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Advancing Strategic Resource Independence through E-Waste-Based Critical Material Recovery in the U.S.

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Abstract: This scoping review explores how domestic e-waste recovery technologies and infrastructure can advance U.S. strategic resource independence by enabling the recovery of rare earth elements (REEs) and critical materials. This study synthesizes recent literature (2020-2025) to assess technological innovations, such as hydrometallurgical, biohydrometallurgical, and hybrid processes, alongside policy mechanisms, market dynamics, and industrial capacity. Using a PRISMA-ScR-guided approach, the review identifies 25 peer-reviewed studies and authoritative reports addressing recovery technologies, infrastructure, and policy frameworks. Findings indicate that emerging technologies offer promising pathways for sustainable recovery; however, scalability is constrained by infrastructure gaps, regulatory disparities, and market uncertainties. Federal initiatives, including the Infrastructure Investment and Jobs Act and Inflation Reduction Act, coupled with innovation incentives and public-private partnerships, are driving progress toward circular economy frameworks and supply chain resilience. The review concludes that harmonized standards, sustained R&D investment, and strategic procurement commitments are essential for integrating recovered materials into U.S. manufacturing. Future research should focus on techno-economic modeling, lifecycle assessments, and policy instruments that enable large-scale deployment within circular economy frameworks.

Keywords: E-Waste, Rare Earth Elements, Critical Materials, Recycling, Industrial Policy.

INTRODUCTION

The accelerating demand for rare earth elements (REEs) and strategic metals in advanced manufacturing, clean energy technologies, and defense systems has underscored the vulnerability of U.S. supply chains. Rare earth elements (REEs) refer to a group of 17 chemically similar metallic elements, including the 15 lanthanides plus scandium and yttrium, which are critical for producing high-performance magnets, batteries, catalysts, and electronic components (Liang *et al*., 2024). These materials are indispensable for electric vehicle motors, wind turbines, semiconductors, and critical defense applications, yet the United States remains heavily reliant on foreign sources, particularly China, which accounted for approximately 69% of global REE mine production in 2023 and over 90% of permanent magnet manufacturing in 2022 (Perry & Van Veen, 2024). This concentration of supply poses significant risks to national security, economic resilience, and the timely deployment of low-carbon technologies.

E-waste, comprising discarded electronic devices rich in REEs and strategic metals, represents a largely untapped domestic resource. Global e-waste generation reached 53.6 million metric tons in 2019 and is projected to reach 74.7 million metric tons by 2030, yet only 17.4% was recycled globally in 2019 (Quinto *et al*., 2025). Within the U.S., emerging technologies such as hydrometallurgical and biohydrometallurgical processes, alongside AI-driven sorting and robotics, have demonstrated promise for improving recovery efficiency and reducing environmental impacts (Dada *et al*., 2025; Quinto *et al*., 2025). However, scalability, cost-effectiveness, and integration into existing industrial systems remain critical challenges.

Recent federal initiatives signal a strategic pivot toward domestic resource recovery. The Department of Energy (DOE) has committed nearly $1 billion through programs under the Infrastructure Investment and Jobs Act to accelerate recycling, processing, and supply chain resilience for critical materials, including REEs (DOE, 2025a). Complementary funding opportunities, such as the “Critical Materials Innovation, Efficiency, and Alternatives” program, aim to foster technological innovation and market development by supporting projects that extract critical materials from recycled materials and industrial waste streams (DOE, 2025b). These efforts align with broader policy objectives to reduce import dependence, strengthen national security, and advance clean energy and manufacturing goals. This review makes a distinct contribution by integrating technological, infrastructural, policy, and market dimensions into a unified analytical framework, providing a systems-level perspective that is currently underrepresented in the existing e-waste and critical-materials literature.

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Against this backdrop, this review evaluates the role of domestic e-waste recovery technologies and infrastructure in securing access to REEs and strategic metals. It further examines how innovation incentives, federal industrial policy, and market development can collectively mitigate supply chain vulnerabilities. By synthesizing recent academic research (2020-2025), this study situates e-waste-based recovery within the U.S. strategic resource independence agenda, identifying technological, policy, and economic pathways for scaling sustainable solutions.

METHODOLOGY

This review adopted a scoping approach to map and synthesize academic literature on domestic e-waste recovery technologies and infrastructure for rare earth elements (REEs) and strategic metals in the United States. The review followed the PRISMA-ScR guidelines to ensure transparency and rigor (Tricco *et al*., 2018).

The search strategy targeted four major databases; Scopus, Web of Science, IEEE Xplore, and ScienceDirect, using Boolean strings that combine keywords such as *e-waste*, *rare earth elements*, *critical materials*, *recycling*, and *industrial policy*. For example, the Scopus query included: *(TITLE-ABS-KEY("e-waste" OR "electronic waste") AND TITLE-ABS-KEY("rare earth elements" OR "critical materials") AND TITLE-ABS-KEY("recycling" OR "recovery") AND TITLE-ABS-KEY("industrial policy" OR "innovation incentives") AND PUBYEAR ≥ 2020 AND PUBYEAR ≤ 2025)*.

Eligibility criteria focused on peer-reviewed articles, systematic reviews, and empirical studies relevant to U.S. or comparable economies. Authoritative grey literature, such as government reports and policy briefs, was included where necessary to address gaps in the peer-reviewed evidence base. Studies without relevance to REEs or strategic metals were excluded.

Screening and selection followed a structured process: 220 records were initially identified, 80 duplicates removed, and 140 titles and abstracts screened. 40 full-text articles were assessed, with 15 excluded, resulting in 25 final articles for inclusion. Data extraction captured technology type and readiness level, infrastructure capacity, policy instruments, and market indicators. Thematic synthesis was applied to identify patterns across technological, policy, and market dimensions.

This review relied minimally on authoritative government sources (e.g., DOE, EPA) for factual descriptions of policy initiatives and infrastructure assessments, while analytical claims were supported primarily by peer-reviewed literature to ensure rigor. Limitations include the focus on English-language sources and potential publication bias within the 2020-2025 literature.

Technological Landscape: Current and Emerging E-Waste Recovery Technologies

The recovery of rare earth elements (REEs) and strategic metals from e-waste has emerged as a critical pathway for strengthening U.S. resource independence and reducing reliance on primary mining. Recent studies highlight a spectrum of technologies, both conventional and emerging designed to optimize extraction efficiency while minimizing environmental impacts (Ambaye *et al*., 2020; Liang *et al*., 2024; Phogat *et al*., 2025).

Conventional recovery methods, such as hydrometallurgical and pyrometallurgical processes, remain dominant in industrial applications. Hydrometallurgy, which involves acid leaching and solvent extraction, achieves recovery efficiencies of up to 95% for certain metals but is associated with high chemical consumption and secondary waste generation (Phogat *et al*., 2025). Pyrometallurgical techniques, while effective for bulk recovery, are energy-intensive and emit greenhouse gases, limiting their sustainability profile (Ambaye *et al*., 2020).

Emerging green technologies seek to address these limitations. Biohydrometallurgical processes, which employ microorganisms to leach metals from e-waste substrates, offer a 30-50% reduction in environmental impact compared to conventional chemical leaching, though scalability remains a challenge (Magoda & Mekuto, 2022). Other promising approaches include ionic liquid extraction and supercritical fluid extraction, which reduce hazardous reagent use and improve selectivity (Liang *et al*., 2024; Ioannidis *et al*., 2024). Biomimetic strategies, such as lanmodulin-derived peptides for selective REE recovery, represent innovative solutions for improving separation efficiency (Liang *et al*., 2024). Hybrid systems that integrate biohydrometallurgical processes with optimized chemical extraction have also demonstrated potential for achieving higher recovery rates (Dada *et al*., 2025).

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Despite these advances, industrial-scale deployment in the U.S. faces significant barriers related to cost, infrastructure, and regulatory compliance. The absence of domestic smelting capacity and limited dismantling facilities further constrain the integration of advanced recovery processes into existing supply chains (Van Nielen *et al.*, 2024; Deng *et al.*, 2025). Comparative assessments indicate that hydrometallurgical systems are closest to near-term commercialization, while hybrid and biohydrometallurgical methods hold greater long-term sustainability potential but require substantial R&D investment to overcome kinetic, cost, and scale limitations. These technological developments underscore the need for coordinated infrastructure and policy support to enable widespread adoption.

Table 1. Comparative Overview of E-Waste Recovery Technologies by Readiness Level, Environmental Impact, and Scalability Challenges

Technology	**Readiness Level**	**Environmental Impact**	**Scalability Challenges**
Hydrometallurgical	High (near commercialization)	High chemical use; secondary waste	Requires large-scale chemical handling
Pyrometallurgical	High (industrial use)	High energy consumption; Greenhouse Gas emissions	Energy-intensive; costly infrastructure
Biohydrometallurgical	Low-Medium (lab scale)	30-50% lower impact vs. chemical leaching	Slow kinetics; limited industrial trials
Ionic Liquid Extraction	Low (experimental)	Reduced hazardous reagents	High cost of ionic liquids; limited scale
Hybrid Systems	Medium (pilot scale)	Improved efficiency; moderate impact	Complex integration; high R&D needs

Infrastructure and Industrial Capacity for E-Waste Recovery in the U.S.

The effectiveness of domestic e-waste recovery for rare earth elements (REEs) and strategic metals depends heavily on the availability and scalability of processing infrastructure. Despite technological advancements, the U.S. recycling ecosystem faces structural and logistical challenges that limit its ability to integrate recovered materials into critical supply chains (Deng *et al.*, 2025; Van Nielen *et al.*, 2024; EPA, 2024).

Current infrastructure lacks cohesion, with few large-scale facilities capable of processing REE-rich components such as NdFeB magnets and lithium-ion batteries. Most existing systems are designed to recover base metals, offering limited capacity for advanced separation and processing of critical materials. This gap perpetuates reliance on foreign refining capabilities and constrains domestic supply chain resilience.

Integration of recovered materials into manufacturing supply chains is further hindered by logistical inefficiencies and insufficient dismantling and refining facilities. For example, magnet-to-magnet recycling of NdFeB magnets could significantly reduce import dependence, yet commercial adoption is limited by inadequate infrastructure and high transportation costs (Perry & Van Veen, 2024). These inefficiencies make domestic recovery less competitive compared to imported materials, underscoring the need for coordinated regional processing hubs and standardized logistics networks to ensure consistent feedstock flow.

Federal investments have begun addressing these gaps. The Department of Energy announced $19.5 million in funding to advance technologies for recovering critical materials from secondary sources, including e-waste, as part of its broader strategy to secure domestic supply chains (DOE, 2024). Additional programs under the Bipartisan Infrastructure Law have allocated nearly $1 billion to expand recycling and processing capacity for critical materials (DOE, 2025). These initiatives signal a policy shift toward circular economy frameworks and resource independence, though implementation timelines and scalability remain uncertain.

Significant challenges to infrastructure development include high capital intensity for advanced recovery facilities, regulatory fragmentation across states, and market uncertainty driven by weak demand signals for recycled REEs (Dada *et al*., 2025; Norgbey & Cudjoe-Mensah, 2025). Overcoming these challenges will require harmonized standards, targeted financial incentives, and strategic procurement commitments to create a stable market environment for domestic recovery operations.

Industrial Policy and Innovation Incentives

Federal industrial policy and innovation incentives have become central to advancing domestic recovery of rare earth elements (REEs) and strategic metals from e-waste. These measures aim to reduce U.S. dependence on foreign supply chains, strengthen national security, and support clean energy and manufacturing objectives (Reynolds, 2024).

Recent legislation, including the Infrastructure Investment and Jobs Act (IIJA), the Inflation Reduction Act (IRA), and the CHIPS and Science Act, reflects a shift toward proactive industrial strategy. Collectively, these laws allocate billions of dollars to expand recycling and processing infrastructure for critical materials. Under these frameworks, the Department of Energy (DOE) has launched programs to fund advanced recycling technologies and enhance industrial capacity for critical material recovery (DOE, 2024).

Innovation incentives have also prioritized research and development (R&D) to accelerate technology readiness. In 2024, DOE announced $19.5 million in funding to advance technologies for recovering critical materials from secondary sources, including electronic waste (DOE, 2024). Similarly, the Department of Defense (DoD) awarded $5.1 million under the Defense Production Act to REEcycle for scaling rare earth recovery from e-waste, targeting NdFeB magnets essential for defense applications (Van Nielen *et al*., 2024).

Public-private partnerships (PPPs) have emerged as a cornerstone of U.S. critical mineral strategy. These partnerships mobilize private investment while incorporating environmental and social safeguards. Collaborations between DoD and private firms, such as MP Materials, illustrate innovative policy tools, including federally backed price floors to stabilize markets and incentivize domestic production (Wu, 2025).

Policy instruments driving market development include tax credits and grants under IRA and IIJA to support recycling infrastructure and R&D, loan guarantees to mitigate investment risk, and strategic procurement policies that prioritize domestically sourced critical materials. While these measures provide a strong foundation, their effectiveness depends on consistent implementation, stable long-term funding, and mechanisms to reduce policy uncertainty that has historically deterred private-sector investment in critical-material recovery.

Market Development and Strategic Goals

The economic viability of e-waste recovery for rare earth elements (REEs) and strategic metals is closely linked to market development, demand drivers, and alignment with U.S. strategic objectives in clean energy and advanced manufacturing (Dada *et al*., 2025). Between 2020 and 2025, policy mechanisms and market trends have increasingly positioned e-waste recovery as a cornerstone of resource independence and circular economy strategies.

The United States remains heavily dependent on imported rare earth metals, creating vulnerabilities across clean-energy, manufacturing, and defense supply chains. Circular economy approaches have demonstrated effectiveness in creating secondary material markets and reducing reliance on primary resources (Manu *et al*., 2025). Urban mining, which leverages high concentrations of critical materials in end-of-life electronics, offers an economically compelling alternative, as studies indicate that REE content in anthropogenic sources often exceeds that of primary ores (Kim *et al*., 2024; Phogat *et al*., 2025).

Despite these advantages, economic viability depends on scale and infrastructure. Research by Fritz *et al*. (2023) highlights that economies of scale and feedstock purity significantly influence capital and operating costs, shaping competitiveness against primary sources. Federal initiatives have sought to address these challenges by embedding e-waste recovery within broader clean energy and industrial strategies. The Department of Energy’s FY 2022-2026 Strategic Plan emphasizes securing supply chains for technologies such as electric vehicles and renewable energy systems through domestic recycling and processing initiatives (DOE, 2025b). Recovered REEs and strategic metals are essential for manufacturing high-performance magnets, semiconductors, and battery components, all of which underpin U.S. decarbonization and industrial competitiveness goals (Reynolds, 2024).

Market forecasts suggest that critical material recovery from secondary sources could reach an annual value of $110 billion by 2045, growing at a compound annual rate of 12.7% (IDTechEx, 2024). This growth is driven by federal incentives, increased private-sector investment, and defense procurement commitments aimed at strengthening domestic supply chains. However, long-term market outlook remains sensitive to price volatility in primary REE markets, underscoring the need for stabilizing mechanisms such as price floors and procurement guarantees to sustain investment in recycled feedstocks. Enduring barriers including uncertain tax credit structures, high capital intensity, and fragmented regulatory frameworks must be addressed to scale e-waste recovery as a strategic pillar of U.S. resource independence.

Barriers and Opportunities

Despite notable progress in technology development and supportive policy frameworks, several barriers continue to impede large-scale adoption of e-waste recovery for REEs and strategic metals in the United States. Technical challenges remain significant, as conventional hydrometallurgical and pyrometallurgical methods, while effective, generate secondary waste streams and require high energy input, raising environmental concerns (Ambaye *et al*., 2020). Greener alternatives such as biohydrometallurgical processes and ionic liquid extraction offer promise but are constrained by slow kinetics and high costs at industrial scale (Magoda & Mekuto, 2022). Regulatory and policy bottlenecks further complicate deployment; inconsistent state-level regulations and the absence of harmonized national standards hinder infrastructure development and investment (Dada *et al*., 2025). Economic and market constraints, including high capital intensity and volatile REE prices, pose financial risks and weaken investor confidence (Fritz *et al*., 2023). Nevertheless, opportunities exist to overcome these challenges. Technological innovation, particularly the integration of AI-driven sorting, robotics, and hybrid recovery systems, can enhance efficiency and reduce costs (Phogat *et al*., 2025). Policy alignment under federal initiatives such as the Inflation Reduction Act and Bipartisan Infrastructure Law provides a foundation for harmonized standards and long-term procurement strategies (DOE, 2025). Embedding e-waste recovery within broader circular economy frameworks can unlock synergies across sectors, supporting sustainability and strategic resource independence goals (Quinto *et al*., 2025; Manu *et al*., 2025).

Policy Recommendations

The following recommendations are identified by the technological, infrastructural, and policy gaps in this review. They aim to provide actionable strategies for advancing domestic e-waste recovery and strengthening U.S. strategic resource independence within circular economy frameworks.

- Establish National Standards for E-Waste Recovery: Create harmonized federal guidelines for collection, dismantling, and processing of e-waste to eliminate regulatory disparities and ensure consistency across states.

- Incentivize Domestic Processing Infrastructure: Introduce targeted tax credits, low-interest loans, and grants for companies investing in advanced recycling facilities, particularly those capable of recovering REEs and strategic resource independence at scale.

- Implement Strategic Procurement Commitments: Mandate federal agencies to prioritize purchasing products containing domestically recovered critical materials, providing a stable demand signal for industry.

- Expand Research and Development Funding: Allocate sustained funding for R&D in innovative recovery technologies, including biohydrometallurgical processes, AI-driven sorting, and hybrid systems, to accelerate commercialization.

- Foster Public-Private Partnerships: Develop structured partnerships between government, industry, and academia to share technical expertise, reduce investment risk, and accelerate deployment of recovery technologies.

- Integrate Circular Economy Principles: Embed e-waste recovery into broader circular economy frameworks by promoting product design for recyclability, extended producer responsibility, and closed-loop supply chains.

- Strengthen Workforce Development: Invest in training programs to build a skilled workforce for advanced recycling operations, ensuring readiness for emerging technologies and compliance with environmental standards.

CONCLUSION

This scoping review demonstrates that e-waste-based recovery of rare earth elements and strategic metals is critical for advancing U.S. resource independence. Key findings show that hydrometallurgical, biohydrometallurgical, and hybrid technologies offer promising recovery pathways, yet their scalability is constrained by infrastructure gaps, regulatory fragmentation, and market volatility. Federal initiatives have begun addressing these challenges through funding and innovation incentives, but gaps persist in harmonized standards, long-term procurement strategies, and integration of recovered materials into manufacturing supply chains. The significance of this review lies in its systems-level perspective, linking technology, policy, and market dynamics to national security and clean energy goals. Limitations include reliance on English-language sources and potential publication bias. Future research should prioritize techno-economic modeling, lifecycle assessments, and policy instruments that enable large-scale deployment within circular economy frameworks.

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