

# Comparative Analysis of Traditional and Innovative Methods for Rare Earth Element Extraction

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## ABSTRACT

This article addresses the application of traditional and innovative methods for rare earth elements extraction, with a focus on their technological efficiency and environmental safety. It discusses approaches based on hydrometallurgical and pyrometallurgical processes, as well as emerging solutions, including bioleaching, hydrogen reduction, electrochemical recovery, the use of ionic liquids, and membrane-sorption technologies. The study emphasizes that modern methods offer significant potential for reducing the carbon footprint and enhancing the resource efficiency of the sector. The comparative analysis highlights the need to integrate both traditional and innovative solutions into sustainable production chains, especially in the context of growing global demand for rare earth elements and the increasing importance of technological independence.

**Keywords** – rare earth elements, environmental safety, hydrometallurgy, pyrometallurgy, bioleaching, hydrogen reduction, electrochemical metal recovery, membrane-sorption technologies, ionic liquids.

## INTRODUCTION

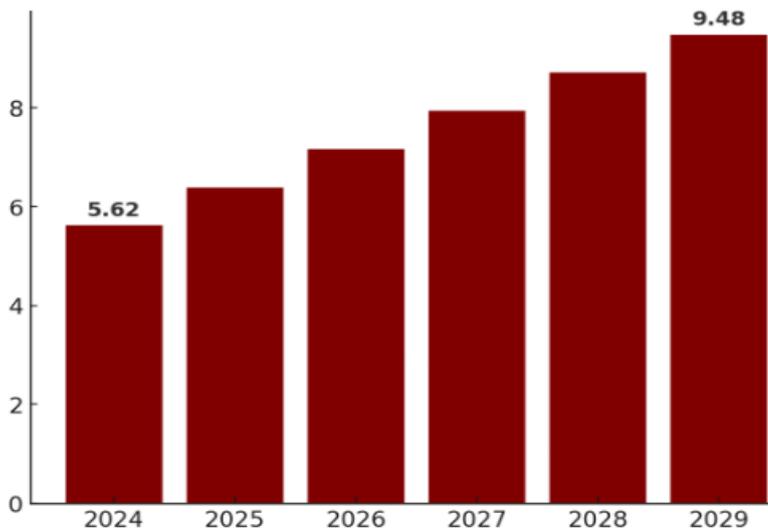
Rare earth elements (REE) are a collection of seventeen chemical elements that share certain physicochemical properties, including excellent magnetic, optical, electrical, and catalytic qualities. These render them crucial material during the production of high-technology products – from electronics and permanent magnets to devices for renewable energy, including wind turbines and rechargeable batteries. Given the strategic importance of REE to defense, aerospace, medical technologies, and the green economy, environmental safety and sustainability of their extractive processes have become of utmost significance.

Conventional REE separation operations, which largely utilize pyrometallurgy and hydrometallurgy technologies, are marked by their high release of dangerous compounds, energy use, and production of dangerous wastes. The objective of the study is to make a comparative assessment of traditional and new methods of REE production from the perspective of environmental friendliness and technological efficiency and to forecast the potential of large-scale industrial exploitation of new solutions.

### Main Part. Characteristics of Traditional Ree Extraction Methods

Modern industry is facing increasing pressure on its mineral resource base, particularly in the segment of strategically important metals, which includes REE. Their extensive use in high-tech and energy sectors makes these resources critically important for ensuring technological sovereignty and industrial security. In the context of market globalization and growing competition for access to REE sources, the resilience of supply chains and the stability of raw material provision acquire strategic significance [1]. According to data from the analytical firm The Business Research Company, the global rare earth metals market reached \$5.62 billion in 2024. Furthermore, it is expected to demonstrate steady positive growth in the medium term, with a projected CAGR of 10.98 % (fig. 1).

**Fig. 1.** Global rare earth metals market size, billion dollars [2]



The rapid growth in demand and the expansion of the global REE market are inevitably accompanied by an increase in extraction and processing volumes. This, in turn, brings to the forefront the issues of technological efficiency of existing extraction methods and their environmental impact. Against this backdrop, a critical analysis of traditional methods – still dominant in global raw material processing practices – gains particular importance.

**Traditional technologies** for REE extraction are primarily based on hydrometallurgical and pyrometallurgical processes (table 1).

**Table I** Traditional technologies for REE extraction [3, 4]

Method	Process principle	Typical reagents / conditions
Hydrometallurgy	Leaching of metals from ores using acidic or alkaline solutions.	Sulfuric, nitric, hydrochloric acids; temperature 60-200 °C; pressure up to 10 atm.
Pyrometallurgy	Thermal treatment of raw materials through smelting, reduction, and refining in furnaces.	Coke, fluxes, reducing agents; temperature 1200-1600 °C.

Despite the high efficacy of these technologies in terms of extraction yields of target components, such methods entail serious environmental impacts. Hydrometallurgy – involving acidic or alkaline leaching – requires substantial amounts of aggressive chemical reagents, notably sulfuric, nitric, and hydrochloric acids, as well as sulfates and chlorides. According to experimental studies, when processing rare earth mining tailings, acid consumption may reach up to 11 kg of hydrochloric acid and 29 kg of nitric acid per ton of starting material, while the yield of REE is less than 0.5 kg per ton – highlighting the low mass efficiency of target product relative to reagent use [5].

Use of acids and salts in the process technology generates liquid industrial effluents containing dissolved heavy metals, radioactive isotopes such as thorium and uranium, and ions of REE themselves. Inefficient or inadequate treatment of these wastewaters may lead to surface and groundwater contamination, deposition of toxic species in biosphere and soil, and serious risk to environmental quality and long-term sustainability of water resources in process and mine locations.

**Pyrometallurgical processes** account for the majority of the energy balance in REE production and also contribute significantly to CO<sub>2</sub> emissions. They also result in the production of HF gases, particulate emissions, and sulfur-containing gaseous species, which, if not contained within the process, can be released to the atmosphere and pollute the immediate environment.

Significant attention in evaluating traditional methods should be given to the **resource intensity** of these processes. According to one study, the REE rock-to-metal ratio can be anywhere from 16 to 3,600 tons of ore per ton of product, depending on the deposit type and the processing technology utilized. Such figures involve ore beneficiation and enormous quantities of water, chemical reagents, and electricity. With accompanied high capital and operating costs, this can render production financially unviable without more subsidies, particularly under conditions of price uncertainty in the international rare earth market.

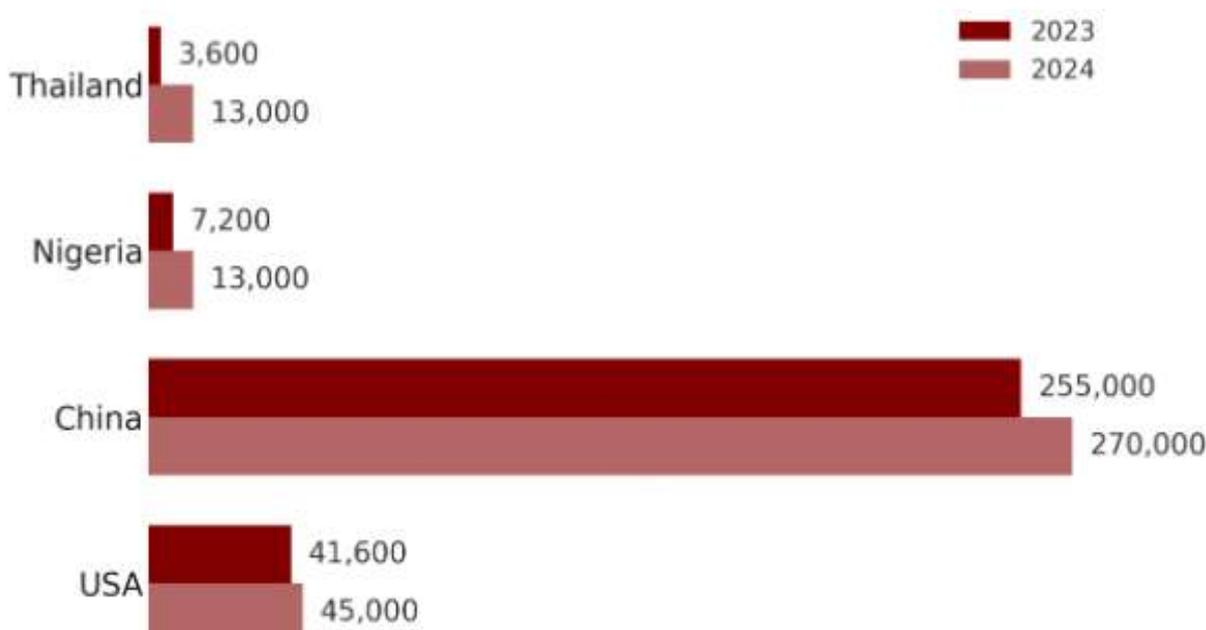
Another problem is posed by **geochemical risks** concerning the mineralogical character of REE ores. Rare earths are usually associated with naturally occurring radioactive elements such as uranium and thorium. Mobilization on leaching can lead to radioactive contamination of process streams and necessitate special waste disposal and worker protection precautions.

Thus, traditional REE extraction processes, as industrially advanced and as well-established as they may be, have a significant environmental price tag and put a heavy burden on the economy [6]. In 2024, the U.S. Geological Survey (USGS) reports, the USA produced 45,000 metric tons of rare earth mineral concentrates at the Mountain Pass mine, but just 1,300 metric tons were processed into compounds and metals within the domestic country. This would indicate the continued dependence on foreign supplies, with roughly 80 % of the REE compounds and metals that are domestically consumed being imported.

### Innovative Approaches To Ree Extraction

According to data from the USGS, global REE production reached approximately 390,000 metric tons in rare earth oxide (REO) equivalent in 2024, reflecting a steady upward trend. The primary contributors to this increase were China, the USA, as well as Nigeria and Thailand, which have demonstrated dynamic growth in REE mining activities (fig. 2).

**Fig. 2.** REE mine production by country in 2023 and 2024 (in metric tons, REO equivalent [7])



At the same time, imports of REE to the USA decreased by 11 %, indicating a shift toward partial localization of production and a reduction in dependence on external suppliers. These trends – increased production, restructuring of supply chains, and tightening environmental regulations – underscore the growing relevance of implementing alternative, sustainable REE extraction technologies capable of ensuring processing efficiency with minimal environmental impact [8].

Innovative REE extraction methods are being actively explored both in research institutions and within pilot-scale industrial facilities. Their development is driven not only by the need to improve efficiency and selectivity, but also by the pursuit of technological diversification and reduced reliance on conventional resources (table 2).

**Table 2** Innovative methods for REE extraction

Method	Brief description
Biobleaching (biotechnology)	Utilization of microorganisms to leach REE from ores and waste under mild temperature and chemical conditions.
Hydrogen reduction	Hydrogen is used to reduce REE oxides, producing water vapor rather than carbon emissions.
Ionic liquids and deep eutectic solvents	Use of alternative low-toxicity solvents instead of traditional acids for selective REE extraction.
Electrochemical extraction	Separation or precipitation of REE through electric current, frequently utilizing renewable energy sources.
Sorption and membrane technologies	Selective REE extraction using specialized membranes or sorbents based on carbon or polymeric materials.

The development of these techniques enables the construction of integrated and sustainable technological chains for both primary raw materials and anthropogenic sources. Hybrid techniques – combining a number of techniques within one cycle, e.g., initial biodegradation, selective sorption, and electrochemical precipitation – are especially important. This opens up the possibility of using modular plants for decentralized REE processing with minimal environmental effects, especially in regions of poor infrastructure.

Although the environmental benefits of novel REE extraction processes are widely recognized, it is essential to underpin these with quantitative metrics based on life-cycle assessment (LCA). By way of illustration, mixed REO production was estimated to emit 258-408 kg CO<sub>2</sub>-eq and require 270-443 MJ primary energy per kg of REO, which underscores the carbon intensity of conventional routes [9].

Besides, Schreiber et al. (2021) in their review highlight that many LCIs lack crucial data on wastewater emissions, radioactive tailings, and indirect emissions, resulting in high uncertainty in environmental impact research [10]. A good example is provided by Wan, Zhou, and Xue (2022), who conducted a carbon footprint analysis of mixed rare earth oxides (REOs) produced from ionic rare earth resources. Their findings indicate that the carbon footprint to yield 1 kg of mixed REOs is 17.8-24.3 kg CO<sub>2</sub>-equivalent with an uncertainty range of approximately 15.54 %, depending on process parameters and recovery efficiency [11].

More recent articles from 2023-2025 provide up-to-date benchmarks for new and secondary-source extraction methods. A white paper by Western Digital and CMR (2023) reports a 95 % reduction of greenhouse gas emissions in the recovery of REEs from end-of-life hard drives compared to conventional mining [12].

While novel REE extraction methods show apparent technological and environmental advantages, their application in the real world is not completely without limitations. In particular, certain approaches still suffer from constraints in recovery efficiency from low-grade and complicated ores, as well as operational challenges of modular and decentralized systems. These include process stability issues, material compatibility, and maintenance requirements, which could affect scalability and long-term operation.

Besides technological challenges, enhanced utilization of new REE extraction methods is also vulnerable to policy and regulatory environments, which vary immensely from one place to another. For instance, the European Union encourages green extraction technologies heavily through initiatives such as the Critical Raw Materials Act and Horizon Europe, which offer favorable environments for innovation-led initiatives. Strategic initiatives in the United States have been directed towards enhancing local production and reducing import dependence, as stimulated by recent Department of Energy programs and infrastructure investment initiatives. Despite these programs providing solid institutional backing, the diversity of regulatory regimes between state and federal levels can affect the coordination and approval timeframes of projects. Such regional variation emphasizes the necessity of balancing technological capability with specific legal, economic, and administrative contexts where such solutions are meant to be used.

### Comparative Analysis Of The Efficiency Of Traditional And Innovative Ree Extraction

Conventional technologies such as pyrometallurgy and hydrometallurgy remain industrially robust with high recovery rates but are associated with high environmental footprint, high energy consumption, and occupational health issues. New technologies, however, are not yet widely applied on large scale but are increasingly being implemented in industry due to their flexibility, lower carbon footprint, and compatibility with resource efficiency principles (table 3).

**Table 3** Comparative characteristics of traditional and innovative REE extraction methods

Criterion	Traditional methods	Innovative methods
Recovery and yield	High recovery from rich ores; reduced efficiency for low-grade ores.	Stable yields from low-grade REE ores; potential use of waste and secondary resources.
Purity of final product	High (especially after purification stages); stable under industrial control.	High (in selective methods: ionic liquids, membranes).
Energy consumption	High, especially in pyrometallurgy; depends on temperature and reagents.	Lower due to milder conditions; possible integration with RES.
Carbon footprint and LCA	High – due to fuel combustion, emissions, acidic waste, slag generation.	Low – in closed-loop cycles: bioleaching, sorption, electrochemical extraction.
Health impact	High risk (corrosive reagents, dust, radioactivity).	Significantly lower due to non-toxic solvents and controlled processes.
Environmental impact	Strong – soil degradation, water contamination due to heavy metal emissions.	Moderate to low – reduced pollutant emissions; better suitability for strict environmental regulations.
Flexibility and adaptability	Limited – tied to raw material and infrastructure.	High – possibility of modular, scalable solutions for distributed and localized production.

Analysis given herein indicates that the choice between the old and new extraction methods is not a choice between extremes. Rather, it must be made based on a combination of raw material nature, availability of infrastructure, environmental limitations, and product specifications to be manufactured. Traditional methods are still feasible in the context of processing bulk high-grade ore, but novel technology has scope to be able to recover REE from secondary and low-grade ores using lower energy and environmental footprints.

The development of the industry should not occur at the expense of what already exists but through its review and reconciliation with emerging technological solutions. This is a transition required to ensure long-term production viability in light of rising world demand and stricter environmental protection requirements.

One of the instances of application of emerging technologies for REE extraction includes the project launched by the West Virginia Water Research Institute, which received funding from the U.S. Department of Energy. In a research laboratory in the National Research Center for Coal and Energy (NRCCE) at West Virginia University, Morgantown, researchers are studying whether REE can be recovered from acid mine drainage (AMD), an element traditionally viewed as an environmental contaminant. The development of such technologies could not only generate employment and support the economy of coal-dependent regions but also transform contaminated sites into strategic resources. The project illustrates the commercial viability of converting regional

environmental risks into sources of critical materials – an especially relevant strategy given the USA's high reliance on REE imports.

In 2023, the U.S. Department of Energy announced the results of the first round of project selections under the FOA-2619 program, funded through the Bipartisan Infrastructure Law [13]. The selected technologies include the use of ionic liquids, low-temperature metallothermic processes, and pilot facilities with throughput capacities of up to 500 gallons per minute. Investment in these projects shows the strategic interest of the USA in the establishment of a domestic high-tech rare earth supply chain and reducing reliance on imports.

Additionally, in 2025, the U.S. Department of Energy launched a unique initiative called Mine of the Future aimed at large-scale pilot demonstrations of emerging technologies. A key component of this initiative is the allocation of up to \$80 million for the establishment of Mining Technology Proving Grounds – field testbeds aimed at accelerating the commercialization of new extraction and processing technologies for critical minerals, including REE [14]. These efforts are designed to improve domestic supply chain strength through the introduction of sophisticated engineering solutions and reduce the country's dependence on external REE sources.

One of the illustrations of circular economy use in the case of REEs is the HyProMag USA project. Established as a joint venture between HyProMag Ltd and CoTec [15] Holdings, the project targets the recycling of spent neodymium–iron–boron (NdFeB) magnets – one of the key industrial products of REEs, such as neodymium, dysprosium, and terbium. In demonstration size, approx. 900 kg of recycled NdFeB alloy were already being produced on pilot plant in Tyseley (UK), while in America the planned capacity is up to 750 metric tons annually of recycled sintered NdFeB magnets and 807 tons of by-products. According to an external carbon footprint analysis, HyProMag USA's product range is a prime example of 2.35 kg CO<sub>2</sub>-equivalent per 1 kg of finished sintered NdFeB block, significantly lower than for traditional primary production. The planned production facility in the vicinity of Dallas–Fort Worth, Texas, is conceived with REE magnet recycling localization and reduction of logistics costs in mind. The HyProMag USA project is thereby a pragmatic means of implementing circular principles into the REE industrial process as well as reducing the carbon footprint and enhancing U.S. resource independence.

Another example of circular economy use in the industry of REE is the business of REEcycle, an American company that specializes in recycling electronic waste, such as end-of-life NdFeB magnets. The company uses patented technology through which rare earth element recovery efficiencies of up to 99.8% are made possible, with neodymium, praseodymium, dysprosium, and terbium being the majority of them. In 2025, the U.S. Department of Defense invested \$5.1 million to support pilot facility construction for REEcycle, highlighting the national strategic significance of the project to enhance national resource security. Compared with conventional mining extraction, REEcycle comes with a lower environmental impact through recycling of waste streams, thereby minimizing dependence on virgin raw material and associated emissions.

Thus, the presented cases confirm that circular economy models and emerging technological solutions can be effectively integrated into the REE supply chain to enhance sustainability, resource independence, and environmental performance.

Despite the intensive development of new REE extraction technologies, their technological readiness remains a bottleneck for industrial implementation at large scale. The majority of technologies are at Technology Readiness Levels (TRL) 4 to 6, i.e., tested at laboratory and pilot scales but requiring upscaling, standardization, and demonstration to be economically viable at full-scale production. Foremost among these are the capital intensity of installations, the challenge of transferring technologies to variable mineral feedstocks, the absence of a developed regulatory framework, and technological risks in integrating new processes into existing infrastructure.

For the promotion of localized and sustainable production of REE, government departments and industrial interests can contemplate the establishment of comprehensive support regimes aimed at encouraging suitable technological and infrastructural options. Some of the steps that can be adopted are the promotion of public–private partnerships to dampen investment risk during the initial stages of implementation, as well as incentives

in the form of setting up modular and decentralized processing facilities within regions of richness but with limited-scale infrastructure. National policies can also impact the development of specialized infrastructure – i.e., regional REE innovation clusters, recycling facilities, and pilot-scale demonstration plants – subject to environmental standards and long-term resource security objectives. Additional emphasis on building workforce training and applied scientific research could further increase domestic capability for sustainable REE production and processing.

## CONCLUSION

The traditional and new technologies of REE extraction represent two alternative technological trajectories, each with its own logic of development, field of application, and restrictions. After rising global demand for REE as well as rising need to enhance resource independence, the answer lies not in opposition to such approaches but in seeking sustainable blends based on raw material quality, infrastructure availability, and environmental and social considerations. The advanced technologies free the potential for treating complex and second-order resources in a non-environmentally intrusive way, while traditional methods offer reliability and scalability to high-grade mineral feedstocks.

The development of the REE sector cannot be a reality without the convergence of scientific studies, government policies, and industrial practice. Trends today – spanning from demonstration projects and financing initiatives to pilot-scale usage – are trending toward a new paradigm of REE recovery that is more responsive, adaptive, and sustainable. Technological efficiency, environmental stewardship, and economic feasibility combined will determine the competitiveness of solutions in the critical minerals development sector in the long term.

## REFERENCES

1. Kitaeva, I. (2025). Strategies for adapting the USA logistics system in the context of the redistribution of raw material flows. *Cold Science*, 16, 4–12.
2. The Business Research Company. (n.d.). Rare earth elements global market report. Retrieved September 15, 2025, from <https://www.thebusinessresearchcompany.com/report/rare-earth-elements-global-market-report>
3. Rivera, R., & Binnemans, K. (2025). Carbon dioxide as a sustainable reagent in circular hydrometallurgy. *ChemSusChem*, 18(3), e202400931.
4. Gkika, D., Chalaris, M., & Kyzas, G. (2024). Review of methods for obtaining rare earth elements from recycling and their impact on the environment and human health. *Processes*, 12(6), 1235. <https://doi.org/10.3390/pr12061235>
5. Peter, F., Pedro, O., & Felipe, P. (2021). Recovery of rare earth elements present in mining tails, by leaching with nitric and hydrochloric solutions. *World Journal of Nuclear Science and Technology*, 11(1), 1–16.
6. Stepanov, M. E., Pshichenko, D. V., Safronov, D. S., & Kolganov, D. I. (2024). Economic efficiency of intelligent drive systems in the mining industry. *Economic Bulletin*, 3(6), 23–31.
7. U.S. Geological Survey. (2025). Mineral commodity summaries 2025: Rare earths. Retrieved September 20, 2025, from <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-rare-earth.pdf>
8. Abdykalykov, A. (2024). Legislative regulation of mineral extraction in the USA. *The Scientific Heritage*, (150), 4–7. <https://doi.org/10.5281/zenodo.14378426>
9. Deng H., Kendall A. (2019) Life cycle assessment with primary data on heavy rare earth oxides from ion-adsorption clays. *The International Journal of Life Cycle Assessment*, 24 (9), 1643-1652.
10. Schreiber, A., Marx, J., & Zapp, P. (2021). Life cycle assessment of rare earth elements: An overview of current research and challenges. *Science of The Total Environment*, 799, 149207. <https://doi.org/10.1016/j.scitotenv.2021.149207>
11. Wan, C., Zhou, D., & Xue, B. (2022). LCA-based carbon footprint accounting of mixed rare earth oxides production from ionic rare earths. *Processes*, 10(7), 1354.
12. Western Digital. (2023). Advanced recovery and rare earth capture at scale. Retrieved September 20, 2025, from [https://documents.westerndigital.com/content/dam/doc-library/en\\_us/assets/public/western-digital/collateral/white-paper/white-paper-advanced-recycling-and-rare-earth-recovery-at-scale.pdf](https://documents.westerndigital.com/content/dam/doc-library/en_us/assets/public/western-digital/collateral/white-paper/white-paper-advanced-recycling-and-rare-earth-recovery-at-scale.pdf)

13. U.S. Department of Energy. (n.d.). Project selections for FOA 2619: BIL advanced processing rare earth elements and critical minerals. Retrieved September 21, 2025, from <https://www.energy.gov/fecm/project-selections-foa-2619-bil-advanced-processing-rare-earth-elements-and-critical-minerals>
14. U.S. Department of Energy. (n.d.). U.S. Department of Energy launches “Mine of the Future” initiatives to bolster the U.S. mining industry. Retrieved September 27, 2025, from <https://www.energy.gov/fecm/articles/us-department-energy-launches-mine-future-initiatives-bolster-us-mining-industry>
15. Hypromag USA project update for its rare earth magnet recycling and manufacturing plants in the United States. Retrieved October 12, 2025, from
16. <https://hypromagusa.com/hypromag-usa-project-update-for-its-rare-earth-magnet-recycling-and-manufacturing-plants-in-the-united-states/>