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The Rare Earth Elements: An in-Depth Exploration of Industrial Utilization, Recycling Potential and Environmental Ramifications

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ABSTRACT: This comprehensive study delves into the extensive spectrum of applications attributed to rare earth elements (REEs), their potential for effective recycling, and the intricate environmental considerations entwined with their extraction and utilization. The realm of rare earth elements is undergoing rapid transformations fueled by technological progress and the escalating demand for these essential components. The spectrum of REEs encompasses the lanthanide series elements, namely La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu, as well as Sc and Y. These metals currently hold utmost significance across a multitude of contemporary technologies, spanning from smartphones, televisions, LED light bulbs, to wind turbines. This paper concisely outlines the environmental perils encompassing human health that stem from REE mining practices and the large-scale disposal of electronic waste containing noteworthy concentrations of REEs. Within these pages, we encapsulate novel strategies aimed at ensuring the future availability of REEs, including recent advancements in REE extraction from Coal Field Ash and innovative e-waste recycling methodologies. Additionally, we spotlight recent breakthroughs in the domain of individual REE separation techniques, encompassing both metallurgical and recycling operations.

KEYWORDS: REE, Exploration, Industrial utilization, recycling potential, environmental ramifications.

INTRODUCTION

Rare earth elements (REEs) constitute a group of seventeen chemically analogous elements positioned in the periodic table, encompassing scandium and the lanthanides. Due to their distinct properties, REEs hold pivotal roles in a diverse range of modern technologies. The wide-ranging industrial applications of REEs hold potential significance for countries such as Nigeria, contributing to their economic development. The escalating demand for REEs has underscored their vital contributions across various modern technologies. However, the extraction and processing of these elements can wield substantial environmental and societal consequences if not approached sustainably. Ensuring proper environmental regulations, responsible mining practices, and a focus on social well-being emerges as essential for Nigeria to harness the advantages of its rare earth resources while mitigating adverse effects. The comprehensive spectrum of REEs encompasses the lanthanide series elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), as well as Sc and Y. This group of metals currently assumes pivotal roles in modern technologies like cell phones, televisions, LED light bulbs, and wind turbines (13). In recent decades, the utility of REEs and their alloys has exhibited remarkable expansion, finding applications in computer memory, DVD technology, rechargeable batteries, autocatalytic converters, superconductors, glass additives, fluorescent materials, phosphate binding agents, solar panels, and magnetic resonance imaging (MRI) agents. These metals have become integral to an array of applications, marking an unprecedented era. Acknowledged as the "vitamins of modern industry" (2), REEs confer distinct physical, chemical, magnetic, and luminescent properties that bestow technological advantages, including reduced energy consumption, enhanced efficiency, miniaturization, speed, durability, and thermal stability (20). Projections by (7) anticipate a 5% annual growth rate in global REE demand by 2020, while (9), through a 3-D graphical representation, highlights the impending scarcity and supply risks associated with elements like Eu, Dy, and Er, among others. Unlike precious metals such as gold, copper, and silver that exist as individual native metals in nature, REEs, owing to their reactivity, manifest within various ores or accessory minerals as either minor or major constituents (16). Spread across a multitude of minerals, including silicates, carbonates, oxides, and phosphates, REEs are notably rare in their compatibility with most mineral structures, existing only in specific geological settings (5). Economically significant sources of REE minerals include bastnasite, monazite, loparite, and lateritic ion-adsorption clays, with over 250 minerals harboring REEs as essential components within their chemical compositions and crystal structures (6). Abundant in the Earth's crust, REEs, in contrast to many other metals, are seldom concentrated in mineable ore deposits. These deposits can be categorized as primary, formed through magnetic, hydrothermal, and metamorphic processes, commonly associated with alkaline igneous rocks and carbonation in extensional settings; and secondary, generated through erosion and weathering, encompassing placers, laterites, and bauxite. These deposits can be further classified based on genetic associations, mineralogy, and form of occurrence (8). Additionally, (19) categorizes economically relevant REE deposits into four groups, taking into account the significant quantities of these elements in coal and marine sediments. REE analyses are conventionally reported in parts per million (ppm) for individual elements, with concentrations calculated using conversion factors based on appropriate oxide formulae (Table 1). Predominantly, China serves as the global epicenter for REE production, contributing to 70% of the world's REE mining output. China's supremacy primarily emanates from the Bayan Obo mining district in Inner Mongolia, housing the largest REE deposit globally (21). As of now, China dominates rare earth mining, processing, and magnet production, accounting for 70%, 85%, and 92% respectively (Figure 1). This dominance is depicted in Figure 2, showcasing the world's major REE producers, while other contributing nations include India, Madagascar, Vietnam, Russia, and Brazil (21). Table 1 outlines the world reserves of REEs by principal countries, emphasizing the distribution of reserves among countries. Notably, the United States Geological Survey (USGS) conducted hyperspectral surveys in Alaska in 2017, evaluating REE potential along with other metal deposits (22). India holds 5% of global REE reserves, with monazite being its primary resource. The nation's significant REE minerals, collectively termed Beach Sand Minerals (BSM), encompass ilmenite, sillimanite, garnet, zircon, monazite, and rutile (2).

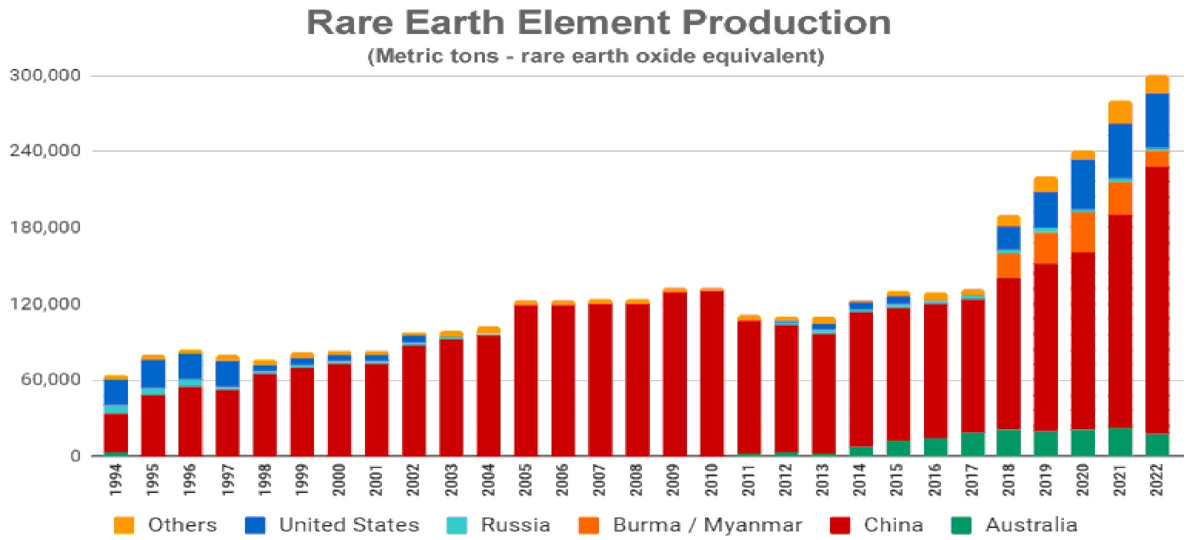

Figure 1: Rare earth element production (https://geology.com/article/rare-earth-elements)

Figure 2: Producer of Rare Earth Elements (https://geology.com/article/rare-earth-elements)

Tables 1: World reserves of REE by principal countries (US, Geological survey, 2018)

Country	Reserves in tones	% share
Australia	3	2.56
Brazil	22	16.67
Canada	830	0.63
China	44	33.33
Green land	1	1.14
India	6	5.23
Malaysia	30	0.02
Malawi	140	0.11
Russia	18	13.64
South Africa	890	0.65
Vietnam	22	16.67
USA	1	1.06
World reserves	132	

Industrial Applications of Rare Earth Elements

Rare earth elements (REEs) wield a wide array of industrial applications and hold the potential to significantly impact the economic progress of nations, including Nigeria. The increasing recognition of their fundamental roles in diverse modern technologies accentuates their significance. Let's delve into the prospective industrial applications of REEs and explore the implications of Nigeria's economic reliance on these elements. REEs serve as indispensable constituents in the electronics sector, spanning smartphones, computers, televisions, and other gadgets. They find application in capacitors, light-emitting diodes (LEDs), superconductors, and sensors. Crucially, REEs contribute to the production of high-performance magnets essential for wind turbines, electric vehicle motors, and generators. Additionally, they play a pivotal role in advancing energy-efficient lighting technologies. The spectrum of REEs holds critical importance in cutting-edge military advancements, including precision-guided missiles, radar systems, and communication devices. Aerospace applications, such as jet engines and satellite technology, also benefit from REE integration. Specific REEs contribute to medical imaging through MRI contrast agents and radiation therapy equipment. Moreover, REEs function as catalysts in various chemical reactions, from petroleum refining to environmental remediation. Their influence extends to enhancing the properties of glass and ceramics, imbuing them with durability, heat resistance, and vibrant colors. These applications encompass optical lenses and laser technology. A substantial proportion of rare earth elements serve as catalysts and magnets in both traditional and low-carbon technologies. Additionally, they find utility in producing specialized metal alloys, glass, and high-performance electronics. Notably, alloys involving neodymium (Nd) and samarium (Sm) result in robust magnets capable of withstanding high temperatures. These magnets are integral to essential technologies such as hybrid and electric vehicle engines, wind turbine generators, portable electronics, and cell phones. However, the increasing demand for REEs and concerns regarding their mining have sparked global apprehension.

Table 2: Global Reserves of Rare Earth Minerals

Country	Mine production 2020	Reserves	% of total reserves
China	140,000	44,000,000	38.0
Vietnam	1,000	22,000,000	19.0
Brazil	1,000	21,000,000	18.1
Russia	2,700	12,000,000	10.4
India	3,000	6,900,000	6.0
Australia	17,000	4,100,000	3.5
United state	38,000	1,500,000	1.3
Green land	-	1,500,000	1.3
Tanzania	-	890,000	0.8
Canada	-	830,000	0.7
South Africa	-	790,000	0.7
Other countries	100	310,000	0.3
Burma	30,000	N/A	N/A
Madagascar	8,000	N/A	N/A
Thailand	2,000	N/A	N/A
Burundi	500	N/A	N/A
World total	243,300	115,820,000	100%

Source: *https://elements.visualcapitalist.com*

Despite the United States possessing 1.5 million tons of reserves, it heavily relies on imports from China for refined rare earth elements. This intricate web of industrial applications showcases the paramount role of rare earth elements in shaping technological advancement. Their versatile influence spans electronics, renewable energy, military technology, medical diagnostics, catalysis, and materials enhancement. As Nigeria and other nations seek to capitalize on these elements, the prudent management of REE resources and international cooperation become vital considerations for sustainable progress.

Recycling Rare Earth Elements: Addressing Supply Concerns

In response to the escalating demand for rare earth elements (REEs) and the growing apprehension about their supply, the concept of recycling has gained significant traction. REEs are present in electronic waste, batteries, and an array of products. Recycling methodologies involve the extraction of REEs from these materials, aiming to alleviate reliance on primary mining. As highlighted by (2), strategic high-tech metals like cobalt, lithium, tantalum, gallium, and REEs are pivotal for the development of efficient, technologically advanced, and environmentally friendly products. Electric vehicles, which require lithium and neodymium, and wind turbines, which rely on neodymium and dysprosium, exemplify the increasing significance of these elements. As the world embraces a cleaner and greener future, the challenge of meeting the surging REE demand is exacerbated by production being concentrated in a handful of countries, including China, the US, Australia, Thailand, Vietnam, India, Madagascar, and Brazil. China's dominance in REE production has persisted, with a domestic output of 210,000MT in 2022. The 2022 quota for rare earth smelting and separation in China was set at 202,000MT. In contrast, the US remains a substantial importer of rare earth materials, with a 2022 demand valued at $200 million. Although Australia's rare earth production has experienced steady growth, output dropped from 24,000MT in 2021 to 18,000MT in 2022. Thailand recorded a 2022 rare earth production of 7,100MT, Vietnam reached 4,300MT, India produced 2,900MT, Madagascar extracted 960MT, and Brazil's production amounted to a mere 80MT in 2022. Piles of electronic waste, rich in REEs, continue to accumulate globally. Transforming this waste into a valuable resource is not only crucial for preserving human health but also for safeguarding the Earth's increasingly strained REE resources. Presently, many nations discard electronics, which are in high demand, especially in regions like the EU, China, and India. Two primary options exist for ensuring a secure REE supply: primary resources from old mines or new deposits, ocean bed sediments, coal ash, etc., and secondary resources from electronic and industrial waste. Electronic waste has the potential to significantly contribute to REE demand. Approximately 50 million metric tons of e-waste are discarded in landfills worldwide annually. However, only about 12.5% of this e-waste is currently being recycled for all metals. Importantly, this e-waste contains substantial concentrations of REEs and other precious metals like gold, silver, palladium, and rhodium. Recent life cycle assessments suggest that recycling consumer materials holds promise as an alternative to conventional production processes (18). Despite its promise, recycling REEs poses numerous challenges at various levels. These elements are often present in minute quantities within small electronic components, such as mobile phones. In certain materials, like touch screens, REEs are uniformly distributed, rendering their extraction more complex. Current limitations on recycling REEs stem from low yield and high costs. However, the feasibility of recycling could improve if recycling becomes mandatory or REE prices soar exceptionally high. To mitigate future REE supply concerns, ongoing global studies are exploring cost-effective methods for recovering REEs from e-waste, as indicated by (3), (10), and (12). These studies encompass automated approaches to disassembling electronic scrap and chemical processes for REE extraction. Progress in these studies suggests that recycling REEs holds the potential to be economically viable and more achievable than tapping into new mineral deposits. As the world grapples with the challenge of sustaining REE supply, the pursuit of recycling emerges as a promising avenue to ensure continued technological progress.

Environmental Impact of Rare Earth Element Mining and Processing

The mining and processing of rare earth elements (REEs) can give rise to significant environmental repercussions owing to the extraction and processing techniques employed. These impacts encompass the destruction of habitats, water contamination, and the generation of radioactive waste. Ongoing efforts are directed towards devising sustainable mining and processing practices to alleviate these adverse effects. The convergence of technological advancements and modern lifestyles has elevated the intake of toxic elements into the human body, resulting in health issues. The contamination of the environment by diverse types of toxic inorganic, organic, and organometallic species constitutes a grave global challenge. While the implications of well-known toxic trace elements like arsenic, lead, cadmium, mercury, and uranium have been studied extensively (17, 15, 14), elements less commonly used in the past, such as REEs and platinum group elements (PGEs), are gaining prominence in modern industries for various applications. Elevated levels of electronic waste (e-waste) contribute to the release of substantial quantities of these elements, alongside other toxic elements, into subsoil and groundwater. Moreover, large amounts of REEs find their way into agricultural soils through phosphate-based fertilizers. Trace elements permeate different environmental pathways, particularly those associated with ground and surface waters, thereby exacerbating environmental pollution and its impact on human health (4, 1). The mining of rare earths can exert severe damage on local ecosystems, particularly in the context of illegal and unregulated mining activities. A critical concern in rare earth mining is that the ore from which they are extracted contains radioactive elements such as thorium and uranium. Effective separation of rare earths from this ore is imperative to mitigate potential hazards. A report by Global Witness investigating the effects of rare earth mining reveals that this practice has escalated in regions like Myanmar due to China's decision to close its mines and outsource production. By mid-2022, over 2,700 illegal collection pools from in-situ leaching had been identified in the mountains, covering an area comparable to Singapore. Communities in these areas reported difficulties in accessing safe drinking water, while local wildlife and fish populations suffered. The in-situ leaching process itself can cause significant damage to the extracted rocks. In China's Ganzhou region alone, more than 100 landslides have occurred as a result of this extraction method, causing substantial harm to the local terrain. Currently, there remain substantial gaps in our understanding of the adverse effects of REEs on human health, their anthropogenic levels, fate in biogeochemical cycles, and individual or cumulative toxicological impacts. More extensive research is needed to identify anthropogenic sources, transfer mechanisms, bioaccumulation patterns, and environmental behaviors of REEs, all with the goal of minimizing future human health risks. Given the widespread utilization of REEs in sectors such as agriculture and medicine, comprehending their toxicological properties becomes paramount. (11) Emphasize the necessity for further studies to accurately assess the impact of trace rare earth elements on human health. The intricate interplay of REEs with the environment underscores the significance of holistic research to safeguard both ecosystems and human well-being.

CONCLUSION: NAVIGATING THE FUTURE OF RARE EARTH ELEMENTS

The mining and processing of rare earth elements (REEs) underscore the need for sustainable management to avert potential environmental and social consequences. Achieving a balance through stringent environmental regulations, responsible mining practices, and an unwavering focus on social well-being is pivotal for Nigeria. The country stands to harness the advantages of its rare earth resources while curbing adverse outcomes. Emerging green technologies, spanning electric vehicles, batteries, solar panels, and wind turbines, are accelerating the demand for REEs. This surge, coupled with rising prices, anticipates significant growth in the demand for these metals. The exploration for REE resources must transcend terrestrial domains and expand to encompass ocean bottom sediments. The prospect of deep-sea mining and the development of cost-effective recovery methods from abundant sources like coal, coal ash, and red mud hold promise for future REE supply. In forging ahead, the imperative of sustainable exploration schemes for diverse REE ore deposits cannot be overstated. Stringent adherence to these schemes is essential to avert further environmental degradation. Restoring damaged ecosystems demands substantial time and financial investment, emphasizing the urgency of preventing harm in the first place. Instead of embarking on new mining ventures, extracting REEs from coal-fired ash, red mud, and implementing electronic recycling initiatives emerge as favorable options for bolstering future REE supply. Vigilant monitoring becomes crucial where phosphate-based fertilizers are employed and in areas conducive to REE mobility, availability, and plant uptake, as well as at e-waste disposal sites vulnerable to surface runoff contamination. The industrial applications of rare earth elements resonate across diverse sectors, furnishing substantial economic potential for nations such as Nigeria. Pioneering a sustainable rare earth industry stands to invigorate economic growth, foster job opportunities, propel technological innovation, and diminishes import reliance.

In summation, steering the trajectory of rare earth elements necessitates a multifaceted approach that harmonizes economic advancement with environmental stewardship. By embracing responsible practices, embracing innovation, and nurturing social well-being, nations can unlock the transformative potential of REEs while securing a greener, more prosperous future.

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