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Sustainable Rare Earth Mining Technologies: Global Trends and a Tailored Model for Vietnam's Development

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ABSTRACT

Vietnam possesses considerable rare earth element (REE) resources, particularly ion-adsorption clay deposits, yet industrial-scale exploitation remains limited due to technological and environmental constraints. This paper provides a comprehensive review of global rare earth mining technologies, with a focus on their applicability to Vietnam. We emphasize the recent breakthrough in electrokinetic mining (EKM) as a sustainable alternative to conventional leaching, highlighting its potential to achieve >90% recovery while significantly reducing chemical use and ecological impacts. The review further discusses the circular economy approach to REE recovery from industrial waste streams such as fly ash, red mud, and titanium tailings. Despite the progress, several research gaps remain: the absence of pilot-scale demonstrations in Vietnam, limited techno-economic and life cycle assessment (LCA) studies, and lack of a domestic REE value chain. By consolidating global experiences and contextualizing them to Vietnam, this study contributes a technology-oriented framework to guide policymakers, researchers, and industry stakeholders. We propose future directions including pilot EKM trials, integrated REE recycling models, and regulatory frameworks supporting “green mining” strategies.

Keywords:

Rare earth elements (REEs); Electrokinetic mining (EKM); Sustainable mining; Circular economy; Vietnam.

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1. Introduction

Rare earth elements (REEs) are critical to modern industries owing to their unique magnetic, luminescent, and catalytic properties, making them indispensable for permanent magnets, clean energy, telecommunications, and defense technologies (Lê Đức An, 2020), (Trường, 2021), (Hải, 2017). Global demand is projected to increase up to sixfold by 2040, with heavy rare earth elements (HREEs) such as dysprosium and terbium experiencing the sharpest growth. However, the supply of REEs remains geographically concentrated—dominated by China—while conventional mining practices have resulted in significant environmental concerns.

Vietnam ranks among the top six countries worldwide in terms of REE reserves, with promising deposits such as Đông Pao, Nậm Xe, Mường Hum, and ion-adsorption occurrences in Lào Cai and Yên Bái. Despite this potential, domestic exploitation has largely stagnated, constrained by technological barriers, high environmental risks, and the absence of a downstream processing industry.

Research gap and objectives. Previous studies have primarily mapped resources and provided qualitative assessments of Vietnam's REE sector. However, there has been limited systematic analysis of advanced mining technologies and their applicability to Vietnam's specific geological and environmental conditions. In particular, the potential of electrokinetic mining (EKM) for ion-adsorption deposits remains unexplored in Vietnam, despite its promising results in China and recent industrial-scale trials. Furthermore, circular economy approaches for REE recovery from waste streams have not been integrated into national strategies.

This paper aims to review global trends and technological advances in rare earth element (REE) mining with a particular emphasis on environmentally sustainable methods; to assess the applicability of electrokinetic mining (EKM) to Vietnam's ion-adsorption deposits while highlighting associated opportunities and challenges; to explore circular economy models for REE recovery from industrial waste streams in the country; and to provide research, policy, and pilot implementation recommendations that can support the establishment of a sustainable domestic REE value chain.

By addressing these objectives, this review seeks to position Vietnam within the global REE landscape and contribute to the design of technology-driven, environmentally responsible strategies for resource utilization.

2. Overview of Rare Earth Deposits and Mining Methods in Vietnam and Worldwide

2.1. Rare Earth Deposits and Mining Methods in Vietnam

According to the *Master Plan for Exploration, Mining, Processing, and Utilization of Minerals 2021–2030, with a Vision to 2050*, Vietnam is projected to mine approximately 2 million tons of raw rare earth ore annually by 2030 (BTNMT, 2023; Đặng Trung Thuận, 2013; An, 2020). Global rare earth resources are estimated at about 120 million tons of REO. Earlier assessments ranked Vietnam second worldwide with reserves of ~22 million tons; however, the latest USGS (2025) report revised this figure to ~3.5 million tons of REO, placing Vietnam sixth globally—still above many developed nations in resource scale. The country's deposits

are mainly concentrated in the Northwest (Lai Châu, Lào Cai, Yên Bái) and along the Central Coast (Quảng Nam, Bình Thuận), with the Đông Pao deposit in Lai Châu identified as the most significant resource for industrial-scale development.

2.1.1. Dong Pao Rare Earth Deposit (Lai Châu Province)

Located in Bản Hòn Commune, Tam Đường District, Đông Pao covers ~133 hectares and contains over 11.3 million tons of geological reserves, representing more than half of Vietnam's resources. The deposit spans ~10 km² and includes ~60 ore bodies, of which 16 are of industrial value. The ore consists mainly of bastnaesite and synchysite, associated with barite and fluorite, and is dominated by light REEs (La, Ce, Pr, Nd), with trace uranium and thorium. Total TREO reserves are ~4.38 million tons, with grades ranging from 0.5% to 39% TREO, averaging 2.5–6.0%. Up to 97% of the REE composition comprises Ce and La. The ore originated from weathering and secondary enrichment within alkaline syenite dikes of the Pú Sam Cáp complex. Thickness varies between 33 and 83 m. Current exploitation uses open-pit mining with drilling, blasting, and selective recovery to improve efficiency.

2.1.2. Other Rare Earth Deposits in the Northwest Region

The Nậm Xe cluster, including North and South Nậm Xe, represents another major resource. North Nậm Xe spans 18–20 km² within alkaline syenite–granodiorite–alkali granite formations (Nguyễn Văn Cường, 1999). Ore minerals include bastnaesite and xenotime, with significant HREE content. Resources are estimated at ~4.09 million tons TR₂O₃, with ~63% LREEs and ~29% HREEs. Average grades are ~1.1% TREO (0.1–7.0%), with associated Nb₂O₅ (0.01–0.17%), U, and Th. Remarkably, HREEs account for ~27% of total REEs, a rare feature with high industrial potential. South Nậm Xe, meanwhile, contains ~2 million tons of placer monazite ore, averaging 0.3–5.42 kg/m³.

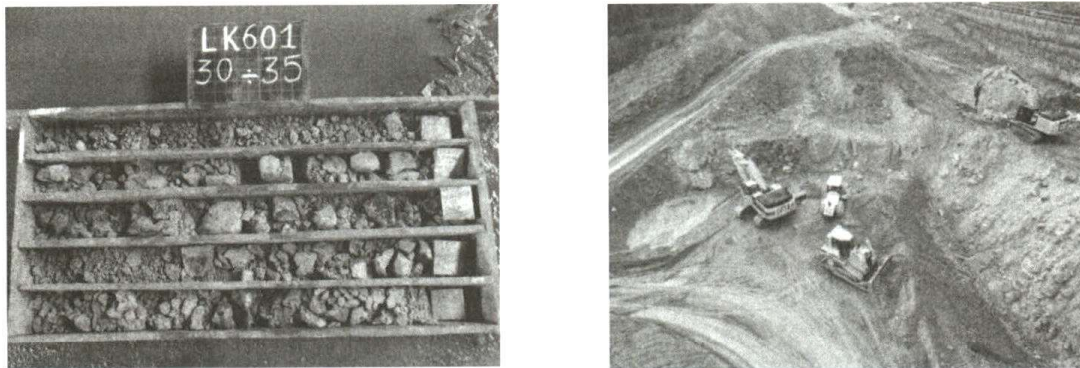


Figure 1. Bắc Nậm Xe Rare Earth Deposit – Lai Châu Province

In Lào Cai and Yên Bái, notable deposits include Mường Hum and Yên Phú. Yên Phú (Văn Yên District, Yên Bái) occurs in A-type alkali granite and contains xenotime and monazite, with associated niobium and uranium (Bình, 2022; Nguyễn Văn Cường, 1999). Estimated resources are ~5,000 tons TR₂O₃, with ore grades ranging from 0.1% to 7.0% TREO and an average of 1.12%. Like Nậm Xe, Yên Phú is enriched in HREEs, which account for ~27% of total REEs. The Mường Hum deposit (Bát Xát District, Lào Cai), linked to peralkaline granite intrusions, also shows significant HREE enrichment, with minerals such as aegirine and arfvedsonite indicating similar potential (Bình, 2022; Nguyễn Văn Cường, 1999).

2.1.3. Placer deposits.

Secondary resources are also present, exemplified by the Bù Khạng placer deposit (Nghệ An Province), where monazite and xenotime accumulate in alluvial sediments derived from granitic rocks (Đặng Trung Thuận, 2013; Bình, 2022). Monazite concentrations range from 0.15 to 4.8 kg/m³. Although smaller in scale than primary deposits, these placers provide an additional source of REEs.

2.2. Rare Earth Deposits Worldwide

Globally, rare earth deposits occur in diverse geological settings, with China, the United States, and Australia being the most prominent producers. Among them, Bayan Obo (China) and Mountain Pass (United States) stand out as world-class deposits, while emerging contributions come from Myanmar, Thailand, India, and Russia.

2.2.1. Bayan Obo Rare Earth Deposit (China)

Bayan Obo in Inner Mongolia, China, is the world's largest rare earth deposit (Intelligence, 2022; BGS, 2022). Exploited through open-pit mining, it comprises two major orebodies (Main and East) hosted in faulted dolomite marble. The ore is geologically diverse, including riebeckite-bearing (iron–sodium rich), aegirine-bearing (sodium pyroxene), and massive or banded bodies enriched in REEs. Bastnäsite and monazite are the dominant rare earth minerals, commonly associated with riebeckite and aegirine. Accounting for more than 40% of global REE output, Bayan Obo has been the cornerstone of China's long-standing dominance in the global supply chain (OECD, 2021; Roskill, 2021; USGS, 2023).



Figure 2. Bayan Obo Rare Earth Deposit (China)



Figure 3. Niobium Deposit

2.2.2. Mountain Pass Rare Earth Deposit (United States)

The Mountain Pass deposit, situated in the Mojave Desert of California near the Nevada border, is the leading rare earth mine in the United States (OECD, 2021; Roskill, 2021). Hosted within a carbonatite intrusion—a geological environment comparable to the Đông Pao deposit in Vietnam—it is exploited by open-pit methods. Bastnäsite is the principal ore mineral, with enrichment in light rare earth elements (Ce, La, Nd). First operated in the 1950s, Mountain Pass was the world's largest REE source until China's rise to market dominance. After a period of closure driven by environmental and competitive pressures, the mine has been revitalized through major investment to meet demand for permanent magnets and to secure the U.S. strategic supply of critical materials. Current operations focus

on bastnäsite extraction and REE concentrate production, reinforcing Western initiatives to reduce reliance on Chinese supply (JOGMEC, 2022).



Figure 4. Mountain Pass Rare Earth Deposit (United States)

Beyond China and the United States, several countries contribute to global rare earth supply. Australia hosts substantial reserves, particularly the Mt Weld deposit, and is rapidly expanding its processing capacity. Myanmar and Thailand exploit smaller ion-adsorption clay deposits, which, despite their modest scale, are relatively enriched in HREEs. Other nations, including India, Russia, Canada, Greenland, and Vietnam, also possess significant resource potential, though their current production remains limited. The overarching trend is toward supply diversification and reduced dependence on China, supported by new mining ventures and investments in advanced extraction and processing technologies.

3. Conventional Mining Methods of Rare Earth Deposits

Based on their geological characteristics and ore properties, rare earth deposits can be broadly classified into three groups, each requiring distinct mining methods to ensure efficiency and suitability.

Hard-rock deposits (carbonatite and alkaline intrusion types). These primary deposits (e.g., Đông Pao, Nậm Xe, Mountain Pass) are typically mined by conventional open-pit or underground methods, as ore bodies are well-defined within host rocks. Extraction involves drilling, blasting, loading, hauling, and subsequent beneficiation through flotation, magnetic separation, and electrostatic separation to recover minerals such as bastnäsite and monazite. Radiation safety is a critical consideration due to the frequent presence of thorium (Th) and uranium (U).

Placer deposits (monazite- and xenotime-bearing). Found mainly in alluvial river sands and coastal beach sands (e.g., Bù Khạng and several sites along Vietnam's central coast), these deposits are exploited using hydraulic or mechanical mining combined with gravity concentration. Ore-bearing sands are dredged or excavated, followed by gravity and magnetic separation to obtain monazite and xenotime concentrates. As monazite contains radioactive ThO_2 , safe handling and disposal of beneficiation residues are required. While placer mining is generally less costly than hard-rock operations, it is often smaller in scale and yields lower recovery rates.

Ion-adsorption deposits. Formed in weathering crusts where REE^{3+} ions are adsorbed onto clay minerals such as kaolinite and halloysite, these deposits are typically enriched in

HREEs but exhibit low grades ($<0.3\%$ TREO), thin mineralized horizons (a few to tens of meters), and minimal radioactive associations. Occurrences have been reported in Vietnam (e.g., Bến Đền in Lào Cai, Hàm Yên in Tuyên Quang), though none are exploited at industrial scale. Conventional mechanical mining is ineffective for such deposits due to their dispersed and low-grade nature. Historically, China applied in-situ leaching with ammonium sulfate solutions, pumping reagents into the ore horizon and recovering REE-bearing liquids through extraction wells. While cost-effective, this method has caused severe environmental degradation, including groundwater contamination, soil acidification, and the formation of toxic leach ponds. In response, China banned new ammonium-based ion-adsorption projects in 2018 to mitigate further ecological damage (Xu, 2025).

In summary, the natural characteristics, geological conditions, and mining practices of rare earth deposits can be systematically grouped into these three categories, with key features and methods outlined in Table 1 and Table 2.

Table 1. Main Types of Rare Earth Deposits

Representative Deposits	Key Characteristics	Principal Minerals
Carbonatit Mine	Magmatic rocks contain the highest concentrations of REEs and represent the principal global source of light rare earth elements (LREEs)	Bastnasite
Alkaline intrusion-type deposits	Magmatic rocks also have the potential to enrich heavy rare earth elements (HREEs), which are of critical importance for advanced technologies	Eudialyte, Apatit, Xenotim
Ion-adsorption deposits	Formed through the weathering of granitic rocks, these deposits constitute the principal source of heavy rare earth elements (HREEs).	REEs adsorbed onto clay minerals
Placer deposits	Accumulations of heavy minerals within sands and gravels from lakes and riverbeds, which historically served as a source of rare earth elements	Monazite, Xenotim

Table 2. Classification of Rare Earth Deposits in Vietnam and Their Mining Methods

Rare Earth Deposit	Province	Deposit Type	Mining Method
Dong Pao	Lai Chau	Carbonatit	Open-pit mining
Nam xe	Lai Chau	Carbonatit	Open-pit mining

Yen Phu	Lao Cai	Carbonatit	Open-pit mining
Muong Hum	Lao Cai	Alkaline intrusion-type deposits	Open-pit mining
Ben Den	Lao Cai	Ion-adsorption deposits	In-situ leaching of rare earths; Electrokinetic Mining (EKM)
Bu Khang	Nghe An	Placer deposits	Hydraulic mining (water-powered mining)

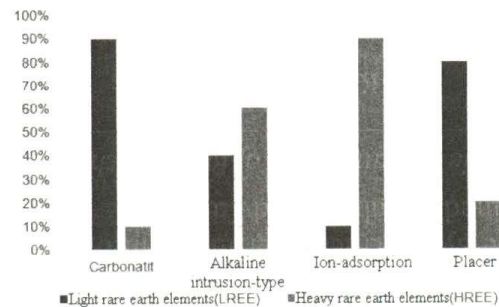


Figure 5. Comparison of Light Rare Earth Elements (LREEs) and Heavy Rare Earth Elements (HREEs) Proportions

Recently, the development of electrokinetic mining (EKM) technology has introduced a novel approach for ion-adsorption deposits, providing an alternative to conventional chemical leaching. The following section presents a detailed discussion of the principles and advantages of EKM, as well as its potential applicability in Vietnam.

4. Electrokinetic Mining (EKM) Technology for Rare Earth Extraction

4.1. Rare Earth Potential of Ion-Adsorption Deposits in Vietnam Rare

Ion-adsorption rare earth deposits, also known as ion-weathered deposits, are the dominant global source of heavy rare earth elements (HREEs), providing more than 90% of worldwide supply. They form through intense chemical weathering of REE-enriched parent rocks (e.g., granite, rhyolite, tuff) under humid tropical conditions, where REEs occur as cations adsorbed onto clay minerals. Although typically low in grade, mineralization is distributed throughout the weathering profile.

In Vietnam, several occurrences have been identified in the northern mountainous region, notably Bến Đền (Bảo Thắng District, Lào Cai Province) and Hàm Yên (Tuyên Quang Province), where REEs are adsorbed within the weathered granite-gneiss crust. Compared with the large-scale ion-adsorption deposits of southern China (Jiangxi, Guangdong), these Vietnamese occurrences are constrained by lower average grades (<0.3% TREO), thinner mineralized zones (~7–20 m), and more limited distribution, remaining classified only as inferred resources without detailed exploration. Positively, they are virtually free of uranium

and thorium, rendering them environmentally safer than hard-rock deposits. With the adoption of “green” extraction technologies, such deposits could be exploited efficiently while meeting international ESG standards.

To date, no ion-adsorption deposits in Vietnam have been developed at an industrial scale, and most remain at the stage of preliminary geological investigation. Consequently, the country has yet to capitalize on its domestic HREE potential. To address this gap, researchers have advanced electrokinetic mining (EKM) as a novel technology that enables environmentally compatible exploitation of ion-adsorption deposits, representing a promising pathway for future application under Vietnam’s geological and environmental conditions.

4.2. Principles of Electrokinetic Mining (EKM) for Ion-Adsorption Rare Earth Deposits

Basic principle. Electrokinetic mining (EKM) employs a direct current applied between electrodes inserted into the ore horizon to mobilize and recover rare earth ions via electromigration and electroosmosis, thereby eliminating the need for large-scale chemical flooding. The electrode configuration typically places the anode above and the cathode either beneath or along the margins of the mineralized zone. Once a DC voltage is applied, the electric field penetrates the deposit, inducing desorption of REE^{3+} cations from clay surfaces through ion-exchange reactions with the electrolyte solution. These ions then migrate directionally toward the cathode under the combined effects of electromigration and electroosmotic flow. The REE-enriched solution is collected at cathodic recovery wells. The process is highly selective: REE ions exhibit faster migration rates than major rock-forming cations (e.g., Al^{3+} , Fe^{3+} , Ca^{2+}), resulting in solutions concentrated in REEs with relatively low impurity levels. A schematic representation of this principle is provided in Figure 6.

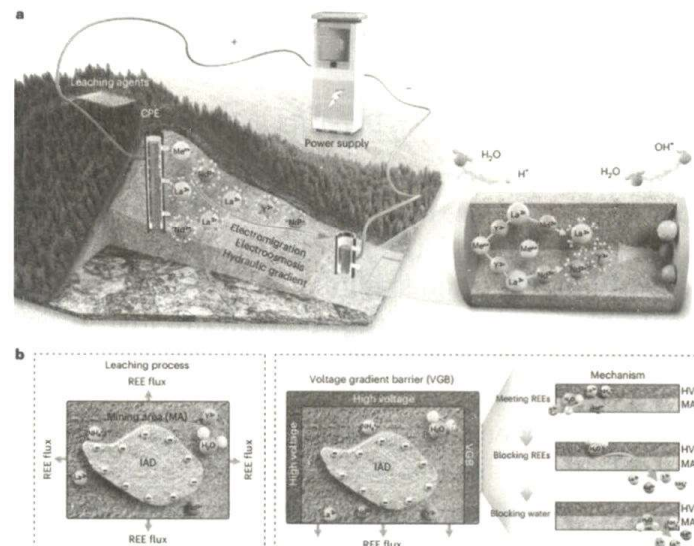


Figure 6. Illustration of EKM technology applied to ion-adsorption rare earth deposits (Wang, G., 2023)

a. In EKM applied to ion-adsorption deposits, leaching agents are introduced into the clay-rich ore zone (CPE), where they permeate the soil matrix and release adsorbed REE ions. Once mobilized, REEs and water migrate directionally from anode to cathode under the influence of electromigration, electroosmosis, and hydraulic gradients generated by the applied electric field, and are subsequently collected near the cathode.

b. The voltage gradient barrier (VGB) mechanism. Left: during conventional leaching, REE flux disperses irregularly without a controlled pathway. Right: under EKM, the applied electric field directs REE ions along a defined route.

Electrolyte supplementation. To improve soil conductivity and enhance ion exchange, EKM introduces a small volume of electrolyte into the ore-bearing layer. Typically, dilute sulfate salts (e.g., MgSO_4 or low-concentration $(\text{NH}_4)_2\text{SO}_4$) are used, amounting to only 20–30% of the reagent volume required in conventional in-situ leaching. This ensures adequate electrical conductivity and supplies exchangeable ions for REE desorption, while significantly reducing chemical inputs. For comparison, conventional leaching with saturated ammonium sulfate can be performed at control sites under similar conditions.

Circulating treatment system. REE-enriched solutions collected at the cathode pass through a multi-stage treatment system: a separation tank removes suspended solids, a purification tank concentrates REEs, and a circulation tank recycles electrolytes. REEs are ultimately precipitated as carbonates or hydroxides to produce rare earth oxides (REOs). Water and reagents are continuously recycled in a closed-loop, minimizing consumption and discharge.

Efficiency and experiments. Laboratory and pilot studies by the Guangzhou Institute of Geochemistry reported REE recovery rates of ~90%, while reducing chemical use by ~80% and metallic impurities by ~70% compared with conventional leaching (Xu, 2025; Wang, 2023; Hu, 2025). Field trials further demonstrated recovery efficiencies exceeding 95% after ~50 days of EKM operation (Fig. 12B), without reliance on traditional mining techniques. These results highlight the dual advantages of maximizing resource recovery and reducing environmental impacts.

Industrial-scale trial. Recent large-scale experiments (~5,000 tons of ore) in southern China confirmed the scalability of EKM (Xu, 2025; Hu, 2025). Reported outcomes include >95% REE recovery, 80% reduction in reagent use, 70% shorter extraction times, and ~95% reduction in ammonia emissions. These achievements were enabled by several technological advances: conductive polymer electrodes (CPEs) with high durability (conductivity ~200 S/m, current endurance up to 70 A for several months), voltage gradient barriers (VGBs) to prevent leakage via counter-electroosmotic control, and intermittent power alternation (IPA) regimes to improve energy efficiency. Collectively, these innovations represent the first successful industrial-scale application of EKM, underscoring its potential as a “green” technology for sustainable rare earth extraction.

4.3. Comparison of Electrokinetic Mining (EKM) and Conventional Extraction Methods

Table 3. Comparison of key performance criteria between electrokinetic mining (EKM) and conventional in-situ leaching for ion-adsorption rare earth deposits. The table highlights differences in recovery efficiency, reagent consumption, extraction time, environmental impact, and scalability, providing a clear assessment of the relative advantages of EKM.

Table 3. Comparison of Electrokinetic Mining (EKM) and Conventional Leaching Methods for Rare Earth Extraction

Criteria	Electrokinetic Mining (EKM)	Conventional Leaching
Ore separation mechanism	Conductive current through soil – stimulating electromigration and ion exchange	Chemical solution percolation through soil – ion exchange
Leaching agent	Electric field + small amount of salts (dilute MgSO_4 , dilute $(\text{NH}_4)_2\text{SO}_4$)	Ammonium sulfate $((\text{NH}_4)_2\text{SO}_4)$ or magnesium sulfate (MgSO_4) solution
Environmental impact	Very low pollution; almost no ammonium emissions	High risk of pollution (NH_4^+ , NO_3^- infiltration into soil and groundwater); soil structure degradation
Energy consumption	Requires electrical input (operational cost but can be optimized by reducing processing time)	Low electricity demand (mainly for pumping solution), but requires prolonged operation
Selectivity	High – directed ion migration limits impurities (Al^{3+} , Fe^{3+} , etc.)	Lower – significant co-dissolution of major rock-forming cations (e.g., Al^{3+} , Fe^{3+} , Ca^{2+})
Soil disturbance	Minimal – no excavation or terrain deformation required	Considerable – soil excavation and alteration, with risks of erosion and slope instability
REE recovery efficiency	Very high – >90%, particularly effective for HREEs	Lower – typically 40–60%, depending on solution concentration and multiple leaching cycles
Applicable scope	Ion-adsorption deposits in weathered crusts (e.g., Bến Đền, Lào Cai, Vietnam)	Traditional ion-adsorption deposits (e.g., southern China before 2018) or deposits where in-situ leaching is feasible

The results clearly demonstrate that EKM outperforms conventional leaching across multiple criteria, offering higher recovery, greater selectivity, and minimal environmental disturbance. Reported recovery rates exceed 90% of total rare earth oxides (TREO), compared with only 40–60% for conventional methods. By replacing large-scale chemical flooding with an applied electric field, EKM reduces reagent demand by ~70–80%, requiring just 20–30% of the chemical input typically consumed in ammonium-based leaching. This substantially lowers operating costs and minimizes the risk of soil and water contamination.

The purity of REE solutions produced by EKM is also markedly higher. Impurity cations (e.g., Al^{3+} , Fe^{3+} , Ca^{2+}) are immobilized and precipitate within the soil, reducing impurity levels in product solutions by over 90% relative to conventional leachates. This simplifies downstream precipitation and refining, further lowering processing costs. In addition, EKM generates virtually no pollutant emissions, with studies showing >95% reductions in ammonium release compared with conventional leaching. Because the process requires neither soil excavation nor solid waste disposal, the original morphology and integrity of the mine site are preserved.

Collectively, these advantages position EKM as a highly promising “green” technology for sustainable exploitation of ion-adsorption rare earth deposits.

4.4. Proposed pilot model for the application of the EKM in Vietnam

To enable effective deployment of EKM, initial implementation should begin with a small-scale pilot at a representative ion-adsorption deposit. In Vietnam, suitable candidates include portions of the Yên Phú deposit (Yên Bái Province) or the Bến Đền occurrence (Lào Cai Province), where ion-clay REE resources have been identified. A pilot covering several hectares, with mining depths of 10–30 m and processing several thousand tonnes of ore, would be comparable to earlier pilot studies in China (14-tonne laboratory tests and a 5,000-tonne field trial).

The pilot system would consist of an anode network installed near the surface and cathode recovery wells placed at depth. A neutral electrolyte, such as dilute MgSO_4 , would circulate through the ore body, while an intermittent power-supply regime is applied to reduce energy consumption. An electric barrier would surround the mining area to prevent leachate migration.

Monitoring should be carried out by a multidisciplinary team of geology and environmental specialists, focusing on groundwater pH, ion concentrations, electrode stability, and temporal recovery efficiency. These observations would be benchmarked against predictive models and, where available, against results from conventional ammonium-based leaching on similar ore types. Together, such data would provide a comprehensive evaluation of technical, environmental, and economic feasibility. The operational framework of the EKM process is illustrated in Figure 7.

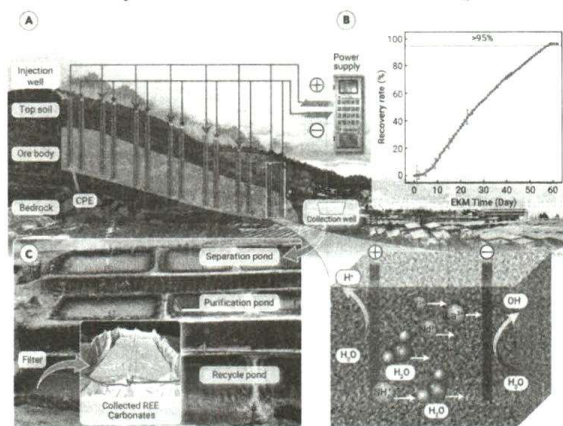


Figure 7. EKM Process – Electrokinetic Mining of Rare Earth Elements (Xu, 2025)

5. Circular Economy Model for Rare Earth Recovery from Waste

Beyond primary ore mining, recovery of rare earth elements (REEs) from industrial waste streams offers a critical component of the circular economy model. Recycling REEs from end-of-life products and industrial residues not only reduces reliance on new extraction but also mitigates environmental impacts. Numerous studies have shown that waste materials such as flotation tailings, red mud from alumina refining, phosphogypsum, and coal fly ash contain appreciable REE concentrations, often ranging from several hundred to several thousand ppm. For instance, analyses of fly ash from the Na Dương coal-fired power plant (Lạng Sơn Province) revealed dispersed REEs, including Ce, Y, Nd, and Dy, at concentrations of several tens of ppm. Such residues therefore represent potential “urban mines,” enabling simultaneous REE recovery and waste management. The distribution of REEs in fly ash from the Na Dương plant is illustrated in Figure 8.

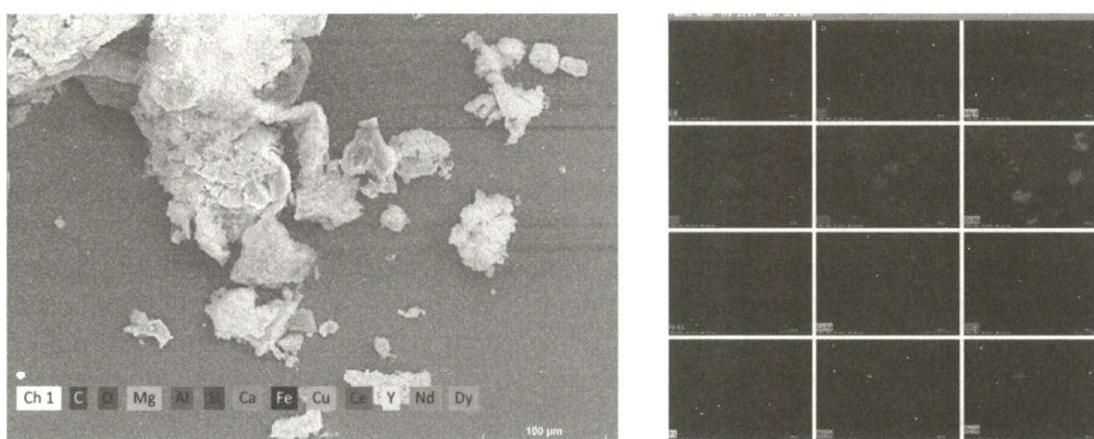


Figure 8. Elemental Distribution in Fly Ash Samples from the Na Dương Coal-Fired Power Plant

The recovery of REEs from industrial waste typically involves three main stages. First, preliminary beneficiation applies physical separation methods (e.g., magnetic separation, gravity concentration, flotation) to enrich REE-bearing minerals or remove silicate gangue. Second, leaching and extraction use hydrometallurgical techniques—either acidic or alkaline leaching—followed by solvent extraction to obtain a concentrated REE solution. Third, precipitation and calcination precipitate REEs as salts (carbonates, hydroxides), which are then calcined to yield high-purity rare earth oxides (REOs). While these hydrometallurgical and chemical processes are well established and applicable in Vietnam, optimization is needed to account for the compositional variability of each waste stream.

Despite the presence of significant REE concentrations in titanium tailings, fly ash, and red mud, Vietnam has yet to establish an industrial-scale recovery model. Advancing this pathway will require several measures:

Targeted R&D investment to characterize each waste type and design tailored processes (e.g., Sc recovery from red mud, Dy and Nd extraction from coal residues).

Policy incentives that support enterprises in piloting circular economy models and provide tax benefits for recycled REE products.

International collaboration with countries such as the United States and South Korea, which have demonstrated successful waste-to-REE recovery projects.

Comprehensive assessments, including life cycle analysis (LCA) and techno-economic analysis (TEA), to ensure technical feasibility and minimize environmental risks.

Domestic value chain development linking waste recovery with refining and downstream processing, thereby creating an integrated supply chain from recycled REE sources to high-value end-use applications such as magnets, batteries, and alloys.

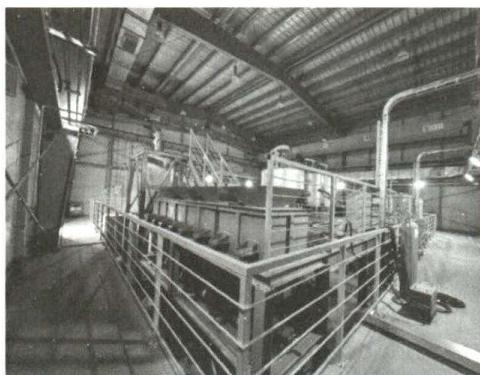


Figure 9. Pilot Recovery of REEs from Fly Ash at KIGAM, South Korea



Figure 10. Pilot Recovery of REEs from Coal Refuse in the Illinois Basin, Kentucky, USA

Several pioneering projects underscore the feasibility of REE recovery from waste. The Korea Institute of Geoscience and Mineral Resources (KIGAM) has conducted pilot-scale studies on fly ash processing, while the U.S. Department of Energy (DOE) has supported a pilot project in Kentucky that successfully produced REE concentrates of ~2% from coal refuse. These initiatives emphasize both technical viability and the value of modular, flexible system design, as demonstrated by U.S. mobile pilot units deployable directly at waste sites.

Vietnam, with substantial reserves of coal combustion residues and bauxite red mud, is well positioned to adopt similar models. By integrating new mining operations (e.g., Đông Pao, Bến Đền) with secondary recovery from industrial wastes, the country could diversify its rare earth supply, alleviate pressure on primary deposits, and accelerate the transition toward a sustainable, closed-loop rare earth industry.

6. Conclusions and Recommendation

6.1. Conclusions

Vietnam holds substantial rare earth resources, including large LREE-rich hard-rock deposits (e.g., Đông Pao, Nậm N Xe), coastal placer monazite, and HREE-bearing weathered crusts (e.g., Bến Đền, Yên Phú, Mường Hum). Despite this potential, most activities remain limited to surveys or small-scale mining, with no integrated mining–processing value chain established.

Effective development requires deposit-specific technologies: conventional mining with strict radiation safeguards for hard-rock ores; gravity and magnetic separation with proper waste management for placer sands; and, most critically, electrokinetic mining (EKM) for ion-adsorption clays as a cleaner, high-efficiency alternative to traditional chemical leaching. In parallel, REE recovery from industrial wastes—such as fly ash, red mud, and titanium tailings—offers a promising circular economy pathway that reduces dependence on primary extraction while addressing solid waste challenges.

6.1. Recommendation

Invest in human resources and R&D. Prioritize training specialists and advancing modern REE technologies, particularly hydrometallurgy, separation, and EKM for ion-adsorption deposits. Strengthening analytical and testing capacities is essential to master the full value chain.

Pilot testing and technology transfer. Initiate a pilot EKM project at a representative site (e.g., Bến Đền, Lào Cai) to validate performance under Vietnamese conditions. Strengthen collaboration with international partners (China, Australia, U.S., Japan, South Korea) for advanced technology transfer, supported by government funding and expertise.

Policy incentives and regulatory framework. Develop favorable policies on taxation, credit, and environmental permitting for “green” mining and REE recycling. Incentivize waste-based recovery projects, while finalizing a comprehensive legal framework that mandates life cycle (LCA) and techno-economic (TEA) assessments for all REE projects.

Build a domestic value chain. Encourage enterprises to expand beyond raw ore extraction into processing and advanced material production (e.g., REO, alloys, magnets, batteries, sensors). Coherent policies on investment, market development, and domestic product protection will be critical.

If effectively implemented, these strategies—anchored in advanced technologies like EKM and supported by circular economy initiatives—could transform Vietnam’s rare earth sector into a sustainable, environmentally responsible, and globally competitive industry.

References

- An, L. Đ. (2020). Hiện trạng phân tích và đánh giá đất hiếm tại Việt Nam. *Tạp chí Địa chất*, 3(57), 26-35.
- BGS, B. G. (2022). *Rare Earth Elements Profile*. BGS Publication.
- Bình, N. V. (2022). Xây dựng bản đồ tiềm năng đất hiếm Việt Nam tích hợp GIS. *Tuyển tập Hội nghị Địa chất toàn quốc*, 105-112.
- BTNMT, B. T. (2023). *Quy hoạch thăm dò, khai thác, chế biến và sử dụng khoáng sản 2025–2035*. Hà Nội: Báo cáo Bộ TN&MT.
- Đặng Trung Thuận, N. X. (2013). Khảo sát tiềm năng đất hiếm tại các khu vực Tây Bắc và Bắc Trung Bộ, Việt Nam. *Tạp chí Địa chất*, 4(68), 35-48.
- Hải, T. T. (2017). Thách thức và cơ hội phát triển ngành đất hiếm tại Việt Nam. *Tạp chí Năng lượng & Tài nguyên*, 9(3), 49-60.
- Hải, T. T. (2017). *Thực trạng và giải pháp đầu tư khai thác đất hiếm ở Việt Nam*. Hà Nội: Hội thảo Chính sách Khoáng sản.
- Hu, M. (2025). Kinetics of Ion Exchange in Magnesium Sulfate Leaching of Rare Earths and Aluminum from Ionic Rare Earth Ores. *Minerals*, 15(3), 290.
- Intelligence, A. (2022). *Rare Earth Elements Market Outlook to 2040*. Adamas Report.
- JOGMEC. (2022). *Japan–Vietnam Cooperation on Rare Earth Development*. Tokyo: Technical Report.

Lê Đức An, T. Q. (2020). Phân tích và đánh giá tiềm năng khoáng sản đất hiếm tại Việt Nam. *Tạp chí KS & Địa chất*, 1(23), 72-81.

Nguyễn Văn Cường, T. T. (1999). *Kết quả thăm dò đất hiếm tại mỏ Nam Nậm Xe và Đông Pao*. Hà Nội: Kỷ yếu Hội nghị KH Địa chất VN.

OECD. (2021). *Raw Materials for the Green Transition*. OECD Publishing.

Roskill. (2021). *Rare Earths: Market Outlook and Trends*. Roskill (Wood Mackenzie) Report.

Trường N. X. (2021). Đánh giá khoáng sản đất hiếm ở Việt Nam và định hướng phát triển ngành. *Tạp chí KH&CN Mỏ*, 16(12), 120-135.

USGS. (2023). *Mineral Commodity Summary – Rare Earths*. US Geological Survey.

Wang, G. (2023). A green and efficient technology to recover rare earth elements from weathering crusts. *Nature Sustainability*, 6(1), 81–92.

Wang, G. (2025). Industrial-scale sustainable rare earth mining enabled by electrokinetics. *Nature Sustainability*, 8(2), 182–189.

Xu, J. L. (2025). Breakthrough in electrokinetic mining: 5,000 tons of ion-adsorption rare-earth ore successfully mined. *The Innovation*, 6(5).