of the leaching solution. Careful choice of the leaching agent and optimization of conditions can help maximize extraction efficiency and selectivity (Kaim et al., 2022).

4.2. *Solvent Extraction*

Solvent extraction is an effective and widely used method for the recovery of REEs from coal ashes. This approach involves using organic solvents that are immiscible with water to selectively extract REEs dissolved in the aqueous phase. Solvent extraction relies on the selective affinity of REEs for organic solvents. The aqueous phase, containing dissolved REEs, is brought into contact with the organic solvent in an extractor. REEs are distributed between both phases due to differences in their distribution coefficients between water and the organic solvent.

The choice of organic solvent is crucial to achieving efficient and selective extraction. Organic solvents should have a high capacity to dissolve REEs and a selective affinity for them. Commonly used solvents include compounds such as organic acids, esters, phosphates, and amines.

After extraction, the organic phase containing REEs is separated from the aqueous phase. Subsequently, REEs can be recovered from the organic phase by adding acidic or basic solutions that change the solubility of REEs and allow for their separation. The recovered REEs can then undergo further purification processes.

Solvent extraction offers advantages such as high selectivity, efficiency, and the possibility to adjust extraction conditions to maximize yield. However, it also presents challenges, such as handling organic solvents and waste treatment. Proper selection of the solvent and optimization of conditions is essential to achieve optimal results (Gupta & Krishnamurthy, 1992; Hiskey & Copp, 2018).

4.3 *Ion Exchange*

Ion exchange methods are promising approaches for extracting REEs from coal ashes. These methods involve introducing charged ions, known as exchange ions, into a solution that interacts with the ashes. These exchange ions swap places with REEs present in the solid matrix of the ashes, allowing their release into the solution. The selectivity of the exchange process largely depends on the chosen exchange ions and interaction conditions (Rao & Sreenivas, 2019).

Selectivity in ion exchange is crucial to ensure the selective extraction of REEs without overly affecting other components present in the ashes. The choice of appropriate exchange ions is fundamental to achieving this goal. Exchange ions are selected based on their ability to form complexes with REEs and their affinity for the solid matrix. Commonly used exchange ions include hydrogen ions (H^+), sodium ions (Na^+), and ammonium ions (NH_4^+), among others (Rao & Sreenivas, 2019).

The ion exchange process occurs at the adsorption sites on the surface of ash particles. Exchange ions adhere to the solid surface, displacing REE ions at the adsorption sites. As REE ions are released, they dissolve into the aqueous solution, forming complexes that can be subsequently recovered (El Ouardi et al., 2023).

Optimizing the conditions of the ion exchange process is essential to maximize extraction efficiency and selectivity. Factors such as solution pH, concentration of exchange ions, interaction time, and solid-liquid ratio play a crucial role in process effectiveness. Understanding exchange mechanisms and the affinity of REEs for exchange ions helps design optimal conditions (El Ouardi et al., 2023).

5. Methods REEs recovery from the liquid phase

The recovery of REEs from liquid phases through precipitation and adsorption techniques plays a significant role in sustainable resource management and technological advancement.

5.1. *Precipitation*

Precipitation is a widely used technique in the recovery of REEs from coal ashes. This methodology is based on the formation of solid compounds from a liquid solution. After the leaching process to dissolve REEs from the ashes, precipitation allows for the conversion of dissolved REEs in the solution into solid compounds (Gupta & Krishnamurthy, 1992; Han, 2020).

The precipitation process involves the controlled addition of a specific precipitating agent to the solution containing the dissolved REEs. This agent induces the formation of insoluble solid compounds of REEs through chemical reactions. The resulting precipitates can be compounds such as hydroxides, carbonates, or phosphates, depending on the precipitating agent used and reaction conditions (Gupta & Krishnamurthy, 1992; Han, 2020).

The selection of the precipitating agent is critical to obtaining high-purity and selective precipitates. Precipitating agents can be inorganic chemicals or organic compounds that react with REE ions present in the solution. The formation of insoluble precipitates ensures that REEs are removed from the solution and can be recovered (Gupta & Krishnamurthy, 1992; Han, 2020).

After the formation of precipitates, they need to be separated from the solution for further processing and purification. Separation is usually done through techniques like filtration or sedimentation. Once separated, precipitates can undergo additional purification processes, such as washing and recrystallization, to remove impurities and obtain high-purity REE compounds (Boudreault et al., 2015).

Precipitation offers advantages such as the ability to obtain high-purity solid compounds and the possibility to adjust reaction conditions to control selectivity. However, it is essential to consider the optimization of precipitation parameters, such as REE ion concentration in the solution, pH, and concentration of the precipitating agent, to maximize process efficiency and avoid the formation of undesirable precipitates (Gupta & Krishnamurthy, 1992; Han, 2020).

5.2. *Adsorption*

Adsorption is an effective extraction method used to recover REEs from coal ashes. In this process, adsorbent materials with an affinity for REEs are used to capture them from the aqueous solution. Adsorption involves the interaction between REEs in the aqueous solution and the surface of the adsorbent material. Used adsorbent materials can be inorganic compounds, polymers, zeolites, or other materials with functional groups that have an affinity for REEs (Zhang et al., 2020). REEs adhere to the surface of the adsorbent material due to electrostatic forces, chemical bonds, or Van der Waals interactions (Pathapati et al., 2023).

The adsorption process generally involves bringing treated coal ashes into contact with the adsorbent material. During this contact, REEs present in the solution are captured by the adsorbent material. Then, the REE-loaded adsorbent material is separated from the solution and undergoes a desorption process to release the captured REEs (Amirshahi & Jorjani, 2023).

Adsorption offers advantages such as high selectivity and the ability to concentrate REEs on the surface of the adsorbent material. However, it also presents challenges such as optimizing adsorption and desorption conditions, as well as regenerating the adsorbent material for reuse (Molina-Calderón et al., 2022).

Desorption and REE Recovery Desorption is a crucial process in the recovery of REEs captured on adsorbent materials. This process involves the controlled and selective release of previously adsorbed REEs from the material, allowing for their subsequent recovery and purification. Desorption is carried out through the application of specific conditions that alter the affinity between REEs and the adsorbent material (Gupta & Krishnamurthy, 1992).

One common method to achieve desorption is by modifying the pH of the system. Changes in pH can influence the chemical interactions and surface charge levels of both REEs and the adsorbent material. By carefully adjusting the pH of the medium, it's possible to decrease the affinity between REEs and the adsorbent material, resulting in the release of captured REEs. Temperature can also play a role in desorption, as an increase in temperature can enhance the kinetic energy of particles and reduce the interaction forces between REEs and the adsorbent material (Smith et al., 2016).

In addition to pH and temperature changes, the use of specific solvents can also be employed to achieve the desorption of REEs. These solvents may have specific chemical affinities with REEs, favoring the release of elements from the surface of the adsorbent material. The choice of a suitable solvent depends on the chemical properties of REEs and the adsorbent material (Kim et al., 2021).

Once REEs have been desorbed, they become available for recovery and subsequent purification. Purification is essential to obtain REEs with appropriate purity levels for use in specific applications. Various purification methods, such as selective precipitation, liquid-liquid extraction, and chromatography, can be applied to separate and concentrate recovered REEs from other undesirable components.

Desorption is a critical step in the process of recovering REEs from adsorbent materials. Manipulating conditions such as pH, temperature, and the use of specific solvents allows for the selective release of captured REEs from the adsorbent material, facilitating their subsequent recovery and purification. This process is essential to maximize the efficiency and feasibility of recovering REEs from unconventional sources.

6. Selection of Extraction Methods

The choice of extraction method for recovering REEs from coal ashes is a critical process that must consider various factors such as selectivity, efficiency, and economic feasibility. Since different types of ashes and concentrations of REEs require specific approaches, it is essential to carefully evaluate the available options. Here, we delve into these aspects and their importance in the REE recovery process (Jha et al., 2016).

The selectivity of an extraction method refers to its ability to specifically capture REEs without interference from other components present in the ashes. Selective methods ensure a more accurate and efficient recovery of REEs, minimizing the loss of valuable materials. Efficiency, on the other hand, relates to the amount of REEs recovered relative to the total amount present in the ashes. Efficient methods maximize recovery and reduce the need for process repetition (Borra et al., 2016).

Economic feasibility is a key factor in determining the choice of extraction method. Costs associated with reagents, equipment, and labor must be balanced against the value of the recovered REEs. Fluctuating prices of REEs in the global market also impact the economic viability of recovery. A detailed economic analysis, considering costs and benefits, is essential to ensure the recovery process is profitable (Borra et al., 2016; Jha et al., 2016; Swain, 2023).

Optimization of extraction conditions is crucial to achieve high efficiency and selectivity. This includes adjusting the concentration of used reagents, reaction parameters such as temperature and pH, and the contact time between ashes and reagents. Careful optimization of these conditions maximizes process performance and minimizes unwanted waste or byproducts (Borra et al., 2016; Jha et al., 2016; Swain, 2023).

Research in the recovery of REEs from coal ashes continues to advance to improve the efficiency and sustainability of extraction methods. Scientists work on developing and refining techniques, exploring new combinations of reagents, and optimizing processes to increase recovery. Collaboration between the scientific community and industry is essential to drive innovation in this field (Swain, 2023).

The choice of extraction method should also consider environmental implications. Methods should minimize waste generation and the release of toxic substances during the recovery process. Furthermore, environmental costs, such as the use of hazardous reagents, must be evaluated in the economic analysis to obtain a comprehensive picture of viability.

7. Environmental Impact and Release of Toxic Substances in REE Extraction from Coal Ashes

The extraction of Rare Earth Elements (REEs) from coal ashes presents environmental challenges related to the potential release of toxic and contaminating substances during the process. These challenges must be addressed to ensure a sustainable and responsible recovery of REEs. Following, we delve into this critical aspect and its importance in REE extraction.

The leaching agents and chemicals used in extraction processes can release heavy metals and other toxic compounds present in the ashes. The interaction between reagents and the ash matrix could mobilize elements like mercury, arsenic, and lead, which are harmful to the environment and human health. The release of these toxic substances raises concerns about soil, water, and air pollution (Liu et al., 2023; Zhang et al., 2020).

The release of toxic substances during REE extraction could have adverse effects on surrounding ecosystems. Soil and water contamination can affect biodiversity, aquatic systems, and the quality of drinking water. Moreover, the release of toxic compounds into the air could contribute to atmospheric pollution and impact air quality in nearby areas. It can also have significant impacts on human health. Released particles and gases can be inhaled by individuals, leading to respiratory problems and other health issues. Additionally, the contamination of drinking water with toxic compounds can pose a direct risk to local communities (Liu et al., 2023; Zhang et al., 2020).

To address these challenges, it is fundamental to implement appropriate mitigation measures. This can include the use of safer and less toxic reagents in extraction processes, as well as the implementation of effluent treatment techniques to minimize the release of toxic substances into the environment. Careful selection of reagents and processes can significantly reduce the risk of toxic substance release (Liu et al., 2023; Zhang et al., 2020).

Effective regulation and continuous monitoring are essential to ensure that REE extraction processes comply with environmental and safety standards. Regulatory authorities should establish clear guidelines for the management of toxic substances and pollution prevention. Additionally, ongoing environmental monitoring can identify potential issues and enable swift action to mitigate negative impacts.

8. Energy and Resource Consumption in REE Extraction from Coal Ashes

The extraction of REEs from coal ashes offers the potential to recover valuable resources but also presents challenges in terms of energy and resource consumption. The sustainability of the process largely depends on energy efficiency and responsible resource utilization. Below, we delve into how these factors impact the extraction of REEs from coal ashes (Balaram, 2023).

REE extraction processes can require a significant amount of energy, especially in techniques involving chemical leaching, separation, and purification. The amount of energy required varies depending on the method and extraction conditions. Selecting more energy-efficient processes is essential to minimize environmental impact and reduce operational costs (Balaram, 2023; Eterigho-Ikelegbe et al., 2021).

In addition to energy, REE extraction may also require other resources such as chemical reagents, water, and construction materials for processing facilities. It's important to assess how many resources are needed compared to the amount of REEs recovered and the benefits generated. Process optimization to reduce resource consumption is essential to ensure long-term sustainability (Humphreys, 2014).

Evaluating the energy balance is crucial to understanding the relationship between energy invested in REE extraction and the benefits gained. Additionally, assessing environmental impact, including carbon footprint and natural resource depletion, is essential to determine whether recovering REEs from coal ashes is a sustainable option compared to other sources (Balaram, 2023; Eterigho-Ikelegbe et al., 2021).

Research and development of more sustainable technologies are critical to addressing challenges related to energy and resource consumption. This can include searching for more efficient extraction methods, optimizing process conditions to reduce required energy, and implementing resource management strategies.

9. Economic Viability of REE Recovery from Coal Ashes

The assessment of economic viability in the recovery of REEs from coal ashes is essential to determine the financial feasibility of this process. A detailed analysis of the economic aspects involved provides a stronger understanding of the costs, benefits, and return on investment in this endeavor (Jyothi et al., 2020; Swain & Mishra, 2019; Dupont & Binnemans, 2015).

Extraction costs are a crucial component in evaluating the economic viability of recovering REEs from coal ashes. These costs encompass a range of expenses related to extraction processes, from chemical reagents to energy and labor. Analyzing these costs in detail provides a more accurate view of the profitability of REE recovery (Pan et al., 2021).

Chemical reagents are essential in REE extraction processes. The costs of these reagents can vary depending on the type of extraction method used, whether it's chemical leaching, ion exchange, precipitation, or others. The quantity and purity of the reagents also affect costs. Selecting suitable chemical reagents that maximize extraction efficiency and minimize costs is a significant challenge (Akar et al., 2012).

REE extraction from coal ashes can require a significant amount of energy, especially in processes involving element separation and purification. Choosing low-energy processes and efficient energy use are key considerations to minimize energy costs. Additionally, the energy used must be compared to the economic and environmental benefits of REE recovery (Massari & Rubert, 2013).

Equipment needed to carry out extraction, separation, and purification processes also contributes to costs. This includes the cost of acquiring, maintaining, and operating equipment specific to each extraction method. Additionally, labor costs, training, and personnel required to operate and oversee processes must be considered.

Optimizing extraction costs is a key goal to ensure economic viability. This involves continuous evaluation of extraction methods, process efficiency, and proper selection of chemical reagents. Research and development of more efficient and cost-effective methods are essential to reduce extraction costs and improve profitability.

9.1. *Market Prices of REEs and Their Impact on Coal Ash Recovery*

In the economic assessment of recovering REEs from coal ashes, the market prices of REEs play a critical role. Market prices of REEs are dynamic variables influenced by a range of economic and commercial factors. Analyzing these prices in detail and their impact on economic viability is essential for making informed decisions.

According to Castor and Hedrick (2006), global market prices of REEs are influenced by several factors, including the demand for REEs in various industries such as electronics, renewable energy, and defense directly affect prices. Growing demand for advanced technologies has increased the need for REEs, which can raise prices. Production disruptions due to factors such as limited raw material supply or geopolitical issues can have a significant impact on prices. Trade policies such as tariffs and export restrictions can affect REE trade flows and thus influence prices. Advances in extraction and recycling technologies can affect the availability of REEs in the market and consequently influence prices.

Monitoring and predicting market prices of REEs is fundamental for estimating potential revenues and evaluating the profitability of recovering REEs from coal ashes. Economic analyses should consider different price scenarios to assess the financial robustness of the process. REE prices can experience volatility due to the aforementioned factors and other unforeseen events. This introduces risks and opportunities in the economic evaluation. Identifying potential risks and considering mitigation strategies, such as long-term contracts, can help reduce exposure to price volatility (Gao et al., 2019).

Cost-benefit analysis is an essential tool for evaluating the economic viability and sustainability of recovering REEs from coal ashes. This comprehensive analysis involves a detailed comparison between the costs involved in extraction and operation and the expected benefits, including revenues and other positive and negative impacts (Graedel et al., 2012). This includes direct and indirect costs associated with extraction methods, the use of chemical reagents, energy, labor, maintenance, and other operational expenses. These costs should be evaluated about the benefits expected to be obtained. The revenue from REE sales encompasses income generated through the sale of recovered REEs in the market, contingent upon market prices, global demand dynamics, and the quality of the extracted REEs. Additionally, the analysis should encompass social and environmental advantages beyond financial gains. These may encompass diminishing reliance on conventional REE sources, fostering sustainability initiatives, job creation, and enhancing energy security.

It is crucial to consider environmental and social costs in the cost-benefit analysis. These can include the cost of mitigating environmental impacts, such as waste management and area restoration. Social costs related to workers and local community health and safety should also be considered. The cost-benefit analysis should also account for risks, such as REE price volatility, changes in market demand, and potential operational issues. Conducting scenario analyses can help understand how different situations could affect financial and environmental outcomes (Proelss et al., 2020).

9.2. *Uncertainty Factors in the Economic Viability of REE Recovery from Coal Ashes*

The economic viability assessment of recovering Rare Earth Elements (REEs) from coal ashes must address a range of uncertainty factors that can influence financial outcomes and decision-making. Recognizing and understanding these uncertainties is essential to gain a complete picture of the sustainability and profitability of this process. REE prices are volatile and can be influenced by factors such as global supply and demand, trade regulations, and technological developments. Sensitivity analysis can help identify how changes in prices may impact revenues and profitability. Changes in environmental and mining regulations can have a significant impact on the costs and operations of REE recovery. It's important to consider potential changes in government policies and how they could affect economic viability (Seliger, 2012).

REE recovery technology is constantly evolving. The introduction of new methods or technological improvements can alter process costs and efficiency. Monitoring technological advancements in the field is essential for making informed decisions. Competition in the REE industry can influence prices and demand for recovered products. Assessing the competitive landscape and market position is important to estimate future demand and potential revenues. The availability and prices of resources and energy used in the recovery process can also change over time. Raw material, energy, and other input costs should be considered in the economic analysis. Financial factors such as interest rates, inflation, and exchange rates can have significant impacts on costs and revenues. Considering different financial scenarios can help evaluate risk and volatility (Asr et al., 2019).

Social and environmental aspects can influence public perception and corporate reputation. Costs associated with managing social and environmental impacts should be included in the analysis.

Ultimately, the economic viability analysis provides essential information for making informed decisions about REE recovery from coal ashes. Given that the REE industry is highly dynamic and constantly evolving, a rigorous and detailed approach to economic evaluation is essential to ensure that REE recovery is not only technologically feasible but also economically profitable and sustainable in the long term.

10. Applications of Recovered Rare Earth Elements (REEs) from Coal Ashes

According to Stauffer et al. (2002), Massari and Ruberti (2013), and Binnemans et al. (2013), recovering REEs from coal ashes not only represents an opportunity to secure the supply of these essential elements but also opens the door to a variety of innovative applications in various industries. These REEs play an integral role in modern technologies ranging from high-tech electronics to medicine and renewable energy. Some key applications of recovered REEs include:

High-Tech Electronics: REEs are vital components in the manufacturing of advanced electronic devices, such as microchips, semiconductors, and memory components. Elements like neodymium and praseodymium are used in the production of magnets and transistors, enabling miniaturization and improved performance of electronic devices. Additionally, REEs contribute to energy efficiency and the extended lifespan of these devices.

Renewable Energy Technologies: REEs are fundamental in the production of renewable energy technologies, such as wind turbines and solar panels. REE magnets, especially those containing neodymium, are used in wind turbines to efficiently generate electricity. Furthermore, REEs play a crucial role in the manufacturing of rechargeable batteries used in energy storage systems and electric vehicles.

Electric and Hybrid Vehicles: The electric mobility industry heavily relies on REEs for the manufacturing of high-capacity batteries and efficient electric motors. Neodymium-iron-boron magnets containing REEs are used in the electric motors of electric and hybrid vehicles, contributing to their performance and efficiency.

Defense and Space Technologies: REEs have applications in the manufacturing of advanced defense equipment and systems, including communication systems, radars, and night vision devices. These elements are essential in producing high-precision equipment used in military and space applications.

- *High-Efficiency Lighting*: REEs are essential for producing high-efficiency LED lighting. LEDs use REE phosphors to convert light emitted by blue LEDs into bright and high-quality white light. This technology has transformed the lighting industry, leading to greater energy efficiency and reduced electricity consumption.
- *Medical and Diagnostic Devices*: REEs also find applications in the medical industry, especially in Magnetic Resonance Imaging (MRI) devices and advanced medical imaging equipment. REE-containing magnets and materials are essential for constructing high-precision equipment used in medical diagnostics and treatments.
- *Ongoing Innovation*: As technology continues to advance, new innovative applications for recovered REEs may emerge. Research in fields such as nanotechnology, biotechnology, and flexible electronics could leverage the unique properties of REEs to develop advanced solutions in emerging areas.

The recovery of REEs from coal ashes not only contributes to the sustainability and security of the supply chain for these elements but also opens opportunities to drive innovation in various key industries. The ability to use recovered REEs in critical technologies promises a more sustainable, efficient, and technologically advanced future.

11. Challenges and Future Research in the Recovery of REEs from Coal Ashes

According to Goodenough et al. (2018), and Binnemans et al. (2013), despite significant advancements in the recovery of REEs from coal ashes, it is undeniable that technical, economic, and environmental challenges persist, requiring ongoing attention and deeper research. This section examines current challenges and explores future research areas that could overcome these obstacles and maximize the potential of recovered REEs:

- *Extraction Efficiency*: Increasing the extraction efficiency of REEs from coal ashes remains a critical challenge. Research and development of more effective and selective leaching and separation methods could allow for a more complete and efficient recovery of REEs present in the ashes. This involves optimizing extraction conditions, exploring new reagents, and gaining a deeper understanding of the interaction mechanisms between REEs and other matrix components.
- *Complex Mineralogy*: The complex composition of coal ashes, which can contain a variety of minerals and compounds, complicates REE recovery and increases the risk of impurities in the recovered products. Investigating the interaction between REEs and other minerals in the ashes would help develop more specific and efficient separation methods, thus reducing cross-contamination and improving the purity of the recovered REEs.
- *Waste Management*: REE extraction from coal ashes can generate waste and by-products, posing challenges in terms of proper management and disposal. Researching approaches to manage and reuse these by-products sustainably is essential to mitigate environmental impacts and maximize process efficiency. This could include recovering other valuable materials present in the waste.
- *Comprehensive Environmental Assessment*: A thorough assessment of the environmental impacts of REE extraction from coal ashes is imperative to ensure process sustainability. This goes beyond the release of chemicals during the process and encompasses considering environmental impacts throughout the entire lifecycle, from extraction to final waste disposal.
- *Cost Optimization*: Continuous optimization of the costs of REE extraction and recovery is essential to ensure long-term economic viability. Identifying more economical raw materials and reagents, as well as improving separation and purification processes, could reduce operational costs and enhance the profitability of the recovery process.
- *Innovation in Separation Technologies*: Research into new separation and purification technologies for REEs could significantly enhance the efficiency and selectivity of recovery processes. Nanotechnology, selective adsorption, and other innovative techniques have the potential to address current challenges and overcome the limitations of conventional separation methods.
- *Exploration of New Ash Sources*: Expanding the search for potential ash sources, such as solid waste incinerators, could increase the availability of recoverable REEs and diversify raw material sources. Investigating the feasibility of REE recovery from different types of ashes can expand production opportunities.
- *Interdisciplinary Cooperation*: The complexity of challenges in REE recovery necessitates interdisciplinary collaboration among chemistry, materials engineering, economics, ecology, and other fields. Encouraging collaboration among experts in different disciplines can lead to more comprehensive and effective solutions that address technical, economic, and environmental aspects holistically.

Overall, addressing these challenges and conducting future research in these areas is essential to advance the recovery of REEs from coal ashes. Overcoming these obstacles would not only improve the efficiency of recovery processes but also contribute to environmental sustainability and the security of the supply chain for these critical elements.

12. Conclusion

In conclusion, the exploration of REEs in coal ashes represents an exciting and promising field of research that addresses challenges in supply, sustainability, and resilience in modern technologies. As the demand for REEs continues to grow in critical industries such as electronics, renewable energy, and defense technology, the search for alternative sources becomes essential to ensure a sustainable and technologically advanced future.

The possibility of extracting REEs from coal ashes, a byproduct of energy generation, presents a unique opportunity to transform what was once considered waste into a valuable source of essential elements. While technical, economic, and environmental challenges are significant, ongoing research and development are paving the way for more efficient extraction methods, advanced separation technologies, and solutions to mitigate environmental impacts.

Economic viability and environmental sustainability are intertwined in this process, and the consideration of factors such as extraction costs, REE market prices, and environmental impacts is essential for making informed decisions. Furthermore, interdisciplinary collaboration, technological innovation, and responsible waste management are key factors in optimizing this recovery process.

While challenges remain to be overcome, from extraction efficiency to waste management and comprehensive environmental assessment, the potential to recover REEs from coal ashes is undeniable. By seizing this opportunity, we can move towards a circular economy and greater independence from traditional sources of REEs, while driving innovation across multiple industries and contributing to a more sustainable and technologically advanced future.

Declaration of competing interests

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

Author contributions

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