NIPES - Journal of Science and Technology Research
www.nipes.org

Advancing Technology and Addressing Toxicity: The Dual Impacts of Rare Earth Elements on Materials and the Environment

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Article Info

Keywords: *Rare earth elements, Environments, Health, Materials, Electric cars, Toxicity*

Received 03 March 2025
Revised 12 April 2025
Accepted 12 May 2025
Available online 18 May 2025

https://doi.org/10.37933/nipes/7.2.2025.19

eISSN-2682-5821, pISSN-2734-2352

Abstract

Rare earth elements (REEs) have emerged as a vital category of material resources, garnering widespread attention in recent years due to their growing importance in the advancement of high-tech innovations and the global transition to a low-carbon economy. As the world accelerates efforts to implement sustainable solutions and reduce dependence on fossil fuels, REEs have become indispensable components in contemporary technologies because of their specialized functionalities. Despite ongoing concerns about unstable supply chains and the environmental impact of their production, global demand for REEs continues to rise. REEs play a critical role in a variety of cutting-edge applications, including renewable energy technologies, electric vehicles, advanced electronics, and defense systems. Their unique physicochemical properties—such as exceptional magnetic strength, luminescence, and thermal stability—make them integral to the materials and devices that support both digital innovation and the green economy. However, extensive mining and long-term utilization of REEs have resulted in significant environmental degradation and posed global public health concerns. The processes involved in REE extraction, refinement, and disposal can generate toxic waste, cause ecological harm, and increase human exposure to hazardous substances. Notably, the specific toxicological effects of REE-associated airborne particulates interacting with the human body remain poorly understood. Given the rising demand, the contrast between technological benefits and environmental/health risks highlights the urgent need for more sustainable practices in REE usage and lifecycle management. This review brings together recent research on REE metallurgy, environmental impacts, and toxicity to inform strategies for sustainable development and policy regulation

1.0 Introduction

Decarbonization has emerged as an important measure to keep the global average temperature increase well below 2 °C above pre-industrial levels [1]. Rare earth elements (REE) are one of the most important elements used for transformation of fossil fuel era into decarbonized future [2, 3], with profound broad and growing applications in clean energy technologies, hybrid vehicles, pollution control, optics, refrigeration, and so on and tends to reduce non-renewable energy sources and emissions from them. Notably, transportation technologies should be improved given their significant environmental impacts and the oil demand of vehicles [4]. However, the development of 'green energy' technologies has resulted in the growth of consumption of natural resources, e.g., growing use of 'permanent magnets', composed of 25–30% of critical materials, such as rare-earth elements (REEs). The 'permanent magnets', called Neodymium magnets (NdFeB), are used in green technologies (sometimes called green elements) such as wind turbines, electric vehicles (EVs) and low energy-efficient lights, renewable energy generation and storage, plug-in hybrid electric vehicles and auto catalysts [1, 3] and they also found applications in other sectors of the global economy including metallurgy (e.g., additives and alloys), defense (e.g., night vision google, cruise missiles), agriculture, science and technology, chemical, electrical, catalytic, magnetic, and magnetic properties, advanced energy components for electronics (e.g., fuel cells, superconductors, lasers, mobile phones, displays, high-capacity batteries), fine chemicals (e.g., polishing products, pigments for glass and ceramic industry), the oil industry (e.g., petroleum cracking catalysts, i.e., lanthanum in fluid-cracking catalyst), and the nuclear (e.g., miniature magnets) and aerospace fields [2] with high priced REEs scandium, europium, terbium, and dysprosium contributing to very high global-warming potentials (GWPs) from production relative to the rest of REE [2]. Emerging and potential applications include using rare earths to absorb ultraviolet light in automotive glass, corrosion protection, and metal coatings in corrosive and salty environments. The futuristic applications of REE are in high-temperature superconductivity, as an alloy of high-temperature aluminum alloys, safe storage, and hydrogen transport for a post-hydrocarbon economy [2].

Generally, REEs are a group of eighteen metallic elements that comprise the fifteen lanthanide series in addition to scandium, indium, and yttrium [5]. These 18 elements are further categorized as light rare earth element (LREEs): lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), and promethium (Pm), Medium rare earth elements (MREEs): samarium (Sm), europium (Eu), and gadolinium (Gd), and Heavy rare earth elements (HREEs): terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc), and yttrium (Y) . The HREEs are regarded as more essential resources because of their extensive applications in photo-electro-magnetism, such as laser media, radiation sources, scintillation crystals, and magnetic materials, etc. which play an irreplaceable role in advanced technology and national defense [6]. Despite having similar electron configurations, rare earth elements (REEs) possess distinct physical and chemical characteristics that make them valuable across a wide array of technological applications. These unique properties impart essential magnetic, luminescent, and mechanical qualities to the products in which they are used. The exceptional behavior of REEs stems largely from their partially filled 4f electron orbitals, which result in chemical traits that are difficult to replicate. As a result, REEs are often irreplaceable in many advanced industrial applications. Their critical role spans various modern technologies, including the production of magnets, batteries, glass, and metal alloys—key components in devices such as computers, lasers, display screens, and other high-tech equipment. Some of the elements experience a higher demand than others due to their critical applications. For example, Nd and Pr, both LREEs, are employed in wind turbines and EVs [2, 7, 8]. There are about 200 known rare-earth containing mineral deposits, mostly as carbonatites, spread around the world. Contrary to a layperson's understanding, REEs are not rare in natural occurrence (cerium is more abundant than tin, and yttrium is more abundant than lead), though REEs have a much lower tendency to become concentrated in exploitable ore deposits [2], in particular HREEs. This being so, only a few mineral species, such as bastnasite, monazite, and RE-bearing clay, have been recovered for commercial production. Bastnasite deposits in China and the United States constitute the largest percentage of the world's rare-earth economic resources. Only a few mineral species, such as bastnasite (a rare earth fluorocarbonate (Ce, La) (CO3) F), monazite (a rare earth phosphate (Ce, La, Y, Th) PO4), xenotime (YPO4), and RE-bearing clay, have been recovered for commercial production. Of these, bastnasites constitute the largest percentage (in the US and China). Monazite deposits in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States constitute the second largest segment. World distribution is shown in Fig. 1[2] .

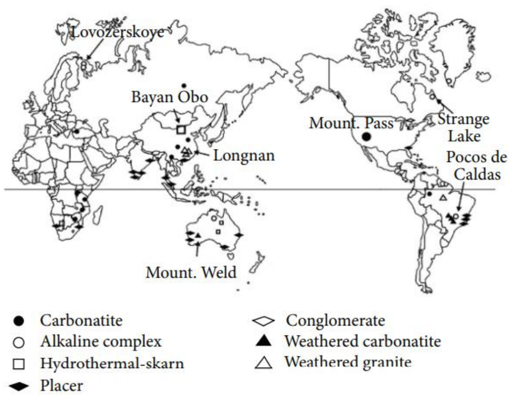

Fig 1: World distribution of rare earths [2]

The United States was once largely self-sufficient in these critical materials from 1950 through 2000 (as illustrated in Fig. 2), but over the past decade has become dependent upon imports. From the early 2000s to 2012, China accounted for around 95 per cent of the global rare earth supply, more than 90% of REE required by U.S. industry, and domestic US industries consumed about 60% [2, 9]. Even today, China accounts for over 85% of global rare earth mining. In addition to their proficiency in extracting rare earth oxides (REOs) from various ores, China is also highly skilled in downstream activities like manufacturing rare earth metals, magnets, and phosphors. The extraction and refinement of

RE ores involve resource- and energy-intensive methods, often accompanied by the release of radioactive thorium [10]; Fig. 3 illustrates the key operational steps involved in extracting individual rare earth elements, mischmetal, and alloys from rare earth deposits [11]. However, this dominance could shift, as the People's Republic has steadily tightened export restrictions since 2004/2005, citing environmental protection and resource conservation by reducing domestic production, shutting smaller, high-polluting production facilities, and introducing export quotas. These quotas, initially 65.600 tons in 2005, decreased to 31,00 tons in 2012. These trade limitations are part of a broader long-term strategy aimed at establishing China as a hub for rare earth-based industries and achieving the benefits of industrial clustering. By restricting access to these critical minerals, China has the potential to do serious damage to the US defense industry and undermine the Trump administration's wider reindustrialization ambitions [10, 12]. Ultimately, this could give Beijing a crucial strategic advantage in long-term US–China competition for military and technological supremacy and add to its existing manufacturing lead. This potential risk to supply may be somewhat absorbed by recycling of in-use stocks of REEs in products (an estimated 440,000 metric tons in 2007). This source can also help to reduce the impact on the environment from the production of virgin REEs [2].

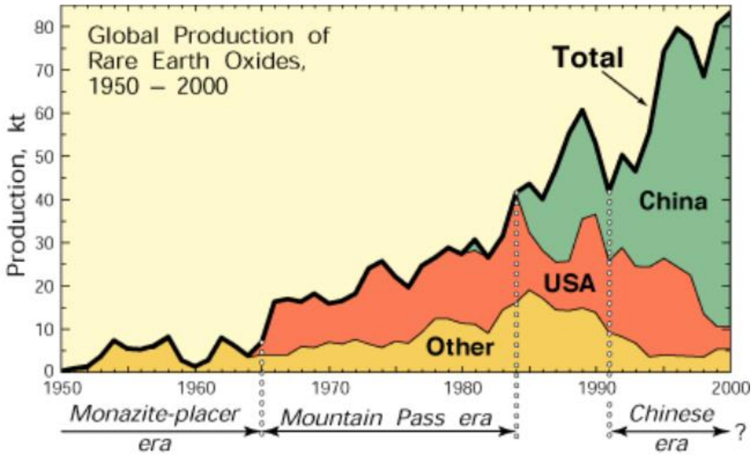

Fig 2. Global rare earth element production (1 kt=10^6 kg) from 1950 through 2000, in four categories

United States, almost entirely from Mountain Pass, California; China, from several deposits; all other countries combined, largely from monazite-bearing placers; and global total. Four periods of production are evident: the monazite-placer era, starting in the late 1800s and ending abruptly in 1964; the Mountain Pass era, starting in 1965 and ending about 1984; a transitional period from about 1984 to 1991; and the Chinese era, beginning about 1991 [9].

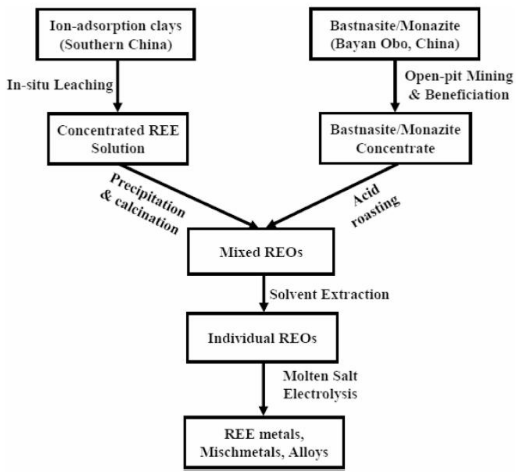

Fig. 3. Schematic of hydrometallurgical processes to produce individual rare earth metals, mischmetal, and alloys [11]

There is, however, an inherent tension in using REEs for green technologies, because the mining and production of those REEs are associated with critical threats to the environment [13]. Many environmental issues surround the production and use of REEs. REEs having similar chemical structures are difficult to separate, compounded by extremely low yield. Thus, apart from the electricity, acids, water, and resources expended in production, there can be huge amounts of waste that can be toxic, with potential damage to the ecosystem [2]. For instance, the processes associated with the production of these magnets lead to the production of toxic and hazardous residues. Therefore, as clean energy technologies continue and increasingly utilize these elements, it is relevant and timely to form a consensus on the best available practices for determining their environmental impacts [13].

2.0. Methods

This study was conducted through an extensive review of the literature. Literature review techniques were used to find relevant technological advancements and toxicology articles. Extensive Internet searching was used as the primary tool for this review. Various websites, including Google Scholar, ScienceDirect, and PubMed, were utilized. Search was conducted using keywords like rare earth, materials, welding, toxicology, worker, environment, occupation, health, or industry. These searches yielded more than 100 references. The references were reviewed further for information regarding occupational or environmental aspects. As a result of this further examination, 69 citations were deemed relevant to this study and are included as references in this report. The major aspects reviewed were the toxicological evaluations of these elements and metallic compounds on materials, human epidemiological studies, and environmental and occupational health impacts on workers. Part of the literature review also included gathering information on the chemical, toxicological, and metallurgical aspects of REE. Also discussed are the prospects of industries with appliances using rare earths, and the significance of preventive efforts for workers' health.

3.0. Rare earth minerals in advancing engineering applications

Rare earth elements (REE) play a crucial role in high-tech applications, earning them the nickname "vitamins" of the modern economy or industry due to their essential yet small-scale presence in a wide range of advanced technologies [14]. As high technology advances, the demand for rare earth elements grows steadily each year. This trend is particularly evident in the pursuit of clean energy solutions and the rapid evolution of electronic devices. Rare earth elements are key components in various advanced technologies, including smartphones, computers, televisions, LEDs, hard drives, and clean energy systems, such as the magnets used in wind turbines.

In recent times, rare earth (RE) elements have been employed as micro-alloying agents in materials like steel, aluminum, and weld metals, thanks to their highly reactive nature and unique chemical characteristics. Their addition leads to notable microstructural modifications [15, 16]. Several researchers have documented the microstructural changes that occur during welding, which are influenced by the complex thermal cycles involved, causing variations in microstructure, oxidation morphology, and material behavior [17-22]. Few other researchers have investigated the corrosion behavior of rare earth (RE) micro-alloyed steels for wide applications in marine environments [16, 23-25]. Due to their ability to modify inclusions, purifying molten steel and aluminum, and enhance properties through microalloying, RE-treated steels are emerging as a promising class of structural materials, and have shown to significantly improve weldability of austenitic stainless steels (ASS) [15, 16, 26-30]. Samanta et.al [15] researched, effect of rare earth elements on microstructure and oxidation behavior in TIG weldments of AISI 316L stainless steel and found that the presence of both Ce and Nb in weld metal shows superior oxidation resistance than to Ce alone. TIG weld microstructures are presented by optical microscopy in Fig. 3.

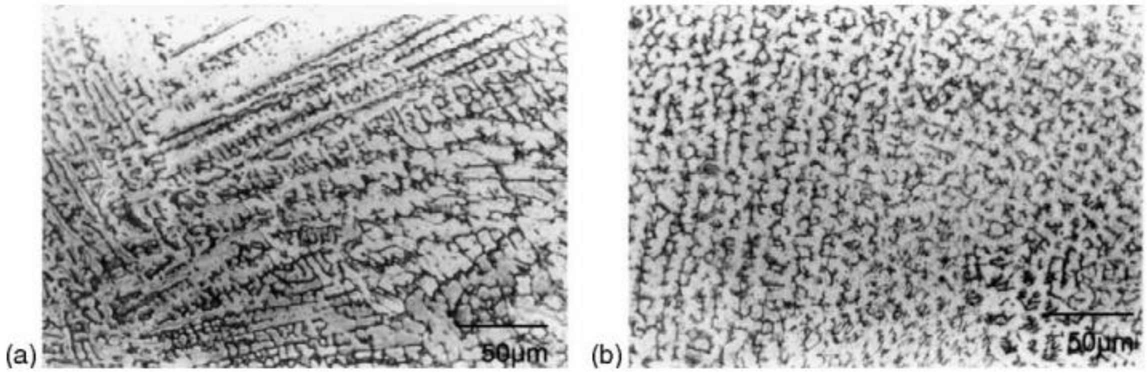

Fig. 3. Optical microstructure of 316L TIG welded zone with 0.03% Ce. (a) Near fusion boundary; (b) weld center [15]

3.1. Rare Earths Metallurgy

Rare earth metals metallurgy refers to the technology and processes used to extract rare earth metals and their compounds from rare earth ores and has been the avenue through which researchers have explored the possible applications of these unique elements [31]. As technology and REEs applications have widened over the past 50 years, the metallurgy of REEs has adapted to incorporate a broader spectrum of knowledge, which involves the chemical behaviors and properties of these elements. This portion of the text will briefly accentuate the extraction, processing, and refinement of REEs, as it is important to point out these processes to fully understand their impacts on the environment.

3.2. Mining and Extraction

Rare earth ores typically occur in low concentrations, making their mining and extraction processes prone to releasing harmful substances, often including radioactive elements, into the environment. Because these elements are widely dispersed throughout the Earth's crust, extracting them is both challenging and highly costly. Furthermore, the development of these resources can adversely affect local ecosystems, polluting water bodies, air, and soil, and impacting living organisms, all of which are crucial to human health and survival. Wastewater from rare earth mining can lead to acidifying nearby soils and groundwater, while solid waste may introduce radioactive substances and heavy metal pollutants. At present, mining is one of the leading contributors to ecological degradation, environmental pollution, and related hazards. The unique methods involved in rare earth extraction and metallurgy have resulted in significant damage to local ecosystems [32]. The main ores of rare-earth elements are bastnasite, monazite, and loparite, which are fluorocarbonates, phosphates, and oxides. All these minerals contain most of the common REEs like Lanthanum, Cerium, Yttrium, Neodymium, etc. The most common method for mining rare earth elements is the open-pit method [33], which involves the removal of overburden, mining, milling, crushing and grinding, separation, or concentration. There are other methods of mining REEs, which include underground mining, dredging, and leaching methods [34]. It is important to know that the method used is highly dependent on the geological characteristics of the deposit [33]. For example, rare-earth containing, ion-adsorption clay deposits, found in Southern China, are usually mined using open-pit methods, without further mineral processing [35]. The world's largest, rare earth (RE) mines—Bayan Obo in China and Mountain Pass in the United States—primarily use open-pit mining techniques, which involve conventional processes such as drilling, blasting, loading, and hauling to the processing plant. In areas lacking water access, different open-pit excavation tools, including scrapers, front-end loaders, shovels, and draglines, are employed (Gupta and Krishnamurthy, 2005). Conversely, underground room-and-pillar mining methods are utilized in locations where rare earth elements are extracted as by-products [36]. Traditional physical beneficiation methods are ineffective at concentrating rare earth elements (REEs) into usable ore concentrates, making chemical leaching the primary technique for extracting these minerals. In ion-adsorption type ores, REEs predominantly exist in an ion-exchangeable form, loosely bound to clay minerals. These ions can be displaced and leached out by introducing cations such as Na^+, NH_4^+, H^+, or Mg^{2+}. Based on this characteristic, ion exchange using electrolytes has been adopted for rare earth extraction, evolving from the initial pool leaching stage to the current third-generation in-situ leaching process. In-situ leaching, also known as solution mining, involves injecting chemical solutions directly into naturally buried ore bodies to selectively dissolve the target elements. The resulting leachate is then pumped to the surface for further extraction and processing. Compared to earlier generations, in situ leaching offers substantial improvements. It enhances resource recovery beyond the capabilities of conventional methods, lowers operational costs, reduces labor requirements, and minimizes the need for extensive infrastructure. Moreover, it is environmentally friendly and helps preserve the natural terrain [6]. Although leaching and precipitation processes of REEs consume significant quantities of these chemicals, such as HCl, H_2SO_4, and NaOH, whose production is linked to substantial environmental pollution, thereby adding to the overall environmental impact of the process chain. This impact can be mitigated by recycling certain chemicals, such as HCl [37]. Bastnasite, which is a carbonate-fluoride ore of cerium, lanthanum, and yttrium, is usually leached using concentrated amounts of sulphuric or chloric acids, while monazite, which is a phosphate bearing most of the rare-earth minerals, can be leached using sodium hydroxide [38]. Underground mining of rare-earth minerals is very rare; however, this method is sometimes necessary due to deposit depth, economic considerations, and sometimes environmental impacts. Typically, more costly than open-pit mining, this method is generally regarded as less environmentally disruptive. Some downsides to this method are that rare-earth deposits are known to harbor some form of radioactivity, which becomes even more dangerous with depth of the mine [39].

3.3. Crushing, Grinding, and Separation

After mining, the ores are processed as most other non-rare-earth minerals are processed. The mined ores are initially broken into smaller bits using a jaw crusher, before they are screened in a vibrating screen and further broken up into powder-like like using a grinder [40]. After getting the powder-like consistency, the minerals are separated from the ore using a flotation method that is based on the differences in hydrophobicity of the mineral particles [41]. Depending on the physical and chemical properties of the minerals, they are further processed using various methods, but the main goal is to separate the minerals further selectively from the ore. These methods are used either as standalone processes or as complements to the previous separation techniques. These methods include magnetic separation, leaching, gravity separation, solvent extraction, electrostatic separation, etc. [42]. After these separation procedures, precipitation and crystallization processes are induced using specific chemicals to selectively crystallize and purify certain rare earth oxides, carbonates, and fluorites, among others [43]. The specific intricacies and chemistry involved in these processes have been extensively studied and are not included in the scope of this study.

3.4. Reduction

To be able to use the REEs for technologically relevant applications, they need to be reduced from metal-bearing ceramics, i.e., oxides, chlorides, fluorides, etc., into metals. These ceramics are highly stable under normal conditions, which makes their conversion extremely difficult [34]. For multiple reasons, including considerations such as melting points and vapor pressure, rare earth minerals undergo initial preparation through various methods before the reduction process.

a. Metallothermic reduction is achieved by capitalizing on the distinctions in the free energies of formation between the mineral and a reductant element. Commonly, elements such as calcium, potassium, sodium, lithium, hydrogen, and carbon, utilized at elevated temperatures, are used as reducing elements for processing rare-earth metals [34]. Multiple different setups have been developed to reduce these ceramics into metals, as the simple addition of these reductants will not reduce them. All these setups include some form of furnace, vacuum, and water pumps, amongst other things that aid the operations.
b. Electrolysis is another reduction method, involving the use of electric current in a molten salt containing rare-earth chlorides and fluorides. This process is like the electrolysis process that has been used for many years to reduce aluminum [44]. Many parameters are involved in this process, type of molten salt electrolyte, temperature, electrodes, current, and voltage, etc. All these variables contribute to the purity of the final REE product. Due to the number of electrolytes and electrodes used in this process, REEs produced using electrolysis are considered to be of lower purity than metals produced using metallothermic processes [44].

4.0. Refining and Purification

The extensive processes involved in processing rare-earth metals from their initial ore stage to the reduction stage often result in the presence of up to 2 % metallic and/or non-metallic impurities [45]. If these impurities are not reduced to acceptable levels, depending on the intended applications, they have the potential to impact certain properties of the metal. Many techniques, which are also used for non-rare-earth applications, have been developed to purify metals. These techniques include zone refining, solid-state, electrolysis, vacuum processing, etc. As highlighted in this section, the production of REEs from start to finish requires numerous steps that consume a lot of energy, water, and chemicals.

5.0. Life-cycle assessment (LCA).

Life-cycle assessment (LCA) has been accepted as the most comprehensive approach to quantify the environmental sustainability of a product or process and can support decision-makers in implementing strategies to enhance their sustainability outcomes. Life Cycle Assessment (LCA) has been widely used in the evaluation of various rare earth elements (REEs). Given the critical role and unique characteristics of rare earths in REE-containing products, LCA studies are essential for promoting cleaner industrial practices and for enhancing the environmental performance of downstream products, such as magnets, that incorporate REEs [46]. The previous section provides the background for a full understanding of the impact of REEs on the environment. LCA is employed as a tool to critically assess the impact of REEs on the immediate environment and the world at large. As part of LCA, the most crucial initial step is the collection of input and output data. Studies in the past have used LCA to analyze REEs' environmental impact, with most of them focusing on the location of ores or the type of ores. Only a few studies have assessed REEs globally, with some of them even including other elements that are not considered REEs. To date, there have been only very limited LCA studies on the production of REEs. Like all material processing, the REE supply chain is also associated with environmental impacts [47]. They are mainly related to the geology of a deposit, mineral type and composition, the methods of extraction, local supply of energy and auxiliary materials, and regulatory conditions that mitigate environmental impacts. Hence, the environmental impacts vary considerably [48].

a) Environmental footprint of the REEs' life cycle

Although LCA standards exist, numerous life cycle assessment studies on rare earth oxide (REO) production show a broad variation in reported environmental impacts. The environmental footprint of the Rare Earth Elements (REEs) life cycle is significant and spans all stages, from mining to end-of-life disposal or recycling [49]. In recent years, extensive research has focused on the urban mining of end-of-life products like permanent magnets, used batteries, phosphor lighting materials, and polishing powder waste. These discarded items are considered valuable sources of rare earth elements (REEs) due to their relatively high REE content [50].

b) Identifying key stages with significant impacts (LCA)

REEs exist in two mineral classes: (1) bastnasite, a carbonate-fluoride class of minerals ($ReCO_3F$), and (2) monazite, a phosphate class of minerals ($RePO_4$) [47]. Analysis indicates that the mining, as well as extraction, beneficiation, calcination, separation, refining, and roasting stages, have the greatest contribution to overall serious environmental and health issues [51] such as land depletion, water pollution, air pollution, and exposure to radioactive materials. It highlights the importance of quantifying the human health and environmental impacts of REOs before their widespread adoption and use in multiple industries. REO production often involves multi-stage mineral mining, beneficiation, and refining plant configurations to recover various REO or concentrates. These processes are often driven by the mineralogy, ore grades, recovery rate, and targeted/by-products of the project and require varying material and energy inputs (e.g., electricity, fuel, chemicals, land, and water etc) [52] and involve a considerable amount of energy and materials use, and consequently, significant environmental impacts are incurred in the form of material/energy consumption, waterborne and airborne emissions, along with solid wastes [53]. Additionally, the mining as well as extraction/roasting phases had the greatest overall contribution to life cycle impacts; therefore, process improvements during these stages will be crucial for minimizing overall energy and environmental burdens [51].

6.0. Environmental impacts and health effects of REE exposure

6.1. Mining practices and environmental consequences

The environment has a profound impact on human health in various ways. Extensive studies have demonstrated that environmental factors pose significant health risks through direct exposure to hazardous substances or indirectly by degrading the ecosystems essential for human survival [54]. The extraction and processing of rare earth elements (REEs) present major environmental challenges due to the nature of their geological deposits and the intensive chemical procedures involved. REEs are deeply integrated into modern life, found in virtually all automobiles, computers, mobile phones, televisions, and energy-efficient fluorescent lighting—just to name a few common applications. However, a key environmental concern for REE producers lies in the radioactivity of ores such as thorium-bearing monazite and xenotime [2]. Activities such as blasting and the discharge of mine wastewater significantly contribute to environmental impact categories, particularly particulate matter formation (PM) and ionizing radiation (IR) [55]. This underscores the often-neglected fact that REEs are emerging contaminants (ECs)—currently unregulated, excluded from standard environmental and health monitoring programs, and classified as micropollutants with low detection thresholds and poorly understood toxicity mechanisms [56].

Like other forms of materials processing, the REE supply chain is both resource- and energy-intensive and associated with various environmental impacts. Rare earth mining is not only costly and technically demanding but also detrimental to surrounding water bodies, air quality, soil health, ecosystems, and, by extension, human well-being. Wastewater from REE operations can acidify nearby soil and groundwater [37]., while solid mining waste often emits radioactive dust from blasting activities. Additionally, mine discharge contributes to environmental contamination through heavy metals, particulate matter (PM), and ionizing radiation (IR) [48]. At present, mining activities—particularly those involving REEs—are among the leading contributors to ecological degradation and environmental pollution. The unique extraction and metallurgical processes involved in REE production have caused considerable harm to local ecosystems [37]. Multiple studies have indicated that high levels of environmental exposure to rare earth oxides (REOs) can lead to adverse health effects. These include acute myocardial infarction, abnormal blood biochemical markers, reduced IQ in children, pneumoconiosis, leukemia, decreased serum total protein levels, as well as symptoms such as itching, heat sensitivity, and skin lesions [57]. Vahidi et.al., [11] Vahidi et al., in their study, noted that the environmental damage associated with rare earth element (REE) production contributed to the closure of the Mountain Pass mine in California. This site, which had been a leading source of REEs during the 1970s and 1980s, ceased operations in 2002 due to the ecological impact of its activities. Rita et al., [58] in their research, they observed that environmental impacts occur at multiple stages, both during mining and throughout the rare earth separation process. They highlighted that ion-adsorption deposits offer an advantage over other types of rare earth deposits due to their relatively low levels of radioactivity. The environmental effects linked to the separation process are primarily due to high energy use from mixer-settler units and calcination furnaces, significant water consumption, and the presence of salt in the neutralized wastewater.

6.2. Toxicity level of rare earth elements

Although the extraction and production of rare earth elements (REEs) have increased significantly, leading to greater environmental and human exposure, there has been a notable lack of toxicological studies on the health impacts associated with REEs in recent years [59]. Recent research has highlighted a sharp rise in the global production of waste electrical and electronic equipment (WEEE**),** a major source of REEs, which has contributed to increasing environmental contamination and heightened health risks. These pollutants are particularly concerning because they are non-degradable and possess a long half-life, allowing them to persist in the environment. Oral and inhalation exposure to REEs can result in chronic accumulation in the human body, potentially leading to long-term toxic effects [60]. REEs enter the environment through the disposal of consumer and industrial products (e.g., landfills), discharges from mining and mineral processing, and effluents/wastewaters from industrial processes that use REEs [61]. The available literature on REE-associated toxicity is confined to a few REEs, mostly Ce, La, and Gd, requiring investigation into the comparative toxicities of others, yet to be neglected. By analyzing the time trend of several publications on REEs, the growing interest of the scientific community regarding the mechanisms associated with REE-toxicity appears evident and reflects the relevance of these elements in many industrial, agricultural, and medical technologies. According to Pagano et al., as depicted in Fig. 4, most of the reviewed literature has predominantly focused on cerium (Ce), with 63 reports—55 documenting toxicity effects and 8 reporting either neutral or beneficial outcomes. Lanthanum (La) also received considerable attention, with 55 studies. Wenyu et al. [60], in their research, reported that inhalation is the primary route of exposure to airborne particulates containing rare earth elements (REEs). Prolonged inhalation of REE particles can result in their substantial accumulation in the lungs. Additionally, these particles can penetrate the body through hair follicles and sweat glands**,** potentially leading to physiological harm. In environments with elevated REE levels, chronic exposure may also allow REEs to cross the placental barrier**,** posing risks of fetal damage due to accumulation. This is the reason why human exposure to REEs is very high and is essentially dependent on: treatments involving REEs (iatrogenic exposure); REE accumulation (bioaccumulation and pollution-induced) in marine and freshwater, air, and soil, especially for individuals residing close to mining areas (environmental exposure); and REE exposure of specialized workers (occupational exposure) [62]. Adverse health effects on aquatic and terrestrial organisms have also been reported. However, there is a need for more comprehensive toxicological studies, as the transfer of effects to species or ecosystems is still not well understood [56]. LC_{50} (lethal concentration 50%) and EC_{50} (median effective concentration) are statistically derived doses used to evaluate toxicity threshold in the biotic ligand model (BLM). A lower LD_{50} (lethal dose 50%)/LC_{50} value indicates higher acute toxicity [63]. Pagano et.al [64] observed the toxicity of the REEs in rainbow trout juveniles. Of the 7 REEs examined, he stated that 4 of them were toxic to rainbow trout in increasing order of toxicity (96 h-lethal concentration): Y > Sm > Gd = Er. Yttrium was the most toxic element with an estimated 96 h-LC50 of 0.7 mg/L. The other REEs (Nd, Ce, and La) were not toxic at concentrations up to 40 mg/L. Correlation analysis revealed that mortality (LC50) was significantly correlated with electronegativity ($r = -0.8$) and marginally so with ionization energy ($r = -0.67$; $0.1 < p < 0.05$), suggesting that the more electronegative REEs were more toxic to rainbow trout.

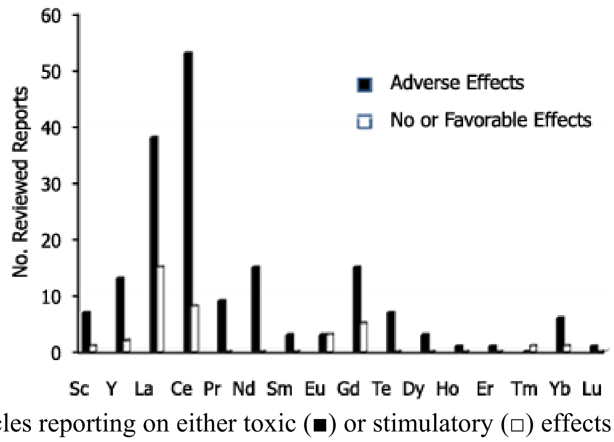

Fig. 4. Published articles reporting on either toxic (■) or stimulatory (□) effects of individual REE [48]

6.3. Health effects on humans and the ecosystem

The extensive use of rare earth elements (REEs) in several technologies is expected to have an impact on human health, including occupational and environmental REE exposures, and the consequences of REE exposures to human health have been subjected to relatively fewer investigations [65]. A body of literature has focused on occupational REE exposures, with the observation of respiratory tract damage. The REE mining and processing occupations have shown REE bioaccumulation in scalp hair, excess REE in urine, vegetables, soil, and street dust in REE mining levels, suggesting exposure route via dilatory and respiratory exposures [56] and defective gene expression. As for other REE occupational exposures, mention should be made of: a) jobs exposed to REE aerosol, such as movie operators; b) e-waste processing, and c) diesel engine repair and maintenance, with exposures to exhaust microparticulate (containing nanoCeO_2 as a catalytic additive). Diesel exhaust microparticles have been studied in animal models, leading to evidence of several pathological effects in animals exposed by respiratory or systemic routes [65]. The ecotoxicity of REEs is often influenced by exposure method, the organism's age, and the REEs' nature and concentration. The dose-response relationships of REEs often exhibit biphasic or hormesis-related trends, characterized by stimulatory or beneficial effects at low concentrations and inhibitory or toxic effects at high concentrations. Accordingly, low concentrations of REEs promote the growth of both aquatic and terrestrial organisms [61].

7.0. Recycling

A major challenge in rare earth element (REE) mining is the "balance problem," where the bulk of REE production is concentrated on light elements like lanthanum (La) and cerium (Ce), while market demand is primarily focused on neodymium (Nd) and dysprosium (Dy). This imbalance can result in an oversupply of La and Ce, while critical needs for Nd and Dy, especially in applications like magnets and batteries, may not be met through primary extraction alone. Recycling offers a potential solution for increasing the global supply of REEs, thus helping to resolve issues of supply chain vulnerability and mitigate REE market price fluctuation, as end-of-life products that are recycled typically contain the more sought-after elements such as Nd and Dy, rather than the more abundant La and Ce. Additionally, recycling REE has the potential to significantly reduce the overall material and energy demands of REO production [8, 51]. Unlike other metal recycling sectors, the rare earth recycling industry is still emerging and as a means of mitigating REE resource scarcity and supply vulnerability. However, the economic and technical viability of REE recycling remains uncertain, and the large time frame required for establishing recycling infrastructure limits its short-term effectiveness [51], with many of its processes in the developmental phase. The growing urgency for recycling is fueled by a sharp rise in demand, material scarcity, and concerns over supply security, challenges further intensified by China's export restrictions. Nonetheless, recycling presents notable benefits, such as reduced environmental impact, decreased reliance on Chinese exports, and access to feedstock that is potentially free from radioactive elements like thorium (Th) and uranium (U) [66]. However, recycling rare earth elements (REEs) remains highly challenging. The amount of REEs present in consumer products varies greatly, from fractions of a milligram to several kilograms, making collection and recovery inconsistent. Other key challenges include the complexity of products containing REEs, the technical difficulty in separating these elements from one another, and the extended lifespan of many REE-based components, such as permanent magnets. Due to these factors, less than 1% of current REEs are recycled. Current recycling efforts are largely limited to permanent magnets, fluorescent bulbs, batteries, and catalysts used in the chemical and petroleum sectors [8]. Although substantial research, mostly on the laboratory scale, has been conducted on REE recycling, progress has been minimal. As of 2011, the recycling rate remained under 1%, largely because of poor collection systems, technological limitations, and especially the absence of economic incentives. Significant advances in REE recycling are urgently needed, and achieving this will require the development of efficient, fully integrated recycling processes [67].

8.0. Research Gaps and Future Perspectives

Rare earth elements (REEs) are critical to the advancement of modern technologies; however, their widespread extraction and use have resulted in considerable environmental contamination, posing significant risks to both human health and ecological systems. While toxicological research on REEs has expanded in recent years, accurately evaluating their full impact remains a complex challenge. Despite ongoing efforts, a comprehensive understanding of the environmental consequences of REE production is still lacking. A particular gap exists in the analysis of illegal REE extraction activities, especially those involving ion-adsorption clays (IACs), where data scarcity hampers environmental assessments [55]. This issue is further compounded by the cumulative toxicity of multiple REEs in real-world exposure scenarios, the limited sensitivity of current detection technologies, and significant variability in biological responses among individuals. As a result, the health risks associated with long-term REE exposure remain poorly characterized [68]. Current toxicological databases disproportionately focus on a few extensively studied elements, such as lanthanum and cerium, while the chronic health and ecological effects of less-studied REEs, including praseodymium, dysprosium, and ytterbium, are still largely unknown. Most available studies focus on short-term or acute effects under controlled laboratory conditions, offering minimal insight into chronic exposure scenarios or ecosystem-level outcomes involving bioaccumulation across food webs. In parallel, inconsistencies in Life Cycle Assessment (LCA) methodologies further complicate efforts to evaluate the environmental sustainability of REEs. Disparities in system boundaries, selected impact indicators, and data reliability—particularly between developed and developing regions—undermine the comparability and credibility of sustainability assessments. These methodological gaps, coupled with uneven access to quality data and divergent regulatory priorities, hinder informed policy-making and international standardization. Moreover, current recycling practices for REEs are both technologically and economically limited, leading to inefficient recovery rates from discarded products. Obstacles such as complex product design, lack of disassembly infrastructure, and weak economic incentives contribute to a continued reliance on primary resource extraction, intensifying environmental degradation, and amplifying geopolitical supply chain risks [69]. To overcome these challenges, there is a pressing need for comprehensive and interdisciplinary toxicological studies that examine a wider array of REEs, their interactions with co-contaminants, and their mechanisms of action. Such research would support the development of safer materials and more robust health regulations. Equally important is the establishment of globally harmonized LCA protocols, underpinned by collaborative databases and adaptive models that reflect spatial and temporal dynamics within REE supply chains. Technological innovation is also vital. Emerging approaches in green chemistry, including bioleaching and electrochemical separation, offer promising solutions for improving the efficiency and sustainability of REE recycling. Integrating circular economy principles—such as modular product design, material traceability, and end-of-life recovery planning—into manufacturing processes can greatly enhance the recyclability of REE-containing products and reduce their overall environmental footprint

9.0. Conclusion

Rare earth elements (REEs) have emerged as pivotal contributors to modern technological advancement, enabling breakthroughs in energy-efficient materials, high-performance electronics, and sustainable manufacturing. Their unique physicochemical properties continue to transform industries ranging from renewable energy to defense. However, these benefits are counterbalanced by significant environmental and health concerns stemming from REE extraction, processing, and disposal. The dual nature of REEs—as both enablers of innovation and sources of ecological and biological toxicity—necessitates a more integrated approach to their development and use. To sustainably harness the potential of REEs, future research must focus on cleaner extraction technologies, closed-loop recycling systems, and the design of non-toxic REE alternatives. Equally important is the formulation of stringent environmental regulations and international cooperation to monitor and manage REE supply chains responsibly. By aligning materials science innovation with environmental stewardship, we can advance the use of REEs in ways that safeguard both technological progress and planetary health

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