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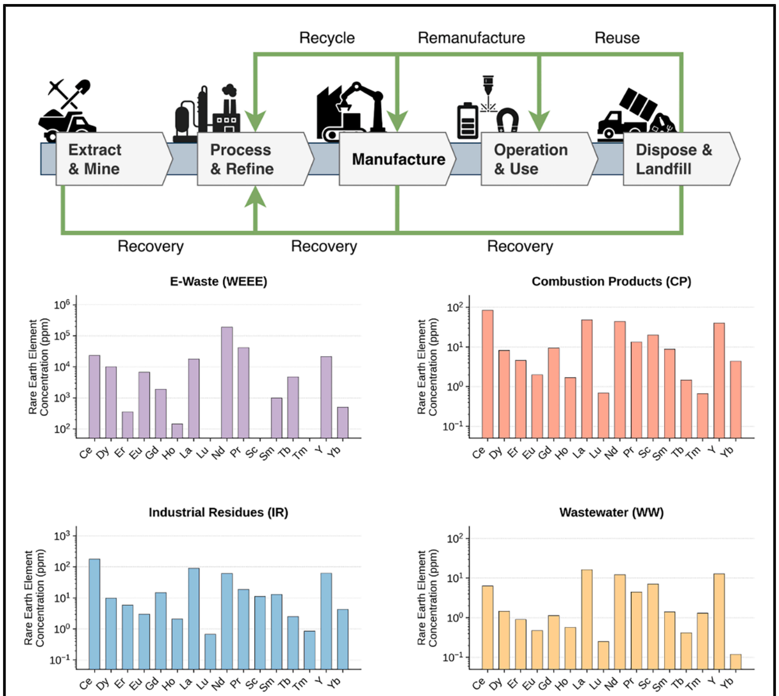
Resource accessibility of rare earths across secondary feedstocks

Graphical abstract



Bars represent median REE concentrations aggregated across 19 secondary feedstock subcategories from a systematic review of 305 studies.

Highlights

- Accessibility framework ranks 19 secondary rare earth feedstocks by viability
- Permanent magnets and lighting phosphors clear breakeven costs above $10,000 per ton
- Fly ash and acid mine drainage face breakeven cost ceilings below $100 per ton

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In brief

Reclaiming rare earth elements from waste offers a path to supply chain resilience, yet the relative viability of secondary sources has remained unclear. This article and framework combine concentration, extraction efficiency, and breakeven cost across 19 feedstock categories, revealing electronic waste as the priority near-term target.

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Resource accessibility of rare earths across secondary feedstocks

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CONTEXT & SCALE Rare earth elements (REEs) are essential to the permanent magnets, phosphors, and catalysts that enable advanced energy and defense technologies. Global supply and production remain concentrated in a small number of countries, exposing advanced manufacturing economies to economic and strategic vulnerability. Reclaiming these elements from waste streams that already exist within industrial economies offers a complementary path to primary mining, one that can reduce dependence on geographically constrained sources without new ore extraction. This study establishes a quantitative baseline for which secondary feedstocks merit near-term investment. End-of-life electronics, particularly permanent magnets and lighting phosphors, hold high concentrations of REEs and align with the recycling tier of the circular economy (CE) hierarchy, where mature processing routes exist and breakeven costs for reclamation exceed $10,000 per metric ton. Industrial residues, combustion byproducts, and wastewater sit in the recovery CE tier and have dilute concentrations that drive breakeven costs below $100 per metric ton, which may be viable only with extraction cost reductions or integrated valorization of coproducts. Reuse and remanufacturing remain thin in the documented literature because most REE-containing components are difficult to recover without destructive processing.

Policy levers that support resource resilience include collection infrastructure for end-of-life electronics, standardized waste characterization for industrial residues, and incentives for co-located processing within existing manufacturing footprints. The framework ranks accessibility per metric ton of feedstock and does not integrate aggregate reserves, trade volumes, downstream separation to commercial purity, or feedstock-specific techno-economic analyses. Future work should pair these per-ton accessibility metrics with feedstock abundance data, region-specific logistics, and quantitative studies of higher-tier circular strategies such as reuse and remanufacturing, where the literature remains thin.

SUMMARY

Global deposits for rare earth elements (REEs) remain concentrated in a limited number of geographic sources, exposing advanced energy and defense technologies to supply risk. Reclaiming REEs from secondary feedstocks offers a path to supply chain resilience, but no prior study has systematically characterized their technical and economic accessibility across feedstock types. Through a quantitative systematic review of 305 studies, this work applies an accessibility framework based on REE concentration, extraction efficiency, and breakeven processing cost to evaluate 19 secondary feedstock categories. Results reveal a large gap between high-grade anthropogenic sources (e.g., permanent magnets and lighting phosphors), with breakeven processing costs exceeding $10,000 per metric ton, and dilute geogenic residues (e.g., fly ash and acid mine drainage), which face allowable cost ceilings below $100 per metric ton. By establishing a baseline for feedstock prioritization, this framework informs near-term reclamation investment and resource resilience strategies.

INTRODUCTION

Rare earth elements (REEs), comprising the lanthanide series with scandium and yttrium, are essential to modern technologies, playing a critical role in high-performance magnets, energy-efficient lighting, electronics, electric vehicles, and advanced defense systems.[1,2] The global demand for these metals has increased due to the rapid expansion of energy technologies, digitalization, defense and strategic purposes, and advanced industrial processes.[3,4] Despite their importance, REEs remain subject to supply risks, with their production dominated by a few countries, leading to concerns regarding market stability and resource independence.[2,5,6] The strategic importance and criticality of REEs have been highlighted extensively in recent policy documents and risk assessments, including within the US Department of Energy (DOE), China, and European Union lists of critical raw materials, as well as within the academic literature.[7–9]

Currently, global REE mining production and reserves remain heavily concentrated in limited geographic regions, which causes imbalanced supply and heightened geopolitical risks (Figures 1B and 1C). Analysis of the global rare earth trade network confirms that this concentration extends to trade flows, where 20% of bilateral trade links account for over 80% of total trade volume and dependency relationships have increasingly centered on China since 2006.[10] While trade dynamics are essential to a complete understanding of supply risk, the present study focuses on the complementary technical dimension of feedstock accessibility. Previous work on mapping REE trade flows demonstrates the comparative volume of REEs through their products and end use, for example, showing how catalysts and permanent magnets use significantly more REEs than phosphors or NiMH battery alloys (Figure 1A).[11] Addressing these potential supply chain imbalances necessitates exploration of secondary sources for societal and resource resilience and supply chain independence.

The conventional approach to obtaining REEs relies on extraction methods that can result in material loss through waste streams.[4,13] A considerable portion of REEs extracted from primary resources is lost in byproducts, industrial residues (IRs), and waste streams, creating a potential new source for these critical elements.[14,15] Furthermore, there are few data on the global status of recycling REEs. The last major reporting was from the United Nations Environment Programme in 2011, which showed REE recycling was less than 1% globally.[16] Specifically for REE-based permanent magnets, recent data estimated the collection rate to be less than 5% but with the capacity to increase to up to 10%–15% based on increased use in products.[17]

In response to the increasing criticality and potential supply risks of REEs, attention is shifting toward the reclamation of these elements from unconventional and secondary feedstocks.[18] This shift aligns with resource optimization principles, which advocate for maximizing the value of resources by reusing and diversifying material inputs.[19] The circular economy (CE) approach has evolved to enhance resource resilience and independence in response to geopolitical and trade uncertainty, including supply chain disruptions.[20] Some emerging literature frames the value proposition of CE as a resource resilience strategy for supply chains, as shown in work studying hydrogen technologies[21] and circular supply chains for critical minerals.[18] One analysis of the US found that just over 1% valorization of domestic byproducts is sufficient to replace current reliance on rare earth oxide (REO) imports.[22] Reclamation of REEs from secondary resources, such as industrial byproducts, mining wastes, and end-of-life (EoL) electronics, is a compelling opportunity for both resourcefulness and economic resilience.[23,24]

Potential secondary sources not only serve as substantial reservoirs of REEs but also contribute to responsible resource management associated with mining and primary extraction.[14,24] Elements that are essential to energy technologies, such as neodymium, dysprosium, europium, and terbium, have been identified as especially critical due to their significant use in high-demand sectors and their complex extraction from traditional mineral deposits.[1,14] While primary mining continues to be economically attractive in many regions, the long-term accessibility of REEs requires maximizing reclamation from secondary and unconventional sources, integrating them within closed-loop systems and circular supply chain models.[13,18,25] Mining from secondary sources may also streamline the permitting process and eliminate the need for new infrastructure development, which commonly causes multi-year delays before primary mining sources become operational.

There are several existing REE reviews that explore different extraction and leaching methods in depth. Examples include the beneficiation and extraction for coal products and waste rocks,[26] bioleaching processes,[26] leaching of HREEs,[27] different sorbent materials,[28] recycling of e-waste (WEEE) feedstocks,[3] triple-bottom line sustainability and circularity,[4] recycling REEs from energy systems,[5] preliminary data on secondary feedstock concentration,[29] or dilute REEs in residual wastes and sediments.[30] Therefore, this study does not proffer a duplicate analysis.

"Conventional" critical minerals describe existing deposits with known enrichment processes counted in the current global production base.[31] This work adopts the definitions that "unconventional" sources include both "secondary" byproducts from anthropogenic processes and naturally occurring geological deposits that require valorization efforts beyond the industry standard.[31] The scope of this work focuses specifically on secondary REE feedstocks. Although initial work provides a preliminary mapping of REE concentrations in selected unconventional feedstocks,[29,30] there is no known study that uses a systematic approach to comprehensively examine secondary feedstock potential, nor one that identifies applicable CE strategies. The systematic approach relies on two sets of papers: the manuscript references used for conceptual grounding and academic background and the database of extracted data taken from a larger set of papers.

More information on trace amounts of REEs in products is important for increasing material footprint transparency, facilitating a CE, and guiding emerging research goals.[32] In this study, the REE reclamation strategies are analyzed within a CE framework that emphasizes reuse and remanufacturing, recycling, and recovery. Specifically, reuse and remanufacturing refer to the direct refurbishment and integration of components back into the value chain with minimal chemical transformation. Recycling

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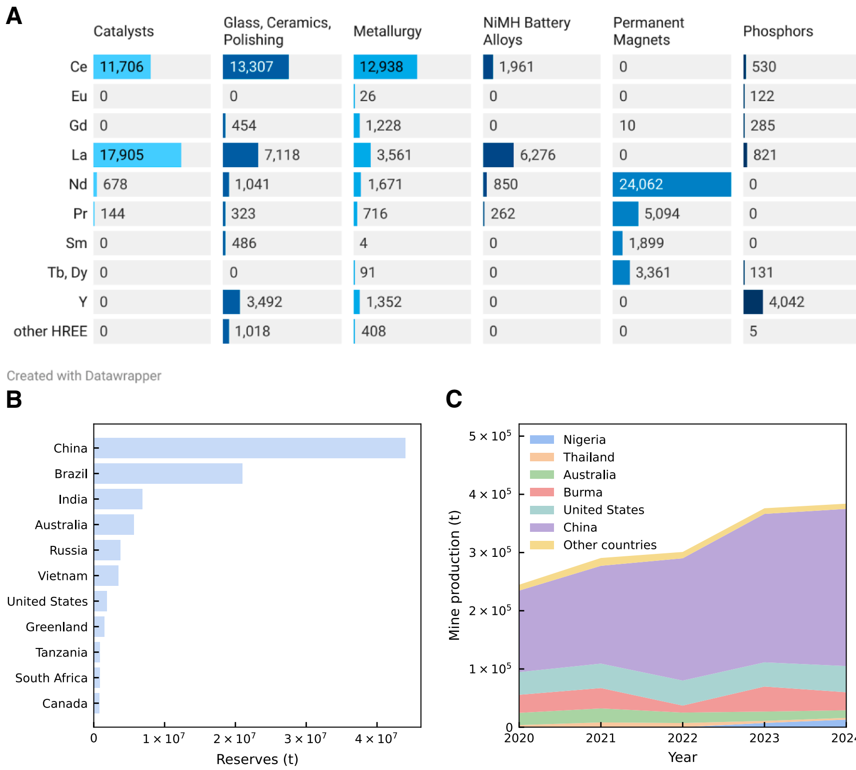

Figure 1. Overview of global REE abundance in current material application and geologic availability

(A) Global REE end uses by product in metric tons.[11]

(B) Global REE reserves in metric tons.[12]

(C) Total REE mining production in metric tons.[12]

All figures were created by the authors with Datawrapper and Python.

involves the extraction and purification of metals from end-of-life products. Recovery encompasses broader strategies aimed at extracting REEs from complex matrices or dilute sources within bulk material streams.[15,25,26] While the full CE hierarchy from reuse through recovery is used as the conceptual frame for this analysis, the quantitative findings are necessarily bounded by what the peer-reviewed literature reports. As shown in the results, documented studies skew heavily toward recovery-tier strategies, reflecting the current state of research rather than a judgment about the relative value of higher-order CE strategies such as reuse and remanufacturing.

This work systematically maps the potential landscape of existing secondary feedstocks for REE reclamation out of recent research, analyzed through the lens of resource optimization principles. Accordingly, the primary research question guiding this study is "how does REE accessibility, defined by elemental concentration, extraction efficiency, and breakeven cost, vary across secondary feedstocks to inform CE resource resilience strategies?"

To evaluate the potential of secondary feedstocks, we define resource resilience as the intersection of resource abundance and economic accessibility. Prior literature and established criticality assessment frameworks have focused primarily on the abundance dimension, evaluating supply risk through geological availability, geopolitical trade flows, regional criticality, and substitutability (Figure 1).[6,11,33] The main contribution of this study is on the complementary accessibility dimension, defined by elemental concentration, extraction efficiency, and breakeven costs for processing across secondary feedstocks. By focusing on these intrinsic technical properties, this analysis provides a universal baseline for feedstock viability that is independent of shifting international trade dynamics or localized supply risks. The work aims to assist policymakers in shaping critical mineral security strategies, help industrial engineers assess secondary feedstocks, and support waste and manufacturing stakeholders in identifying viable reclamation opportunities.

RESULTS

REE concentrations in secondary feedstocks

Across the potential secondary feedstocks for REEs, the results were categorized into the main category and a secondary subcategory. Figure 2 shows the number of samples analyzed per country, a selection of six geographically dependent feedstocks, and the median total REE (TREE) values per country. The main feedstock categories were combustion products (CPs), wastewater (WW), IRs, biogenic sources, and WEEE (Figure 3). The subcategories of the data were further split into IR: lutetium-yttrium oxyorthosilicate (LYSO) crystals, IR: metallurgical slag, IR: phosphogypsum, IR: red mud, IR: mine tailings and waste rock, IR: polishing powder, IR: process tailings and residues, WEEE: permanent magnets, WEEE: batteries, WEEE: lighting phosphors, WEEE: consumer electronics, WEEE: catalytic converters, CP: fly ash, CP: bottom ash, CP: incinerator ash, WW: industrial process wastewater, WW: acid mine drainage, and WW: environmental water sources, biogenic sources, and an "other" category (Figures 3, 4, and S1). Figure S1 reports the median concentration values per REE, and Table S1 also shows the TREE concentration, interquartile range (IQR), and the number of feedstock samples analyzed per feedstock.

For WEEE, Figure 3 reveals that permanent magnets show the highest median concentration of REE, followed by batteries, lighting phosphors, catalytic converters, and consumer electronics. Consumer electronics showed a wider spread and larger IQR due to the variability of products included in the category, which mainly consisted of printed circuit boards, hard disk drives, cathode ray tubes, liquid crystal display screens, and some mobile devices. The preparation of WEEE often includes dismantling and shredding, which is additional labor for the products and can result in large concentration ranges depending on the preparation.

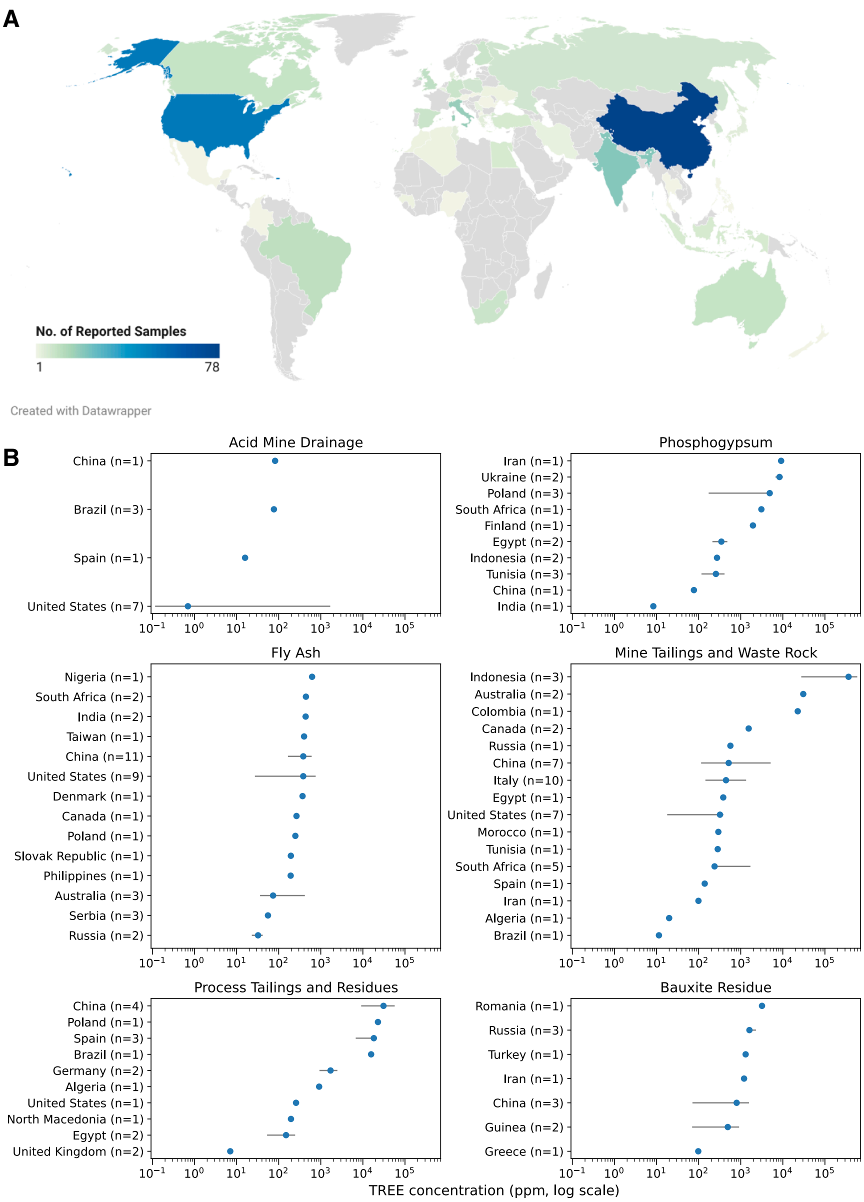

Figure 2. Illustration of the global distribution of secondary feedstocks analyzed within this study

(A) Map of the number of reported feedstock samples from the literature analyzed per country.

(B) Selected geographic-dependent secondary feedstock data are shown against the number of samples analyzed per country. The median TREE concentration data are charted as a dot, with the range of TREE concentration values indicated with the scale bar.

For the IRs, the highest concentration category was process tailings and residues, followed by bauxite residue, metallurgical slag, phosphogypsum, and then mine tailings and waste rock. Mine tailings and waste rock, at a median concentration of nearly 400 ppm, included many different types of geographically dependent minerals (mostly coal refuse and granite waste but also radioactive element mines, tin, gold, and zirconium). The process tailings and residues category is also multivariate and includes industrial treatment sludge, steel-making dust, spent fluid catalytic cracking catalysts, and clay production residues with an approximate median TREE concentration of 2,500 ppm. Bauxite residue also shows a high TREE concentration value of about 1,000 ppm. Ce, La, Nd, and Y were the highest REEs across the IRs. The industrial sand analysis focused on the extraction of scandium from an industrial garnet sand sample and saw a TREE concentration of 652 ppm.[34] Several studies specifically looked at LYSO crystal waste, often used for positron emission tomography (PET) scanners.[35–37] The polishing powders consist of only cerium and lanthanum, as using cerium oxide for glass polishing is known for its high finish quality and efficiency.

For the CPs, the primary category was fly ash, with a few bottom ash and coal ash samples. The median concentration of TREE for CPs is around 300 ppm. Some work has examined incinerator ash from municipal solid waste and found a lower, but not negligible, TREE concentration of about 100 ppm.[30,38]

The typical WW source was acid mine drainage, which showed a relatively low median concentration of TREE of less than 100 ppm, although some studies found TREE concentrations over 1,000 ppm.[39,40] A primary motivation for using acid mine drainage is that it is already a hazardous material, so that extracting REE might be done in tandem with material processing. One study examined produced water (flowback water mixed with subsurface water from oil and gas production) in the Permian Basin and the Eagle Ford formation in Texas but found a TREE concentration of less than 1 ppm.[41]

A few other studies were found to examine unique alternative sources of REEs. These included urine samples from magnetic resonance imaging patients (TREE concentration: 146 ppm),[42] deep-sea polymetallic nodules (TREE concentration: 2,500 ppm),[43] plant fronds that grew at a mining site (TREE concentration not reported),[44] and stormwater retention ponds (TREE concentration: 105 ppm).[45] The number of relevant samples per secondary feedstock, along with the median TREE, light REE (LREE), heavy REE (HREE), and Sc, is shown in Table S1. The data can be compared with the estimated concentration of REEs naturally occurring in the Earth's upper crust.

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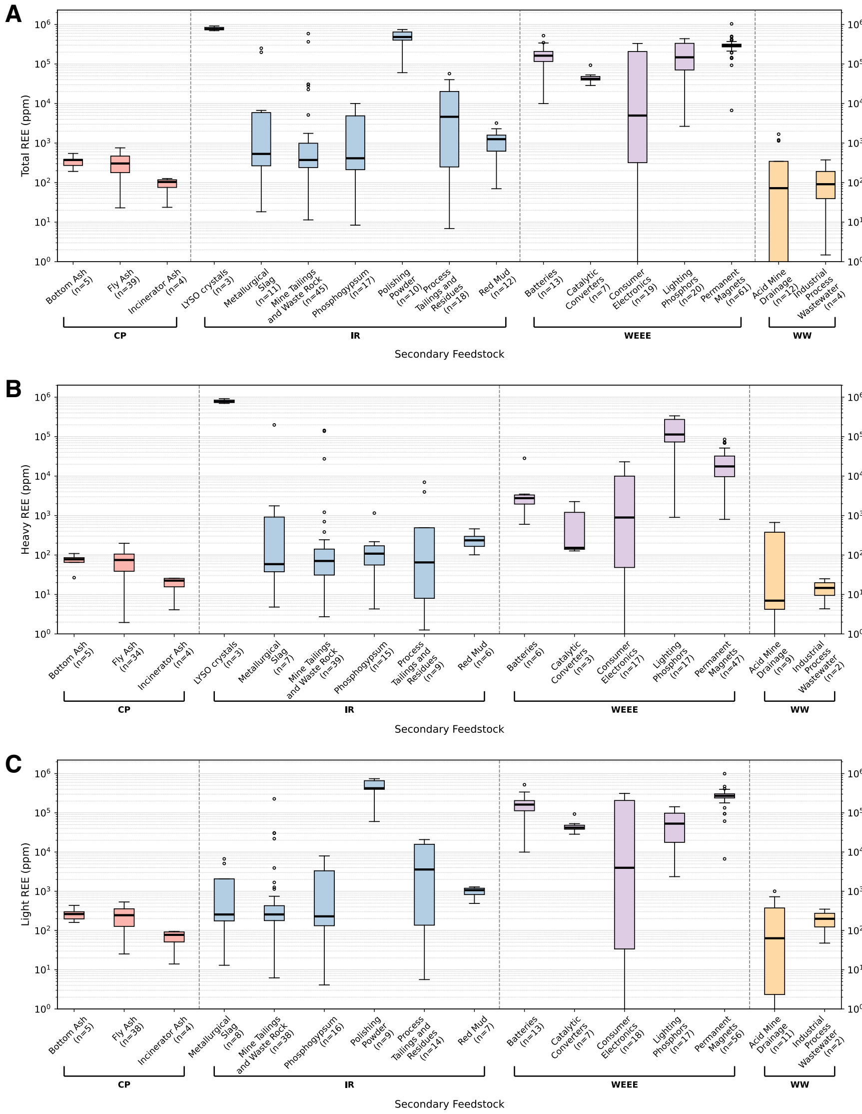

Figure 3. Boxplots of the found concentrations of the total REE, heavy REE, and light REE per feedstock category along a log-scale axis in ppm

The concentration of (A) total REEs (TREEs), (B) heavy REEs (HREEs), and (C) light REEs (LREEs). The median is reported in the center along with the interquartile range. All feedstocks are grouped by their main category (CPs, combustion products; IR, industrial residue; WEEE, waste electrical and electronic equipment; WW, wastewater). Only feedstocks with at least two reported studies are shown in these figures.

REE extraction strategies

Given previous studies that reviewed individual REE extraction approaches in depth, the extraction categorization in this study was kept at a high level to provide directional observations. The categories used included hydrometallurgy (e.g., acid leaching, ion exchange, and solvent/liquid extraction), pyrometallurgy (e.g., high-temperature roasting, plasma, smelting, and metallothermic reduction), biometallurgy (e.g., microbial leaching, bioleaching, and agroleaching), electrometallurgy (e.g., molten-salt electrolysis and electrostatic separation), and physical methods (e.g., magnetic separation and fibers).

The results showing the extraction yield percentage for each extraction method and CE strategy for each feedstock are given in Table 1. The most common approach to extraction is hydrometallurgical. This is typically more selective and results in fewer byproducts. The downsides include hazardous material management associated with the acids, but there are growing alternative approaches using molten salts for extraction.[46] The pyrometallurgical and electrometallurgical extraction studies were mainly for WEEE feedstocks. Pyrometallurgy has lower selectivity for HREEs and often requires subsequent hydrometallurgical purification. Studies that used a combined approach saw higher effective REE yields on average than hydrometallurgy alone.[47–49] Hybrid approaches were used that combined mild acid leaching with ionic liquids or mechanochemical pretreatment. One study reviewed used a solvometallurgical extraction for cathode-ray-tube waste.[50]

Bioleaching is of growing interest to the community because of its passive approach and minimal environmental harm from either acid waste or energy demand. Although bioleaching is less effective and less selective, it also precipitates out more coproducts. The median extraction yield was about 72% using bioleaching approaches and was typically used for WEEE and mining residues. Various fungi and bacteria were used for bioleaching, including *Aspergillus niger*,[51] *Penicillium expansum*,[52] *Helianthusannuus*,[53] *Gluconobacter oxydans*,[54] *Methylorubrum extorquens AM1*,[55] *Lolium perenne* L.,[56] *Acidithiobacillus ferrooxidan*,[57,58] and *Acidithiobacillus thiooxidans*.[59,60]

Resource resilience strategies

The fundamental challenge lies in the cost competitiveness of different CE strategies relative to primary mining. Lower-concentration REE feedstocks frequently require higher extraction costs.[61] It is critical to establish clear cost targets that take into consideration variable extraction efficiency rates and different distributions of REE that change the overall available value. Figure 5 shows the breakeven cost thresholds calculated for each main feedstock category based on feedstock concentration and extraction efficiency.

Breakeven costs represent the maximum allowable extraction cost per metric ton of feedstock that maintains project viability. Feedstocks with higher breakeven costs have better economic

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Figure 4. Median REE concentrations (ppm) by individual element for each secondary feedstock, colored by feedstock category

Feedstocks are sorted by peak element concentration. The *y* axes are independently scaled per image to highlight within-feedstock REE distributions, and the *x* axes show individual rare earth elements (CPs, combustion products; IR, industrial residue; WW, wastewater; WEEE, e-waste).

Table 1. Representative circular economy strategies and extraction methods for selected secondary feedstocks

Secondary feedstock	Extraction yield (%)	CE strategy	Extraction method	*n*
Combustion products				
Fly ash	64.7	recovery-M	hydrometallurgy	11
	64.8	recovery-M	hydrometallurgy; physical	2
Incinerator ash	49.0	recovery-D	hydrometallurgy	2
Industrial residue				
LYSO crystals	97.8	recovery-M	hydrometallurgy	3
Metallurgical slag	83.2	recovery-M	hydrometallurgy	6
	93.4	recovery-M	hydrometallurgy; pyrometallurgy	2
Mine tailings and waste rock	75.8	recovery-E	biometallurgy	5
	53.5	recovery-E	hydrometallurgy	12
Phosphogypsum	96.0	recovery-M	hydrometallurgy	7
Polishing powder	95.3	recovery-M	hydrometallurgy	9
Process tailings and residues	95.0	recovery-D	hydrometallurgy	3
	84.9	recovery-E	hydrometallurgy	3
	56.7	recovery-M	biometallurgy	2
	78.6	recovery-M	hydrometallurgy	4
Bauxite residue	64.2	recovery-M	biometallurgy	2
	64.1	recovery-M	hydrometallurgy	4
E-waste				
Batteries	96.0	recycle	hydrometallurgy	12
Catalytic converters	97.7	recycle	hydrometallurgy	3
	64.9	recycle	hydrometallurgy; physical	2
Consumer electronics	73.8	recycle	biometallurgy	2
	83.6	recycle	hydrometallurgy	6
Lighting phosphors	91.4	recycle	hydrometallurgy	10
	81.6	recycle	pyrometallurgy	2
Permanent magnets	95.4	recovery-M	pyrometallurgy	2
	95.0	recycle	hydrometallurgy	37
	95.0	recycle	hydrometallurgy; pyrometallurgy	5
	99.3	recycle	pyrometallurgy	3
Wastewater				
Acid mine drainage	96.3	recovery-M	hydrometallurgy	4
	97.5	recovery-E	hydrometallurgy	10
Industrial process wastewater	88.9	recovery-M	hydrometallurgy	2

For each feedstock-strategy-method combination, extraction yield is the median of per-sample average REE extraction efficiencies (%), and *n* is the number of samples contributing to that median. Only combinations with two or more measured samples are shown. These data are illustrative of the relative efficiencies of different extraction methods per feedstock.

potential due to higher REE concentrations and basket prices. WEEE and LYSO crystal waste demonstrate the most favorable economics across all scenarios, while CPs and WW-based extraction face the most challenging cost constraints.

While international trade and material abundance dictate immediate market availability and individual countries' strategies, this analysis focuses on the technical metrics of concentration and extraction for the most efficient strategies. REE reclamation feasibility in general exhibits high sensitivity to market conditions and operational parameters. Further work on primary and secondary feedstock-specific revenue projections validates these results, showing that WEEE has high potential and a correlation with REE concentration and price.[62] A study on NiMH battery recycling found feasibility with revenue covering 130% of costs, assuming recycling costs between $2,900 and $3,500 per metric ton.[63] Hard-disk-drive recycling shows favorable economics with a minimum selling price for didymium oxide of $130 per kilogram.[64] However, success depends critically on extraction efficiency and initial concentrations.

The specific industrial process to extract the REEs from the feedstock is irrelevant to the breakeven targets, as this analysis only provides upper thresholds for profitability. We utilize CE strategy nomenclature as a taxonomical aid for the assessment. The CE strategies are largely a function of whether the material is a manufactured product at the EoL or a disposed bulk material from a manufacturing process and at what point along a processing lifestyle the secondary feedstock is accessed (Figure 5).

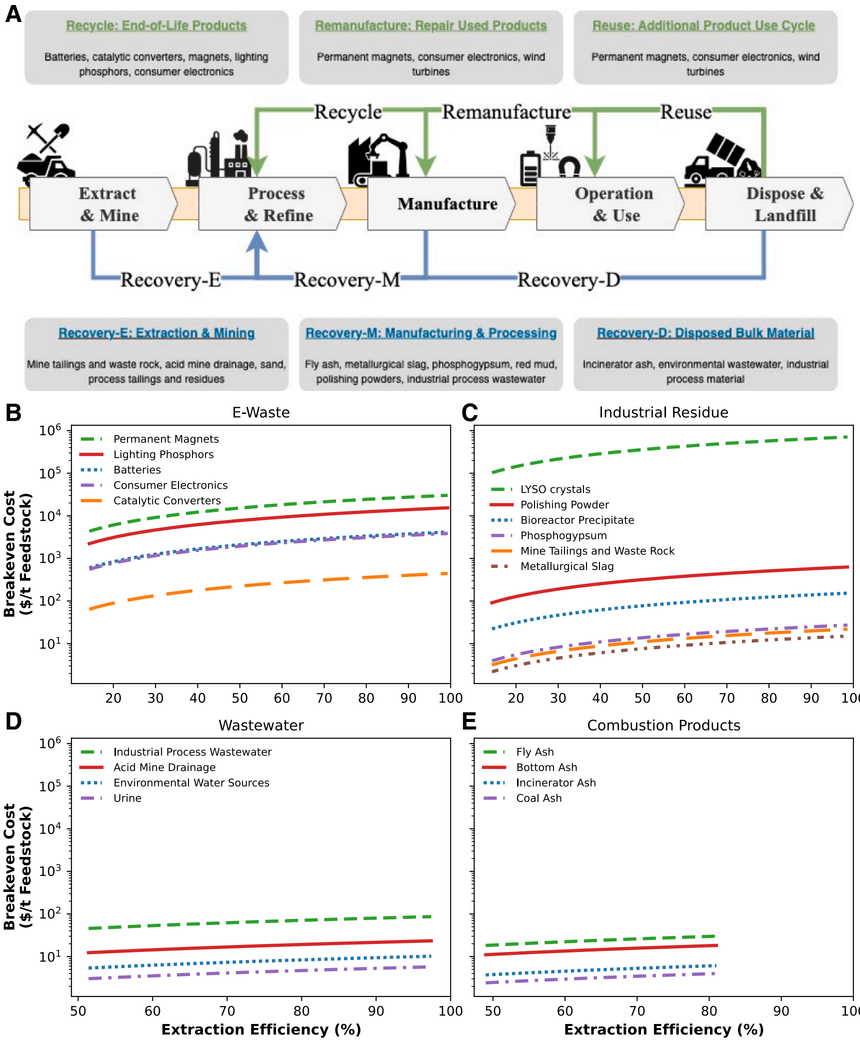

Figure 5. Overview of resource resilience strategies and calculated breakeven costs per secondary feedstock type

(A) Framework of circular economy strategies for REE-containing secondary feedstocks.

(B–E) Breakeven threshold curves defining the maximum allowable processing cost (USD per metric ton of feedstock) to maintain profitability as a function of extraction efficiency, for (B) e-waste, (C) industrial residue, (D) wastewater, and (E) combustion product feedstocks. Thresholds are derived from the median REE concentration per feedstock and the oxide-adjusted average basket price per REE. The *y* axes are log scaled to illustrate the order-of-magnitude differences in economic viability across feedstock categories.

Among academics in CE, there is consensus on a hierarchy of strategies within a 10-R framework, ordered by relative effectiveness in keeping materials in use for longer and closing the material loop.[19] The CE strategies found relevant for REE applications are positioned as lower in the hierarchy, indicating inherent material value loss upstream and up to the point of intervention. Figure 5 shows the CE strategies applicable to REEs at different life cycle stages and the categories of feedstocks that have been identified. The specific CE strategy for each feedstock is analyzed separately, along with the extraction method, in Table 1.

Recovery is a unique CE strategy. In popular CE literature, the recovery strategy often refers to energy recovery when incinerating material with no other potential use,[19] but this work defines three distinct subcategories of recovery for obtaining REEs from a bulk material stream.[32] Figure 5 demonstrates recovery-D (disposed bulk materials' EoL), recovery-E (residues and byproducts from extraction and mining waste streams), and recovery-M (residues and byproducts from manufacturing and processing waste streams). Recovery-M typically includes CPs, metallurgical slag, phosphogypsum, industrial process material, bauxite residue (red mud), and industrial process WW. Recovery-E typically includes mine tailings and waste rock, process tailings and residues, and acid mine drainage. Lastly, recovery-D typically includes incinerator ash and some IRs.

There were very few documented instances of the reuse and remanufacturing of REE-containing products. Reuse constitutes the direct reuse of a discarded product that is still in good condition, and remanufacture is the use of parts from a discarded product in a new product with the same function.[19] The few studies that explicitly mentioned reuse were from simulation studies that looked at material flow analyses and life cycle assessments. Reuse and remanufacturing strategies most often occur in WEEE products such as permanent magnets and consumer electronics. One study that specifically examined the remanufacturing of NdFeB magnets focused on applications in wind turbines.[65] Largely, the consensus view in the literature is that most of the WEEE studies focus on disassembly for material reclamation rather than true remanufacture or reuse of the product.

Recycling can be defined as processing materials to obtain the same, or lower, quality.[19] In this work, recycling implies an industrial process used for EoL products after their use. Because of this definition, the recycling strategy is used extensively for WEEE feedstocks. For example, rare earth magnets go through different levels of processing to be useful again. Recycling of magnets can occur at the base-material level, through focused element recycling, or through whole-magnet recycling. Thus, sometimes, the phrasing of recycling whole magnets or remanufacturing becomes blurred.

Taken together, the three-metric framework reveals a clear stratification of secondary feedstock viability. WEEE feedstocks, and permanent magnets in particular, occupy a dominant

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position across all three dimensions: highest REE concentration, highest documented extraction efficiency, and the widest margin for economically viable processing costs. Critically, permanent magnets and lighting phosphors also concentrate the elements of greatest strategic concern, including neodymium, dysprosium, praseodymium, and terbium, which are simultaneously high demand, high supply risk, and high value. This convergence of concentration, extraction maturity, and element criticality makes WEEE the most compelling near-term target for CE investment. IR feedstocks such as LYSO crystal waste exhibit even higher absolute concentrations but are limited in scalability by their narrow industrial origin. IRs occupy a middle tier, where high extraction efficiencies are achievable but break-even costs constrain viability of feedstocks with TREE concentrations not reliably above 1,000 ppm. CPs and WW sources face cost constraints that preclude standalone REE extraction in most scenarios without byproduct co-valorization. These findings suggest that near-term CE investment should focus on WEEE recycling infrastructure and LYSO crystal recovery, while the longer-term viability of bulk IRs depends on advances in low-cost extraction and integrated zero-waste processing models.

DISCUSSION

Maximizing resource recovery and minimizing waste

Efforts to build robust supply chains for REEs often focus on maximizing resource resilience through recycling, reuse, and efficiency, thereby reducing their input. However, this narrow approach tends to ignore the large volume of material discarded after REE extraction. The semantic difficulties of a zero-waste scheme are the distinction between waste and byproducts and whether the resulting material has value, which is a contextual definition.[66] Although the aspirational goals of a CE with no energy and material waste are limited by entropy, the identification and utilization of high-value material streams construct a compelling argument for implementation.

This principle is exemplified by CPs and related IRs, in which post-extraction residues rich in silica, alumina, and other compounds can be transformed into value-added materials, creating a recovery pathway that maximizes resource utilization alongside critical metal extraction. Compared with other feedstocks, CPs often have a lower amount of TREEs, while they have relatively high percentages of La, Ce, Nd, and Y. Several studies have demonstrated that after leaching of REEs from CPs, the remaining SiO_2-rich residue can be converted into value-added products. Alkaline extraction followed by acid precipitation yields reactive amorphous silica, suitable for use in cement, ceramics, or silica gel production.[67,68]

Other wastes such as alumina (Al_2O_3), iron oxides, and calcium/magnesium compounds can be utilized in advanced applications such as catalyst supports or cement and construction materials.[69,70] A recent example of zero-waste implementation can be found in the processing of deep-sea polymetallic nodules. After sulfur dioxide-based reductive leaching and subsequent separation, valuable metals are reclaimed, and the silica-based leach residue, which exhibits low leaching toxicity, is proposed for repurposing as a construction material.[43] This approach supports efficient resource management, reduces disposal needs, and generates secondary revenue streams that can offset processing costs.

Successful business models require concentrated feedstock sources with predictable composition, such as data center WEEE or industrial waste streams. An Italian quarry waste analysis, with historical stockpiles valued at 7–26 million EUR,[71] demonstrates how co-location with existing operations may provide cost efficiencies. Revenue from multiple elements and recycling of the solvent also drives feasibility by reducing net extraction costs.[64] With improved logistics, dysprosium recycling alone might reduce global raw material demand by 75%.[72]

The typical waste from REE extraction can serve as an input into another high-volume supply chain, such as infrastructure or building materials. However, the challenges that arise from any waste-stream utilization occur with path-dependent lock-in. The identification and use of secondary feedstocks for REEs and their byproducts necessitate the continued availability of the initial feed, which is not guaranteed.[66] Revenue projection models of primary and secondary feedstocks, using Monte Carlo analysis, demonstrate that profitability is driven primarily by REOs, with coproducts constituting a smaller portion of revenue.[62] A waste-utilization strategy takes a broader view by aiming to profitably use the entire feedstock, finding extractable value from REEs, critical minerals, and residual materials. Rather than discarding residues, it keeps all materials in use, closing material loops.

Feedstock composition profiles and byproducts

The compositional diversity of secondary feedstocks is essential for evaluating their potential not only in REE extraction but also associated byproduct valorization. This analysis calculated the breakeven cost based on the REE values alone. However, little research has been done to assess the added potential of additional byproducts from secondary REE feedstocks. For each of the studies analyzed, the coproduct or byproduct profile was assessed to identify trends of association between feedstock, REE, and potential residual elements of value (Figure S2). These findings could further enhance the value of the secondary feedstocks.

Comparative analysis of datasets demonstrates that WEEE offers the most extensive profile of co-recoverable elements across all feedstocks examined, supporting critical applications from electronics manufacturing to renewable energy technologies (Figure 5). Permanent magnets within electronic waste contain high concentrations of iron, boron, and cobalt, the most frequently co-recovered elements reported.[47,73] Other subcategories, such as consumer electronics, contribute indium, erbium, silver, and gold,[74,75] while lighting phosphors and catalytic converters produce additional high-value elements, including platinum, palladium, manganese, and zirconium.[76] For instance, cobalt in lithium-ion batteries and copper in circuit boards can be efficiently dissolved using sulfuric or nitric acid and subsequently extracted via solvent extraction or electrometallurgy.[77–79] This compositional heterogeneity makes WEEE a uniquely attractive feedstock for critical material reclamation.

IRs, CPs, and WW-derived sources generally contain lower concentrations of REEs compared to electronic waste but exhibit relatively higher abundances of trace elements. IRs such as mine tailings, bauxite residue, and phosphogypsum show high variability in both composition complexity and by-product content. These feedstocks contain a wide range of trace elements, including vanadium, chromium, antimony, cesium, titanium, or sometimes radioactive components such as uranium and thorium.[80–82] Combustion byproducts, particularly fly ash, are characterized by substantial amounts of iron, aluminum, and manganese, along with trace levels of strontium, lead, and titanium.[83–85] WW-derived sources, such as acid mine drainage, can yield gold, thorium, uranium, or silicon.[86–88] Ultimately, IRs have considerable geospatial variation in concentration and abundance due to their geographic origins (Figure 2).

Valorizing byproducts can also reduce hazardous waste volumes and improve economic viability, including aluminum from acid mine drainage.[89] One study examined the hydrometallurgical extraction of lanthanum from spent fluid catalytic cracking catalyst. The researchers were able to extract about 86% of the initial 6,755 ppm of lanthanum in the material, as well as extract aluminum.[90] In addition, on account of the percentage of oxides being higher than required for fly ash substitution in cement, the researchers also produced mortar samples for testing with the initial spent catalyst and the solid leached residue. While some secondary feedstocks, such as fly ash, offer relatively high concentrations of certain major and trace elements, others, such as acid mine drainage, provide access to rare and high-value elements but in lower volumes. An optimized feedstock valorization strategy can mitigate environmental impacts, reduce landfill burdens, and advance CE objectives.

Industrial barriers and recommended future work

Despite growing recognition of the need for advanced REE resource-recovery approaches, the transition from laboratory demonstrations to industrial implementation faces barriers that limit economic viability. These barriers operate across multiple scales, echoing broader CE implementation challenges.[91] A more complete resource-recovery strategy for REEs would target upstream reclamation stages to minimize material loss.[19]

Industrial infrastructure gaps are a significant barrier. Hard disk drive recycling in the US is economically limited by high material loss, long-distance transport costs, and lack of processing infrastructure.[92] The absence of localized processing capacity forces reliance on international supply chains that undermine economic viability. REE market volatility, combined with small-scale operations, creates substantial business risk. The lack of an established collection infrastructure limits feedstock quality and availability, reducing extraction efficiency. These barriers mirror broader CE studies in which low virgin material prices and high upfront investment costs emerge as primary impediments.[91] Future studies should explore existing and possible take-back schemes, reverse logistics, and circular business models for REE sources.

The limited techno-economic analyses available usually focus on WEEE feedstocks, reflecting both the higher REE concentration in electronics and the nascent development of other pathways. Most recycling technologies remain at a low technology readiness level (TRL). One study from Spain examined acid mine water separation and achieved a TRL of 5.[93] Studies on supercritical fluid extraction and bioleaching approaches of NdFeB magnets often assume a TRL of 4.[94,95] The technological immaturity creates investment uncertainty and limits proven, scalable solutions. However, recent technological advances, such as flash Joule heating, demonstrate cost savings and reductions in energy consumption and water and acid use.[96,97] In addition, supporting not only lab-scale but also industrial-scale innovation can strengthen supply chain resilience.[98] This is further evidenced by the deficit of high TRL technologies found for REE extraction from secondary feedstocks.

To preserve REE in a useful life cycle stage, more studies should be conducted on extending the life cycle of REE-containing products before EoL processing. Resource-recovery strategies that prioritize reuse, remanufacturing, and refurbishing of REE-containing products, or reducing REE use by maximizing efficiency, should receive more attention.[20,66] There appears to be little work on CE strategies on the consumer side of REE use, as most studies address the potential at the production level. This might be addressed by targeted industrial initiatives for REE-containing products that encourage product longevity (e.g., right to upgrade) and efficient material recovery.[98] Industrial policy approaches for the bulk industrial materials could include production standards for re-looping waste, differentiation of waste streams, or definitions and treatment requirements for waste management facilities.[98]

Lastly, incorporating AI and maturing technologies may unlock research and industrial opportunities for access to REEs. AI could be used to map existing feeds using supply chain data, project raw feed data, or predict new promising feeds based on market parameters. Similarly, AI may suggest the best extraction method based on learned process parameters from existing studies.

Achieving necessary scale and coordination for a CE for REEs will require coordinated policy interventions and public-private partnerships to subsidize the economic gap and scale these technologies.[32,98] Where this work assessed the technical accessibility of REEs, it should be supplemented with resource abundance analyses to form a full resource resilience strategy. Resource resilience and domestic production strategies are important for securing REEs critical to advanced technologies, which should be supported by an understanding of which feedstocks currently exist and what opportunities hold promise for the future.

METHODS

Data extraction

This study was conducted using a quantitative systematic literature review, as in other papers.[99,100] This approach is systematic in the selection of papers but uses quantitative analysis to report results rather than narrative analysis. This approach allows quantitative trends to be drawn from each selected paper and is complemented by a narrative analysis of a subset of the papers. Therefore, there is a distinction between manuscript references that provide the conceptual foundation and the extraction database of papers used for quantitative mapping and analysis.

Using Scopus as the database of published works, the search was for original research articles (i.e., peer reviewed) published in English within the 10 years leading up to April 16th, 2025.

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The following search string was used in Scopus: (TITLE-ABS-KEY ("rare earth*" OR "REE") AND TITLE-ABS-KEY ("secondary sourc*" OR "alternative sourc*" OR "secondary feedstock*" OR "alternative feedstock" OR "end-of-life" OR "end of life" OR "scrap" OR "waste") AND TITLE-ABS-KEY ("recycl*" OR "reuse*" OR "remanufactur*" OR "recover*" OR "Circular Economy") AND TITLE-ABS-KEY ("extraction" OR "processing" OR "material flow" OR "co-product*" OR "by-product*" OR "by-product*" OR "resource potential" OR "logistic*" OR "supply chain") AND NOT TITLE-ABS-KEY ("primary mining" OR "ore mining" OR "virgin material*" OR "primary extraction")) AND PUBYEAR >2014 AND PUBYEAR <2026 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar")). These terms were selected to find papers that allude to CE practices for REE by using secondary feedstocks.

The initial results provided 848 papers that were uploaded into the software Covidence. One author performed the initial identification of relevant papers that measure, analyze, model, or predict the amount of REEs from some secondary source through the title and abstract screening. 180 papers were initially deemed irrelevant. The authors further removed papers published before 2020 to focus on publications that report recent concentration and extraction data. There remained 407 papers for two authors to conduct an independent full-text review based on the exclusion criteria listed below.

- Critical minerals (that are not REEs).
- Virgin, primary, or raw ore and materials for REEs.
- Focuses only on optimizing a part of the process or developing a new leaching, enriching, or separation technique.
- Uses proxy liquors (simulated mixtures) that do not test using the secondary feedstock.
- Suggests, without testing, their method could be used for secondary feedstock.
- Review papers.

Both authors had to agree for a manuscript to move to data extraction. Many studies were excluded at this point because the research used synthetic feedstocks rather than raw secondary feedstocks. Additional reasons for exclusion included the wrong study design or output irrelevant to this work or the discovery of a review paper or a non-peer-reviewed paper. After all exclusions, the final list included 305 papers (Figure S3).

The next step was to extract the relevant data from each publication, which was performed by one author and checked by another. The extraction template was designed by the authors following the initial screening steps. The data of interest included bibliometric information, research type and geographical basis, identification of up to three unique feedstock samples, extraction type, extraction yield efficiency, potential co/byproducts, economic notes, CE notes, and logistical notes. The REE concentration data are thus usually primary data generated by the researchers when characterizing the feedstocks. Some papers only had life cycle assessments or material flow analyses and did not provide feedstock concentration data. Most papers examined only one sample of a single feedstock, but a few examined multiple samples. If more than three feedstock samples were characterized in the same study, the data were averaged per type and reported in the extraction template.

A major challenge in this work is the variety of ways researchers might report initial feedstock concentration. This would depend on the nature of the feedstock itself but could be reported as a percentage of the mass of the REO or the volumetric results from inductively coupled plasma mass spectrometry. The data were normalized to an elemental ppm mass basis when possible; otherwise, the study was kept but the data were not included, for example, in instances of reporting aqueous solution concentration used for mass spectrometry. The general lack of homogeneity in the reporting of experimental procedures and results makes formal comparison between studies difficult.

REE analysis

The extracted data were then cleaned and analyzed using Python. The full dataset was split into subsets based on whether they included specific data of interest, such as the inclusion of an economic analysis, and were pulled out for analysis. If papers had two or three feedstocks, the entry row was duplicated or triplicated in kind so that each entry reported data for only one feedstock. Life cycle stages used in this work follow common conventions used in similar work.[32] The units were normalized to ppm for the concentration for each feedstock and summed into HREE, LREE, scandium, and TREE categories. This work considers HREEs to include gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and yttrium. LREEs include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, and europium. Scandium has a low atomic weight and is typically removed from groupings, whereas yttrium is grouped with HREEs because of its similar ionic size and chemical properties.[11,33] Multiples of feedstocks in the "other" category were condensed into singular feedstocks. Lastly, individual data frames and comma-separated value files were extracted for independent visualization. When values are reported for sub-samples, the median is used to mitigate outliers in each feedstock.

Economic assessment

Established REE concentrations and extraction yield ranges for each secondary feedstock are used to develop informed targets for the cost of REE extraction for each feedstock. We define the breakeven cost, C_{BE} ($/t feedstock), as the maximum allowable levelized cost of recovery (i.e., extraction processing) for the project to maintain economic viability. This means that recovery costs up to the breakeven point should be profitable based on prices for the constituent REEs and ignoring potential value from coproducts. This work does not calculate any specific levelized cost of recovery, which is the sum of annualized total capital, annual fixed operating and maintenance costs, and annual variable operating costs divided by the annual feedstock processed.[101] Individual techno-economic analyses for specific processes per feedstock could determine whether the levelized cost of recovery exceeds the breakeven costs.

The breakeven cost for a given feedstock f equals the value contained in the REE extracted per metric ton of feedstock, computed as the product of the rare earth concentration C_{REE} (ppm), the basket price P_B ($/kg REE), and the extraction efficiency percentage R (%); see Equation 1. The basket price P_B is the composition-weighted sum of individual metal prices $P_{m,i}$, calculated as the 3-year average of REO prices reported by the USGS from 2023 to 2025 divided by the metal-to-oxide ratio[33] and the fraction of REE i per kilogram of TREE, $f_{REE,i}$ (Equation 2; Table S2). REE prices exhibit significant historical volatility, and the breakeven thresholds should be interpreted as indicative rather than prescriptive.

$$C_{BE,f} = C_{REE,f} \cdot P_{B,f} \cdot R \quad \text{(Equation 1)}$$

$$P_{B,f} = \sum_i P_{m,i} \cdot f_{REE,i} \quad \text{(Equation 2)}$$

Limitations of the study

There are some limitations resulting from the research method and analysis used in this work. Although a systematic review aims to reduce bias in its curation and selection of literature, inherent prejudice exists in the selection of databases and key terms used for filtering. In addition, review papers, gray literature, conference papers, preprints, and commentaries were excluded from analyses. The papers reviewed were only those published in English. Critically, the categorization of feedstocks was broad, given the expansive nature.

The accessibility framework presented here ranks feedstocks by technical extraction potential per metric ton of material, not by total available mass. High-volume feedstocks such as CPs and mine tailings may represent larger absolute REE reservoirs than production-adjacent IRs, and low-grade but high-volume streams may still contribute meaningfully to total recoverable REEs once abundance data are integrated.

For example, global coal fly ash has an annual production of over 750 million metric tons worldwide,[97] whereas LYSO crystal waste is a niche industrial product missing aggregate volume estimates and illustrates the importance of scale for per-ton accessibility rankings. A complete resource resilience assessment should therefore complement this per-ton accessibility analysis with region-specific volume and reserve estimates, linked to established criticality frameworks that incorporate geographic concentration, substitutability, and price volatility.[6] Supplementary work on discrete, but scant, feedstocks in categories such as process tailings and residues should also be conducted.

This framework also does not address downstream separation and purification to application-grade purity, which remains a bottleneck concentrated in specific regions. The geographic concentration challenge for REEs extends beyond mining to refining and separation, and the purity of extracted rare earth products directly impacts their uptake in supply chains. Additionally, the breakeven cost data are sensitive to market volatility and the country of reference, so these thresholds should be interpreted as indicative rather than prescriptive.

Nevertheless, the recency of this work supplements previous attempts to map feedstocks from earlier literature[29] and includes significantly more samples and feedstocks. Although two authors were involved in the selection, extraction, checking of final data, and cleaning and analysis of data, human error may contribute to errors in the analysis. Discrepancies were resolved by the two checkers through discussion after initial selection.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Qingxu Jin (billjin@msu.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

The extracted REE data have been deposited at Mendeley Data and are publicly available as of the date of publication at https://doi.org/10.17632/y9dbgc6th7.1.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.S.B., Y.T., F.S., and Q.J.; methodology, B.S.B. and Q.J.; investigation, B.S.B., Y.L., and Q.J.; data curation, B.S.B., Y.L., D.A., and A.G.F.; formal analysis, B.S.B., Y.L., and A.G.F.; software, B.S.B.; visualization, B.S.B., A.G.F., and Q.J.; writing – original draft, B.S.B., Y.L., A.G.F., and J.K.; writing – review & editing, B.S.B., Y.L., D.A., A.G.F., J.K., Y.T., F.S., and Q.J.; supervision, Q.J.; project administration, Q.J.; funding acquisition, Q.J.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used Claude in order to increase the clarity of the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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