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Systematic Review

Technological Pathways for Rare Earth Elements Recovery from WEEE: A Systematic Mapping Review

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Abstract

Rare earth elements (REEs) are essential to many low-carbon and digital technologies, yet the primary supply is geographically concentrated; waste electrical and electronic equipment (WEEE) could act as an "urban mine", but recovery pathways remain fragmented. We synthesize the evidence through a structured literature review of Scopus and Web of Science indexed studies focusing on WEEE-derived feedstocks for REE recovery: 148 records were screened and 51 papers met the inclusion criteria. Reporting of the search and study selection process follows PRISMA 2020. We coded each study by WEEE source/fraction, core technology family, and process configuration, target REEs, performance reporting, environmental proxies, and maturity, and discussed gaps against circularity goals. Results show an intense concentration on a few feedstocks, permanent magnets (22 studies), fluorescent lamps (16), and batteries (6), with only limited attention to multi-source streams. Hydrometallurgical routes dominate, while biometallurgical options are less explored. Recovery is more frequently reported than selectivity and environmental indicators, and most solutions remain at proof-of-concept maturity. Due to the heterogeneity of feedstocks, process configurations, and reported metrics, the findings were synthesized qualitatively (no meta-analysis). This review highlights priorities for future work: multi-source and heavy rare earth elements focused feedstocks, more selective and intensified flowsheets, harmonized performance reporting, and scale-up supported by life-cycle and cost assessments.

Keywords: rare earth elements; WEEE; urban mining; recycling

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1. Introduction

Rare earth elements (REEs)—the 15 lanthanides plus scandium and yttrium—are indispensable enablers of modern technologies [1]. They are key constituents of high-performance permanent magnets, fluorescent phosphors, catalysts, polishing powders, and battery materials that underpin electric vehicles (EVs), wind turbines, consumer electronics, efficient lighting, medical devices, and a broad range of defense and aerospace systems [2]. As such, REEs sit at the core of the twin green and digital transitions, linking climate-neutrality targets with industrial competitiveness and national security. Global demand for REEs is expected to grow rapidly over the following decades, driven primarily by the deployment of low-carbon power and mobility technologies. The International Energy Agency forecasts that demand for REEs in clean energy applications could increase by a factor of four to seven by 2040 under accelerated transition scenarios [3]. In the European

Union (EU), recent studies show that demand for rare-earth-based permanent magnets may rise roughly sixfold by 2030 and sevenfold by 2050, reflecting the scale-up of wind and EV platforms [4].

Beyond the overall increase in demand for rare-earth-based permanent magnets, particular attention should be paid to Heavy Rare Earth Elements (HREEs), especially dysprosium (Dy) and terbium (Tb), given their critical functional roles. Neodymium–iron–boron (NdFeB) magnets based solely on Light rare-earth elements (LREEs) typically operate efficiently up to temperatures of about 60 °C, above which a significant loss of coercivity occurs. The addition of small amounts of Dy or Tb substantially enhances thermal stability, enabling magnet operation at 200–240 °C, which is essential for electric vehicle traction motors and wind turbine generators. Despite their low concentration in end-of-life products, HREEs are therefore strategically indispensable, and their recovery poses specific technological challenges that are still insufficiently addressed in current recycling research. Yet the upstream supply of REEs remains highly concentrated: China accounts for the majority of global mining and more than 80–90% of separation and refining capacity, exposing downstream industries-especially in Europe and North America-to significant supply and price risks [5,6]. Over the last fifteen years, these vulnerabilities have triggered a strategic policy response on both sides of the Atlantic. Within the EU, REEs have been classified as critical raw materials (CRMs) since the criticality assessment was conducted in 2011 [7]. This prompted the EU to enact the Critical Raw Materials Act (CRMA), adopted in 2024. The policy sets binding 2030 benchmarks for domestic capacities along the value chain:

a. At least 10% of the EU's annual consumption of strategic raw materials should be extracted within the Union;
b. At least 40% processed on the continent;
c. At least 25% must be supplied from recycling;
d. Dependence on any single third country must be kept below 65% at each major processing stage.

Therefore, the CRMA explicitly frames circularity and secondary raw materials as pillars of supply-chain resilience, calling for increased recovery of CRMs from waste streams and for the development of dedicated recycling value chains.

It is worth noting that the EU did not interconnect such REE-related policies with the ones regarding Waste Electrical and Electronic Equipment (WEEEs; e.g., WEEE Directive 2012/19/EU and subsequent updates), which are one of the most relevant feedstocks for the recovery of REEs [8]. In this respect, WEEE has been defined as a strategic "urban mine" for REEs, since electronics, lighting, and mobility products incorporate REEs in several key components, like: NdFeB and SmCo magnets in hard disk drives, traction motors and generators; phosphors in fluorescent lamps and display backlights; NiMH batteries and certain Li-ion cathode formulations; and specialty glasses and ceramics in optical devices. Several studies have shown that the average REE concentrations in selected WEEE fractions can be one (and even more) order of magnitude higher than those in typical primary ores, especially for NdFeB magnet scrap and lamp phosphor powders [9].

At the same time, the United States concerns about REE supply security induced to enact a suite of federal strategies and funding programs. First of all, the U.S. Department of the Interior has issued a list of critical minerals, prominently including rare earths; moreover, the U.S. Department of Energy (DOE) has published successive Critical Minerals and Materials Strategy reports outlining risks, technology priorities, and policy actions. The DOE's Critical Materials Innovation Hub coordinates R&D projects on substitution, more efficient use, and recycling of critical materials, with a strong focus on rare-earth magnets. Complementary initiatives such as the National Blueprint for Lithium Batteries 2021–2030 and subsequent industrial policy packages explicitly promote domestic

processing and recycling infrastructure for batteries and magnets. Finally, recent DOE funding calls dedicate substantial resources to technologies for the rare-earth magnet supply chain, critical-mineral separation from industrial wastes, and circular business models for advanced materials [10].

In principle, this "urban mine" should provide competitive, low-footprint feedstock for REE recycling, aligning environmental objectives with the supply-security goals of EU and U.S. policies. Therefore, recycling REEs from WEEEs is increasingly framed as both an environmental necessity and a strategic industrial opportunity. In practice, however, recovering REEs from WEEE is logistically and technologically challenging. WEEE flows are heterogeneous in composition, highly fragmented across many product categories, and often contaminated by coatings, binders, and co-materials that complicate pre-treatment and separation. Currently adopted collection and dismantling systems were not designed to account for REE recovery, and only a small subset of recovery facilities currently perform magnet or phosphor extraction at scale. On the processing side, multiple technological pathways have been proposed, but they differ markedly in terms of recovery efficiency, selectivity, reagent consumption, energy demand, environmental footprint, and technological readiness. However, to the best of our knowledge, comparative studies are very few and sporadic [11–14].

Against this backdrop, there is a clear need for a technology review based on the extant literature to shed new light on the following research questions (RQs):

RQ1. Which WEEE-derived sources and fractions have been investigated as feedstocks for REE recovery?

RQ2. Which core technology families have been proposed, and how are they configured (including pre- and post-treatments)?

RQ3. How do these technologies perform in terms of both technical and environmental aspects?

RQ4. What is the maturity level (technology readiness levels (TRL) and scale) of the proposed technologies, and where are the main gaps relative to policy targets on circularity and supply security?

To achieve these research aims, a structured literature review based on the Seuring and Gold (2012) [15] model was developed. A total of 148 Scopus and Web of Science indexed journal articles and reviews were selected, allowing for the development of a set of future research avenues. The rest of the paper is organized as follows: Section 2 summarizes the adopted methodology and outlines the four implemented steps (material collection, descriptive analysis, category selection, and material evaluation). Section 3 contains the obtained findings, while Section 4 is devoted to the development of Future Research Avenues (FRAs).

2. Methodology

2.1. Review Design

We conducted a structured literature review tailored to technology assessment, following the four-step content-analysis process model proposed by Seuring and Gold (2012) [15]. The method, which has already been applied in several literature reviews [16,17], comprises the following steps: (1) material collection, (2) descriptive analysis, (3) category selection, and (4) material evaluation (Figure 1). Below are the single steps described. Reporting of the search and study selection process follows the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) recommendations and is summarized in the PRISMA flow diagram and PRISMA checklist (Supplementary Material). The review protocol was not registered.

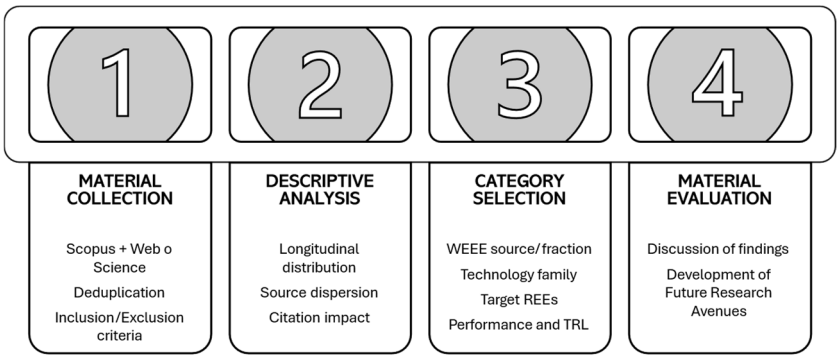


Figure 1. Overview of the adopted review methodology based on the four-step content analysis framework proposed by Seuring and Gold (2012) [15]. The overall screening and selection process follows the PRISMA 2020 guidelines (source: own elaboration).

2.2. Material Collection

The first step, referred to as "material collection," involves gathering the set of publications focusing on REE recovery from WEEE. In this respect, the authors selected the Elsevier Scopus dataset, as it is a widely recognized source for literature reviews and is more transdisciplinary than other datasets (e.g., PubMed). More specifically, the following string was searched in Title, Abstract, and Keywords: "rare earth* recovery". Scopus was selected as the primary database due to its broad multidisciplinary coverage and its widespread use in technology-oriented and engineering-focused literature reviews. The exact search was also run in Web of Science as a robustness check. We limited our attention to journal articles and reviews written in English and searched in May 2025. We obtained 146 documents, whose full texts were carefully analyzed by each author to evaluate their consistency with the research aims. To address potential limitations in database coverage, the same search strategy was also applied to Web of Science. This complementary search returned 129 records. Cross-checking against the Scopus dataset revealed that only 2 documents were not indexed. Therefore, the combined multi-database check did not change the final set of included papers (n = 51) and supports the robustness of the retrieval strategy for this systematic mapping review. In this respect, the following inclusion/exclusion criteria were applied:

(i) Studies that explicitly refer to feedstocks derived by WEEE; therefore, the ones regarding primary mining/refining inputs (e.g., Asgari et al., 2024 [18]) and/or other non-WEEE wastes (e.g., Allaedini et al., 2019 [19]) were excluded. At the same time, documents regarding only post leaching phase applied to simulated and not WEEE-derived inputs were not included (e.g., Alcaraz et al. [20]).

(ii) Attention was limited to documents adequately describing the adopted technology (e.g., in terms of feedstock characterization and/or operating conditions) and offering at least one characterization in terms of the technology's performances (e.g., recovery%, selectivity/purity, TRL scale, environmental impact(s) in terms of energy and/or reagent use).

(iii) Finally, papers focused only on a theoretical investigation not considering real feedstock inputs were excluded (e.g., Wang et al. [21]).

All the above criteria were mandatory and jointly applied during the screening process. To improve transparency of the screening process, the reasons for full-text exclusion are summarized below. Out of 148 retrieved records, 97 papers were excluded after full-text assessment, and 51 met all inclusion criteria and were therefore included in the review. The exclusion breakdown shows that the dominant reason was the absence of a clearly WEEE-derived feedstock (88 out of 97 excluded papers). In particular, a large share of excluded studies addressed REE recovery from other waste streams (37 papers) or from non-WEEE primary mining-related contexts (28 papers), confirming that a substantial

portion of the literature on "rare earth recovery" is not directly applicable to urban mining pathways based on end-of-life electrical and electronic equipment.

A second recurring pattern concerns studies relying on simulated systems and/or post-leaching stages without a real WEEE-derived input. Across the excluded set, simulation-based approaches were common (e.g., simulated leachates or theoretical systems, often coupled with non-WEEE feedstocks), and several papers focused solely on post-leaching separation steps without adequate characterization of the WEEE source. Finally, a smaller number of papers were excluded because they were out of scope (7 papers) or because the waste source/component was not sufficiently specified for consistent classification (2 papers). Overall, this breakdown supports the methodological choice to apply strict inclusion criteria, ensuring that the mapped evidence base reflects technological pathways grounded in real WEEE-derived fractions and enables consistent coding across feedstock, process configuration, and maturity indicators. All papers were independently screened by all co-authors against predefined criteria; rare discrepancies (<1% of total records) were resolved through discussion until consensus was reached. At the end of the process, 51 documents were finally selected (Appendix A). No automation tools were used in the screening process.

2.3. Descriptive Analysis

Step 2 performs a descriptive analysis of the dataset content across basic bibliometric dimensions, profiling sources, document types (journal articles vs. reviews), and year of publication.

Selected documents were published from 2002 to 2025, with a peak in the last year (9 papers). The data summarized in Figure 2 clearly show that scholarly interest began at the start of the new century, but the majority of publications date from the last five years. This seems to be consistent with the growing interest in REE recovery, also driven by geopolitical tensions, which have prompted the USA and the European Union to enact specific norms.

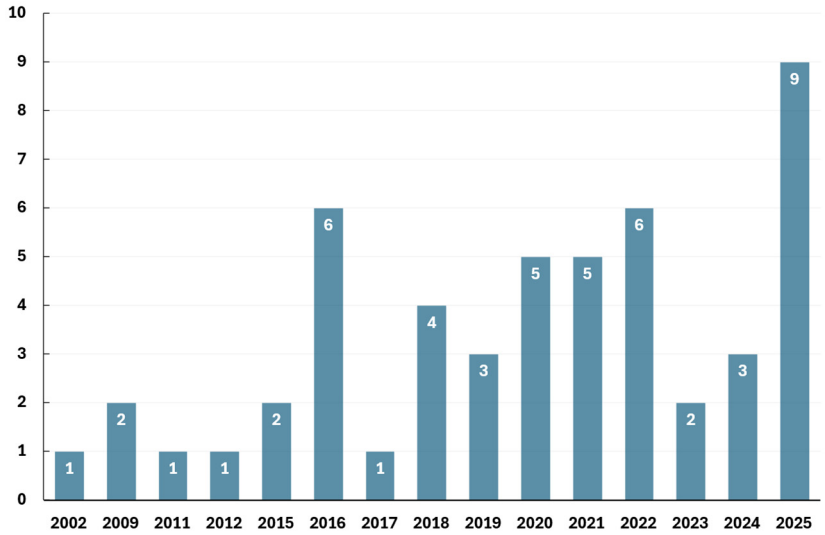


Figure 2. Distribution of the selected studies by year of publication (2002–2025), showing a strong increase in research activity over the last five years (source: own elaboration).

Regarding document type, 9 of 51 documents are reviews, while the remaining 42 are journal articles. Finally, documents were published in 37 sources, of which only six published at least two articles/reviews (Table 1). The large number of sources and the fragmentation of publications across different journals indicate broad disciplinary coverage,

including not only hard sciences (such as chemical/process engineering, materials, and environmental sciences), but also social sciences (such as environmental management).

Table 1. Distribution of the selected studies across journals (number of publications per journal).

Journal	Number of Publications
Hydrometallurgy	6
Journal of Environmental Chemical Engineering	4
Journal of Environmental Management	3
Separation and Purification Technology	3
ACS Sustainable Chemistry and Engineering	2
Waste Management	2
Ceramica	1
Ceramics International	1
Chemical Engineering Research and Design	1
Chemical Engineering Science	1
Chemie-Ingenieur-Technik	1
ChemistrySelect	1
Chinese Chemical Letters	1
Engineering	1
Environmental Science and Technology	1
Environmental Science: Processes and Impacts	1
European Chemical Bulletin	1
Green Chemistry	1
JOM	1
Journal of Alloys and Compounds	1
Journal of Cleaner Production	1
Journal of Power Sources	1
Journal of Sustainable Metallurgy	1
Materials Today Sustainability	1
Materials World	1
Minerals	1
Minerals Engineering	1
Mining, Metallurgy and Exploration	1
Molecules	1
Process Safety and Environmental Protection	1
Processes	1
Resources, Conservation and Recycling	1
Separations	1
Sustainable Materials and Technologies	1
Transactions of the Indian Institute of Metals	1
Transactions of the Institutions of Mining and Metallurgy, Section C: Mineral Processing and Extractive Metallurgy	1
Water Research	1

Source: own elaboration.

Table 1 shows that the evidence base is scattered across a wide range of journals (37 sources for 51 papers), with only a few outlets publishing more than two contributions. This fragmentation reflects the interdisciplinary nature of REE recovery from WEEE, spanning extractive metallurgy, chemical engineering, environmental sciences, and resource management. At the same time, it suggests that research efforts are still dispersed across communities, potentially limiting the consolidation of shared metrics and comparability across studies. However, the recent publication of the majority of selected papers and their widespread coverage in terms of thematic context negatively affects average citations, which are generally low (Table 2). In this respect, it is worth noting that only five

papers were cited more than 100 times, and only one has an average citation ratio higher than 15 [11].

Table 2. Breakdown by average citation.

Average Citations per Year	Documents
0	11
1	4
2–5	19
6–10	14
More than 10	3

Source: own elaboration.

2.4. Category Selection

The third phase, called "category selection", refers to the coding framework and operational labels adopted for classifying the contents of the selected documents. More specifically, considering the earlier presented RQs, the following criteria were adopted:

- Source of WEEE fractions/components (e.g., NdFeB magnets, lamp/LCD phosphors, NiMH, catalysts).
- Core extracting technology family (hydrometallurgy, pyrometallurgy, biometallurgy) and their integration, also considering adopted pre- and/or post-treatments (if any);
- Obtained REEs.
- Performance evaluation of the proposed extraction technology: this evaluation was based on both technical (e.g., recovery degree and selectivity rate) and environmental (e.g., energy demand and chemical use) factors. technology maturity according to the ISO TRL classification which defines nine levels of increasing maturity: TRL 1 (basic principles observed and reported), TRL 2 (technology concept and/or application formulated), TRL 3 (analytical and experimental proof-of-concept of critical functions and/or characteristics), TRL 4 (component and/or breadboard functional verification in laboratory environment), TRL 5 (component and/or breadboard critical function verification in relevant environment), TRL 6 (model demonstrating the essential functions of the element in an appropriate environment), TRL 7 (model demonstrating the element performance for the operational environment), TRL 8 (actual system completed and accepted for operation, "qualified"), and TRL 9 (actual system proven through successful operation in the intended operational environment, "proven") [22].

2.5. Material Evaluation

The final step in Seuring and Gold's process model is the material evaluation. Each of the 51 papers included was carefully analyzed and coded by each author according to the criteria described earlier. In cases of disagreement during coding, consensus was reached through discussion following a supplementary analysis of the texts. Given the heterogeneity of feedstocks, process conditions, and reported performance indicators, we conducted a qualitative synthesis; no meta-analysis was performed.

3. Findings

When considering the source of WEEE-derived feedstocks (RQ1), it is clear that scholars mainly focused on specific components (e.g., personal computers' hard disks) or their fractions (e.g., permanent magnets) (Table 3), while only two studies address the case of multi-source feedstocks [14,23]. When considering a single feedstock, three typologies were mainly investigated: permanent magnets (22 documents), fluorescent lamps (16), and batteries (6). The last column reports the total number of contributions corresponding to

the fractions listed in the previous column (i.e., the sum of the sub-categories (fractions) for each EOL product/component).

Table 3. Breakdown by feedstock input.

EOL Product/Component	Fraction	Number of Documents	
Permanent Magnets (NdFeB)	Powdered NdFeB Simulated NdFeB leachate	18 4	22
Fluorescent lamps	Green phosphor Mixed phosphor powders Red phosphor	1 13 2	16
Battery	Black mass Anode (NiMH batteries) Powdered mix of electrodes (NiMH batteries)	1 1 4	6
PCB	Powdered PCB	1	1
Phosphor products	Mixed phosphor powders	1	1
Multi source	NdFeB PM & Catalysts not specified	1 1	2
Not specified			3
Total			51

Source: own elaboration.

The significant attention devoted to NdFeB/SmCo magnets clearly reflects the critical role these materials play in the economy, especially in the context of the twin digital and green transition [24,25]. Consequently, scholars have broadened their field of inquiry into this topic, also analyzing detailed elements such as the testing of alternative solvents (e.g., ionic liquids and deep eutectic solvents [26]) and innovative process configurations [27,28]. Finally, only ten documents regarding permanent magnets, out of the 22 selected ones, specifically refer to the original EOL products they originated from. More specifically, the most frequently cited are electric vehicles (4 documents) and hard disks (4), while mobile phones and turbines are mentioned only once.

Studies on other feedstocks are generally narrow in scope; for instance, those related to Lamp/LCD phosphors focus almost exclusively on the degree of recovery and selectivity achieved by the proposed technologies. At the same time, research on NiMH batteries concentrates primarily on the pre-treatment stage and electrolyte handling. In order to characterize technologies proposed to recover REEs from WEEEs (RQ2), the following level of analysis was considered:

(a) Single core technologies adopted to recover the REEs;
(b) Hybrid approaches based on a combination of at least two core technologies;
(c) Combination of pre-/post-treatments and core technologies;
(d) Comparison of alternative technologies.

Based on the collected data, three core technologies emerged: hydrometallurgy, pyrometallurgy, and biometallurgy. As is known, hydrometallurgical technologies involve the dissolution of the feedstock in an appropriate liquid medium, followed by selective separation and purification of REEs by precipitation, solvent extraction, or ion exchange [29]. On the contrary, Pyrometallurgical routes have a long tradition in extractive metallurgy and have been widely applied for the recovery of base and precious metals from primary ores and, more recently, from secondary resources such as spent catalysts and WEEE [30]. Such technology involves high-temperature treatments aimed at either directly extracting REEs or modifying the chemical matrix to facilitate subsequent hydrometallurgical recovery.

Finally, biometallurgical approaches have been industrially applied for several decades to recover copper and other metals (e.g., Au, Co, Ni, Zn, U) from low-grade ores and mine wastes [31]. However, its application to the treatment of industrial residues and/or end-of-life products is relatively recent. Such an emerging and environmentally friendly approach relies on the metabolic activity of microorganisms or the biochemical action of biologically derived agents to solubilize REEs. It is worth noting that biometallurgy requires a longer processing time (even more than a week) compared to the other two (which are generally completed in a few hours) [32,33]. The collected data clearly show that scholars mainly focused on hydrometallurgy (47 documents), with studies beginning in 2002 and rapidly increasing from 2016 onward. At the same time, studies on pyrometallurgical processing of WEEE (11 documents) started only in 2011 and have remained limited overall. Finally, studies on biometallurgy (4 documents) were initiated only in 2016 and appear to be sporadic (Figure 3).

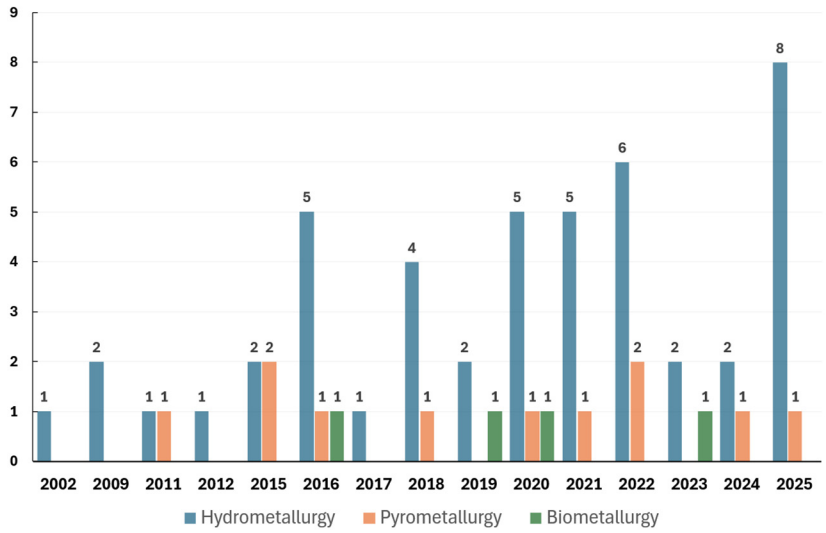


Figure 3. Temporal distribution of the selected studies according to the main core technology adopted for REE recovery from WEEE (source: own elaboration).

It is worth noting that five documents propose a combination of two core technologies, always including the hydrometallurgical as a second step. More specifically, four of them [34–37] adopt a pyrometallurgical initial step, and only one adopts a biometallurgical approach [14,38]. Scholars mainly focused on the extraction phase, regardless of the adopted technology family. In this respect, since 2011, few studies (12) have been focused on the combination of core technologies with pre- and/or post-treatments (Figure 4). Among the former (pretreatments) the most investigated were based either on a roasting step (8 documents) or mechanical one (e.g., grinding; 5 documents); both of them aim to improve the solubilization of REEs in the following extraction step. On the contrary, scarce attention (only two documents [13,39]) was given to microwave pretreatment. Finally, quite unexpectedly, given the considerable attention to permanent magnets as feedstock, only one explicitly refers to hydrogen processing of magnet scrap (HPMS) pretreatment combined with roasting [24].

At the same time, only one document proposes a post-treatment step based on membrane use [40].

Finally, four documents offer a comparative analysis of different core technologies. More specifically, three [11,13,39] compare hydro- and pyrometallurgical approaches, while only one [23] also includes a bio-metallurgical approach. In terms of timespan, this compari-

son began in 2016 but was mainly focused on 2020–2022; since then, no further comparative studies have been published.

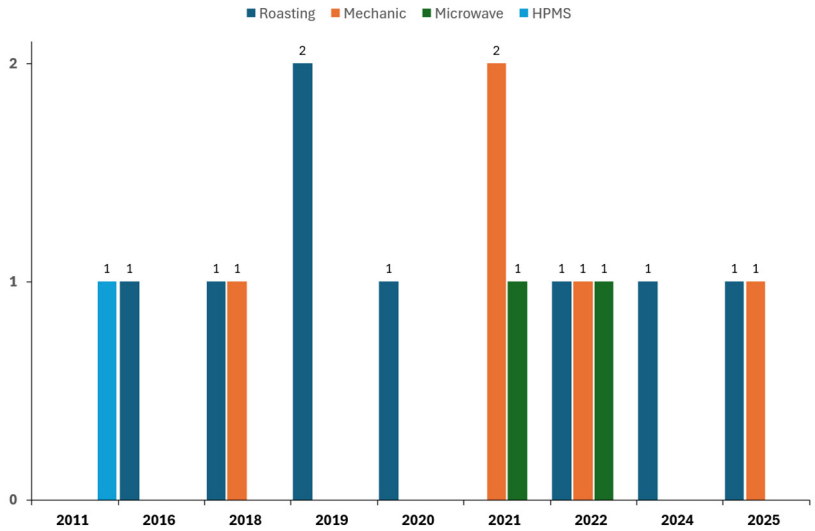


Figure 4. Distribution of the selected studies according to the type of pre-treatment adopted prior to REE recovery, highlighting the predominance of roasting and mechanical activation (source: own elaboration).

When considering the output of proposed recovery technologies (RQ 3), it emerges that 45 of the sampled studies report a mix of REEs, while only 6 report a specific REE (Nd in 5 of them). To further characterize the data, valuable insights emerge from separating the Light REEs (LREE; e.g., Nd, Ce, La) from the Heavy REEs (HREE; e.g., Dy, Tb, Eu). In this respect, the majority of selected studies focus on LREEs due to their massive presence in permanent magnets, which are the most investigated feedstock source. As a consequence, the few studies on HREEs are almost exclusively focused on Tb and Dy, which are present in permanent magnets but at low concentrations. In addition, lamp phosphor powders represent an important secondary source for HREE-related elements (e.g., Y and Tb, and, depending on phosphor composition, Eu). Yet, technological research on these fractions is often limited to laboratory leaching and does not systematically address the complexity of downstream separation. From a process perspective, HREE recovery is challenged by (i) low-grade and highly variable concentrations in real WEEE streams, (ii) co-dissolution of major elements (e.g., Fe, Co, Ni, Ca, Al, P) that reduces selectivity and increases reagent demand, and (iii) the need for multi-stage separation to achieve individual REE purity. Future research should therefore explicitly target HREE-rich fractions, improve selective separation strategies (e.g., advanced solvent extraction schemes, ionic liquids/deep eutectic solvents, or tailored sorbents), and report standardized metrics enabling cross-study comparison. While evaluating the performances of proposed technologies (RQ3), two main issues were considered, namely technical and environmental ones. The technical evaluation was based on two measures:

(a) Degree of REE(s) recovery efficiency–calculated as the ratio of recovered REE(s) to the total amount of such element(s) contained in the feedstock (e.g., grams of recovered Nd out of the total amount of Nd in the permanent magnet);

(b) REEs selectivity rate, measured as the percentage of recovered REE(s) on the total weight of the output stream; such an indicator shows the purity level of the obtained output.

As previously noted, 45 of the selected papers address a mix of recovered REEs, while the remaining six focus on a single REE (five on Nd). Independent of the output compo-

sition, the vast majority of sampled studies do not provide any quantitative results on REE recovery efficiency. More specifically, only 13 (out of 45) of the multi-REE studies and 3 (out of 6) of the single-REE studies include such a performance indicator. In any case, the declared rates are higher than 90% of the original feedstock's content. However, it is worth noting that such a performance indicator is almost exclusively reported when hydrometallurgical technologies (either implemented stand-alone or in integration with pre- and post-treatments) are adopted. The recovery rate is reported in only one of 11 studies adopting a pyrometallurgical approach [41] and in one of five studies considering technology integration [42]. Such findings support the idea that hydrometallurgical technologies are the most effective solution for REE recovery from WEEE. The predominance of hydrometallurgical routes in the extant literature can be attributed not only to their high recovery performance but also to their relative process flexibility, compatibility with heterogeneous WEEE feedstocks, and ease of integration with established separation techniques (such as solvent extraction and selective precipitation). These features make hydrometallurgy particularly attractive for early-stage technology development, despite its environmental drawbacks. Beyond the core extraction step, the reviewed studies adopt a variety of downstream recovery and purification methods that largely determine overall selectivity and product quality. In hydrometallurgical routes, REEs are typically recovered from leachates through (i) selective precipitation (commonly as oxalates, carbonates, hydroxides, or phosphates), often implemented in multiple stages to remove major co-metals (e.g., Fe, Co, Ni) before REE precipitation; (ii) solvent extraction, which remains the most established approach for separating REEs from transition metals and, when required, for fractionating LREEs and HREEs through staged extraction/stripping schemes; and (iii) less frequently, ion exchange, adsorption on functionalized sorbents, membrane-based separations, or antisolvent/crystallization strategies. In pyrometallurgical pathways, high-temperature treatment is primarily used to modify phase composition or concentrate REEs into a manageable intermediate (e.g., slag or an oxidized product), which is then commonly subjected to a subsequent hydrometallurgical separation step; this hybrid approach reflects the limited intrinsic selectivity of thermal treatments for individual REEs [5].

The predominance of precipitation and solvent extraction is therefore not only historical but also functional: precipitation offers operational simplicity and low-cost bulk recovery, whereas solvent extraction provides the selectivity and scalability required to meet purity specifications, at the expense of higher chemical use and more complex process integration. Conversely, emerging approaches (e.g., ionic liquids/deep eutectic solvents, tailored sorbents, or bio-derived ligands) are often proposed to improve selectivity and reduce environmental burdens. Still, they remain at low TRL due to kinetic limitations, sensitivity to real feedstock impurities, limited recyclability data, and scarce evidence on continuous operation. Overall, the review indicates that many studies report recovery yields without providing full mass balances, product purity, or stage-wise selectivity metrics, which hinders robust cross-study comparison and process benchmarking. At the same time, the selectivity rate is reported in only 37 of the 45 multi-REE documents and in all six mono-REE documents. However, such a performance indicator is almost exclusively expressed in terms of range (e.g., high) rather than with a quantitative value. Finally, performance levels vary from medium (five documents) to medium/high (three) and high (32). In this respect, it is worth noting that performance levels below high were observed for both hydrometallurgical and pyrometallurgical approaches, whereas biometallurgical approaches are associated only with high selectivity levels. Therefore, the latter core technology seems to perform better, but it should be noted that it requires a longer processing time.

A cross-study quantitative synthesis of selectivity was not feasible because most publications report selectivity using non-harmonized definitions (e.g., purity of precipitate, separation factor, distribution coefficient, or qualitative statements such as "high/medium"), often without complete mass balances or uncertainty estimates. To improve comparability, future studies should standardize performance reporting by providing: (i) mass-based recovery (%) for each REE (and key co-metals), (ii) product purity (%) and/or separation factors for critical separation steps, (iii) reagent consumption normalized per kg of recovered REE (kg reagent/kg REE), (iv) energy demand normalized per kg of recovered REE (kWh/kg REE), (v) process time and number of stages, and (vi) an explicit statement of scale and validation environment to support consistent TRL assignment.

As a result, a statistical meta-analysis of selectivity values is not feasible. This evidence confirms that the main bottleneck for quantitative benchmarking is not the absence of selectivity as a topic, but the lack of harmonized definitions and standardized, stage-wise reporting.

When analyzing the environmental performance of proposed technologies, two issues were evaluated, namely, energy (Table 4) and chemical consumption (Table 5). As for energy, the evaluation was based either on parameters cited in the selected papers (when available) or on the appraisal of each core technology in the extant literature [5,43–47]. However, in eight out of 51 documents, it was not possible to identify an adequate estimate, mainly due to the review and comparative nature of the papers [12,48,49]. At a global level, the vast majority of studies on hydrometallurgical and pyrometallurgical technologies classify energy consumption as medium to high. On the contrary, the few documents on biometallurgy indicate either a low or a low/medium energy requirement (Table 4). To avoid ambiguity, note that the review includes 51 papers. At the same time, some subsequent tables (Tables 4–6) report totals greater than 51 because they refer to the number of coded technology occurrences rather than the number of unique publications. In particular, several studies propose hybrid flowsheets or provide comparative assessments of multiple technological pathways. In these cases, the same paper was coded under each relevant technology family so that a single publication may contribute to more than one category.

Table 4. Breakdown by energy consumption and core technology.

Core Technology	Energy Consumption						
	L	**L/M**	**M**	**M/H**	**H**	**n.a**	**Total**
Hydrometallurgy	5	6	18	4	6	8	47
Pyrometallurgy				1	5	5	11
Biometallurgy	2	1				1	4

Source: own elaboration.

Table 5. Breakdown by use of chemicals and core technology.

Core Technology	Use of Chemicals						
	L	**L/M**	**M**	**M/H**	**H**	**n.a.**	**Total**
Hydrometallurgy	1	6	23	6		11	47
Pyrometallurgy	1		2	2		6	11
Biometallurgy	2					2	4

Source: own elaboration.

Table 6. Breakdown by TRL level and core technology.

Core Technology	TRL Level													
	1	**2**	**3**	**3/4**	**4**	**4/5**	**5**	**5/6**	**6**	**7**	**8**	**9**	**n.a.**	**Total**
Hydrometallurgy			18	1	12	1	4	3	1				7	47
Pyrometallurgy			3				1	2					5	11
Biometallurgy			1	1		1							1	4

Source: own elaboration.

A similar dichotomy was also found when considering the use of chemicals by typology (e.g., HCl vs. acetic acid), the use of different solvents (as in 41 of the 47 documents related to hydrometallurgy), and the adopted dosage. More specifically, hydrometallurgy and pyrometallurgy technologies are less environmentally friendly than biometallurgy. However, some studies related to the former technologies specifically considered the possibility of recirculating chemicals to reduce environmental impact [50,51].

Finally, when considering the TRL level of the proposed technology (RQ4), only 38 documents provided sufficient information to perform this evaluation. The majority of evaluated papers (22 out of 38) refer to the proof-of-concept level (TRL 3). At the same time, only 11 had at least partial validation in a "relevant environment" [22]. Moreover, studies on hydrometallurgy are the most developed, while those on biometallurgy typically focus on the laboratory level (Table 6). In this review, TRL assessment was performed only when the manuscript provided sufficient information on the experimental scale and validation environment.

The analysis of TRLs highlights a substantial gap between laboratory-scale experimentation and industrial implementation. Most of the reviewed technologies remain clustered around TRL 3–4, corresponding to proof-of-concept and early validation stages. Only a limited number of studies report pilot-scale demonstrations (TRL $\geq$ 5), and none describe fully integrated industrial operations. This gap reflects not only technological challenges but also systemic barriers, including feedstock heterogeneity, limited downstream processing capacity, and the absence of standardized performance indicators. As a result, the current technological landscape appears misaligned with policy targets, such as those set out in the EU CRM Act, which implicitly require scalable, robust, and economically viable recycling solutions. Beyond recovery efficiency and selectivity, the comparison of technological pathways for REE recovery from WEEE requires a broader set of evaluation criteria, including feedstock adaptability (ability to handle heterogeneous and impurity-rich streams), process integration complexity, cost-related feasibility (when information is available), environmental implications, processing time, and industrialization potential (TRL and scalability). Hydrometallurgical processes generally exhibit high recovery yields and operational flexibility. Still, they are associated with significant chemical consumption and wastewater generation, with downstream separation often being the primary driver of complexity and costs. Pyrometallurgical approaches are robust to feedstock variability but are characterized by high energy demand and limited selectivity for individual REEs, unless coupled with subsequent hydrometallurgical purification. Biometallurgical routes, although still at an early development stage, show promising selectivity and potentially lower environmental burdens, at the expense of longer processing times, sensitivity to process conditions, and limited scalability. From an industrial perspective, hydrometallurgy currently appears as the most mature option, while biometallurgy represents a potentially disruptive pathway if kinetic limitations and scale-up challenges can be overcome. Overall, the lack of harmonized metrics for cost, environmental impact, and product quality specifications remains a significant obstacle to rigorous cross-technology benchmarking.

The radar chart shown in Figure 5 is based on a qualitative scoring approach developed to enable a comparative assessment of technological pathways characterized by heterogeneous datasets and non-harmonized performance indicators. Each criterion was evaluated using a three-level ordinal scale (Low = 1; Medium = 2; High = 3), derived from explicit statements in the reviewed papers when available, or from consolidated technological knowledge reported in authoritative reviews. This approach does not represent a quantitative performance metric nor a substitute for Life-Cycle Appraisal (LCA). Still, it serves as a structured visual synthesis to support critical discussion on trade-offs among technical performance, environmental implications, technological maturity, and industrial feasibility.

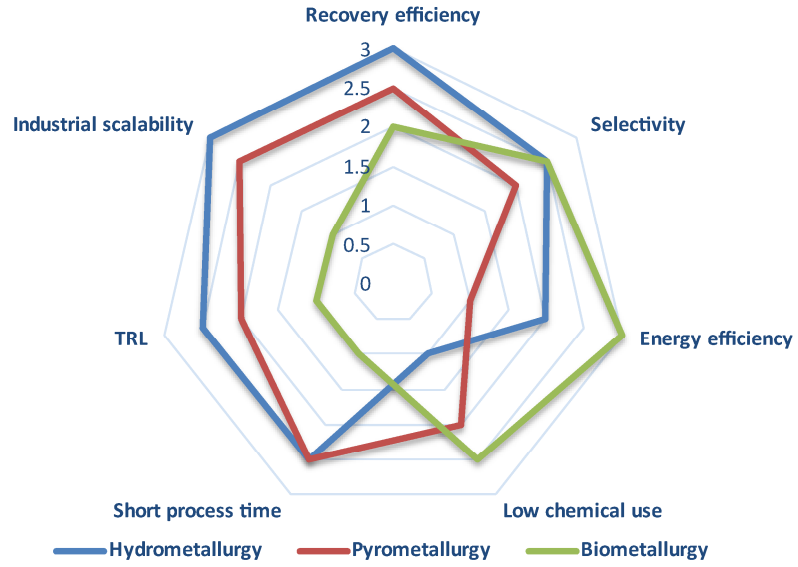


Figure 5. Qualitative multi-criteria comparison of the main technological pathways for REE recovery from WEEE.

Although WEEE is increasingly framed as an "urban mine", the mapped evidence reveals several gaps that currently limit a concrete contribution to circular economy targets. First, most studies rely on highly selected, single-component feedstocks (e.g., isolated NdFeB magnets or specific lamp phosphor fractions), whereas real-world circular systems must cope with mixed and impurity-rich streams generated by collection and dismantling practices; consequently, robustness to feedstock variability remains insufficiently demonstrated. Second, the literature is strongly skewed towards LREE-rich streams. At the same time, HREE-oriented recovery (e.g., Dy/Tb in magnets and Y/Tb/Eu-related lamp fractions) is comparatively underrepresented, despite its strategic relevance and the complexity of its separation. Third, many studies demonstrate high recovery at laboratory scale but provide limited evidence on product quality specifications, closed-loop reagent management, and residue valorization, which are essential conditions for circular implementation beyond mere metal dissolution. Fourth, the predominance of TRL 3–4 confirms a scale-up gap: pilot-scale demonstrations, continuous or semi-continuous operation, and integration with downstream refining remain rare. Finally, the lack of harmonized performance indicators (recovery, stage-wise selectivity/purity, normalized energy and reagent use, and uncertainty) prevents robust benchmarking across pathways. It slows the translation of research outputs into industrial decision-making.

4. Conclusions

The earlier technology review allowed us to characterize the extant literature with respect to several criteria, ranging from WEEE inputs to adopted technologies. Moreover,

the sampled studies were evaluated with respect to both technical and environmental performance and TRLs. The earlier summarized findings allow for the development of some FRAs that could support further studies in the near future. Below, emerging FRAs will be described in light of the different RQs discussed earlier. As far as the WEEE's feedstock (RQ1), it clearly emerges that attention was focused on specific components and even fractions (e.g., permanent magnets). In the near future, scholars could pay more attention to the use of multi-source feedstocks (FRA 1), while also considering the difficulties of selectively collecting each input in sufficient quantities to support large-scale plants [24]. Among other WEEEs, attention should be further focused on fluorescent lamps, which contain HREEs (e.g., Y and Tb) and have been rarely investigated. When considering core technologies (RQ2), hydrometallurgy clearly emerges as the most investigated, whereas biometallurgy is rarely mentioned. In this respect, it should be noted that the latter technology (biometallurgy) is characterized by lower environmental impacts (both in terms of energy and chemical use) and higher selectivity. Moreover, further studies should include comparisons across different core technologies (only 5 of the 51 sampled studies) and the adoption of pre- (12) and post-treatments (1). At the same time, the HPMS approach requires further attention, given the significant role of permanent magnets as a feedstock input. Finally, new hybrid approaches should be further investigated, as recently shown by Taglieri et al. [52] in the case of catalysts. As far as technical performance is concerned (RQ3), future studies should provide more quantitative data on the recovery efficiency achieved (13 of the 51 sampled studies). This is especially true for studies based on pyrometallurgy and biometallurgy core technologies. Finally, selectivity ratios should be better quantified (not only as a range), especially when biometallurgy approaches are adopted, since they perform better in this respect. In this respect, future studies focused on this technology should specifically focus on accelerating bioleaching kinetics to reduce the time required to extract REEs. At the same time, environmental impacts should be further investigated using an LCA approach (as in the case of Ippolito et al. [36]). This could also support further studies on closed-loop chemistry approaches [53] and/or the adoption of alternative solvents [26]. Based on the obtained LCA data, future research should also implement a Life Cycle Cost approach to support investments at an industrial scale. Finally, future studies should improve the TRL (RQ4) of proposed technologies through full-scale demonstrations by pilot plants. In this respect, scholars should focus on the 47 Strategic Projects (located across 13 EU Member States) that the European Union recently selected to boost domestic strategic raw material capacities. Such Strategic Projects cover 14 of the 17 strategic raw materials listed in the Critical Raw Materials Act, and three of them specifically refer to REEs [54]. Overall, the literature still shows a predominance of laboratory-scale, feedstock-specific demonstrations. In contrast, industrial deployment requires robustness to real-world variability, consistent product specifications, and integration with downstream separation and refining capacity. Bridging the gap from TRL 3–4 to TRL $\geq$ 5 will likely depend on process integration, closed-loop reagent strategies, and the adoption of standardized metrics linking technical performance to environmental and economic outcomes. Without such convergence, technological progress risks remaining fragmented and insufficient to meaningfully contribute to a circular economy that thoroughly targets critical raw materials. Based on the mapped evidence, future research should prioritize a limited number of actionable directions. (FRA1) Multi-source and realistically mixed feedstocks should be increasingly investigated, integrating upstream dismantling/sorting constraints and addressing variability through robust pretreatment and conditioning strategies. (FRA2) HREE-oriented recovery must be strengthened by targeting HREE-rich fractions (e.g., lamp phosphors) and by designing separation schemes that explicitly address low concentrations and co-dissolution effects. (FRA3) Hybrid and intensified flowsheets should be developed by coupling core technolo-

gies with selective pretreatments (e.g., roasting, mechanochemical activation, HPMS) and advanced downstream separation/purification, aiming to reduce the number of unit operations and increase selectivity. (FRA4) Industrialization requires pilot-scale demonstrations, including continuous or semi-continuous operation, closed-loop reagent management, and the systematic integration of life-cycle assessment and life-cycle costing. (FRA5). Finally, harmonized performance reporting (recovery, purity/selectivity, normalized energy and reagent use, and uncertainty) is essential to enable evidence-based comparison and to support investment and policy decisions aligned with circular economy targets. Finally, like other structured literature reviews, this study is not free from limitations. Among them, the criteria adopted in the search and screening process (e.g., database selection, keywords, and inclusion/exclusion criteria) may have led to the omission of relevant contributions, particularly those published in languages other than English or in the grey literature. These limitations, however, do not undermine the work's main insights; instead, they suggest that future updates could broaden the scope of the analysis as the scientific and policy debate continues to evolve.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/recycling11040065/s1. Figure S1: PRISMA 2020 Flow Diagram; Table S1: PRISMA 2020 Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

CRMA	Critical Raw Materials Act
CRM/CRMs	Critical Raw Material(s)
DOE	(U.S.) Department of Energy
EOL	End-of-Life
EU	European Union
EV/EVs	Electric Vehicle(s)
FRA/FRAs	Future Research Avenue(s)
HPMS	Hydrogen Processing of Magnet Scrap
HREE/HREEs	Heavy Rare Earth Element(s)
ISO	International Organization for Standardization
LCA	Life-Cycle Appraisal
LCD	Liquid Crystal Display
Li-ion	Lithium-ion (battery)
LREE/LREEs	Light Rare Earth Element(s)
NdFeB	Neodymium–Iron–Boron (magnet)
NiMH	Nickel–Metal Hydride (battery)

REE/REEs	Rare Earth Element(s)
RQ/RQ1–RQ4/RQs	Research Question(s)
TRL	Technology Readiness Level
US/USA	United States/United States of America
WEEE/WEEEs	Waste Electrical and Electronic Equipment

Appendix A

Table A1. List of the studies included in the systematic review (authors, title, and year of publication).

Ref.	Authors	Title	Year
[37]	Abrahami S.T.; Xiao Y.; Yang Y.	Rare-earth elements recovery from post-consumer hard-disc drives	2015
[49]	Azimi G.	Technological advancements in rare earth elements recovery from ionic clays: A comprehensive review	2025
[55]	Bandara H.M.D.; Field K.D.; Emmert M.H.	Rare earth recovery from end-of-life motors employing green chemistry design principles	2016
[56]	Brewer A.; Dohnalkova A.; Shutthanandan V.; Kovarik L.; Chang E.; Sawvel A.M.; Mason H.E.; Reed D.; Ye C.; Hynes W.F.; Lammers L.N.; Park D.M.; Jiao Y.	Microbe Encapsulation for Selective Rare-Earth Recovery from Electronic Waste Leachates	2019
[57]	Dasgupta K.; Vijayalakshmi R.; Anitha M.	Recovery of Nd(III) in coexistence with Fe(III) ions from aqueous phase using functionalized multiwalled carbon nanotubes: An environmental benign approach	2016
[13]	Dhawan N.; Tanvar H.	A critical review of end-of-life fluorescent lamps recycling for recovery of rare earth values	2022
[58]	Innocenzi V.; Ippolito N.M.; De Michelis I.; Medici F.; Vegliò F.	A hydrometallurgical process for the recovery of terbium from fluorescent lamps: Experimental design, optimization of acid leaching process and process analysis	2016
[35]	Innocenzi V.; Ippolito N.M.; Pietrelli L.; Centofanti M.; Piga L.; Vegliò F.	Application of solvent extraction operation to recover rare earths from fluorescent lamps	2018
[59]	Innocenzi V.; Vegliò F.	Recovery of rare earths and base metals from spent nickel-metal hydride batteries by sequential sulphuric acid leaching and selective precipitations	2012
[36]	Ippolito N.M.; Amato A.; Innocenzi V.; Ferella F.; Zueva S.; Beolchini F.; Vegliò F.	Integrating life cycle assessment and life cycle costing of fluorescent spent lamps recycling by hydrometallurgical processes aimed at the rare earths recovery	2022
[60]	Ippolito N.M.; Ferella F.; Innocenzi V.; Trapasso F.; Passeri D.; Belardi G.; Vegliò F.	Effect of mechanical activation on terbium dissolution from waste fluorescent powders	2021
[61]	Itoh M.; Miura K.; Machida K.	Novel rare earth recovery process on Nd-Fe-B magnet scrap by selective chlorination using NH4Cl	2009
[11]	Jha M.K.; Kumari A.; Panda R.; Rajesh Kumar J.; Yoo K.; Lee J.Y.	Review on hydrometallurgical recovery of rare earth metals	2016
[62]	Jiang Y.; Deng Y.; Xin W.; Guo C.	Oxidative Roasting–Selective Pressure Leaching Process for Rare Earth Recovery from NdFeB Magnet Scrap	2020
[63]	Klemettinen A.; Adamski Z.; Leśniewicz A.; Rycerz L.	Semicontinuous Process of Rare Earths Recovery from End-of-Life NdFeB Magnets on a Large Laboratory Scale	2023
[64]	Korkmaz K.; Alemrajabi M.; Rasmuson Å.; Forsberg K.	Recoveries of Valuable Metals from Spent Nickel Metal Hydride Vehicle Batteries via Sulfation, Selective Roasting, and Water Leaching	2018
[65]	Korkmaz K.; Alemrajabi M.; Rasmuson Å.C.; Forsberg K.M.	Separation of valuable elements from NiMH battery leach liquor via antisolvent precipitation	2020

Table A1. *Cont.*

Ref.	Authors	Title	Year
[66]	Li L.; Xu S.; Ju Z.; Wu F.	Recovery of Ni, Co and rare earths from spent Ni-metal hydride batteries and preparation of spherical Ni(OH)2	2009
[40]	Lin J.; Kou J.; Wen X.; Xu H.	Migration and Enrichment of Rare Earth Elements in the Flotation Process of Rare Earth-Bearing Collophanite	2025
[67]	Liu C.; Luo W.; Li Y.; Wang Z.; Xu S.; Wang X.	Extraction of rare earth Eu from waste blue phosphor strengthened by microwave alkali roasting	2024
[68]	Liu C.; Yan Q.; Zhang X.; Lei L.; Xiao C.	A one-pot process based on P44414Cl-HCl aqueous biphasic system for recovering rare earth elements from NdFeB permanent magnet	2022
[69]	Lorenz T.; Fröhlich P.; Bertau M.	Recycling of Rare Earths from FeNdB-Magnets by Solid State Chlorination	2017
[14]	Lukowiak A.; Zur L.; Tomala R.; LamTran T.N.; Bouajaj A.; Strek W.; Righini G.C.; Wickleder M.; Ferrari M.	Rare earth elements and urban mines: Critical strategies for sustainable development	2020
[38]	Meng X.; Zhao H.; Zhao Y.; Shen L.; Gu G.; Qiu G.	Effective recovery of rare earth from (bio)leaching solution through precipitation of rare earth-citrate complex	2023
[70]	Nogueira M.; Matos I.; Bernardo M.; Pinto F.; Fonseca I.; Lapa N.	Recovery of Nd3+ and Dy3+ from E-Waste Using Adsorbents from Spent Tyre Rubbers: Batch and Column Dynamic Assays	2025
[71]	Onoda H.; Iinuma A.	Selective preparation of neodymium phosphates from iron mixed solution by two-step precipitation	2020
[72]	Onoda H.; Iinuma A.	Effects Of Dissolution Conditions On The Recovery Of Samarium Phosphate From Practical Magnets	2022
[73]	Onoda H.; Iinuma A.	Selective formation of neodymium phosphate from iron-neodymium magnet waste	2022
[34]	Ou Z.; Li J.; Wang Z.	Application of mechanochemistry to metal recovery from second-hand resources: A technical overview	2015
[74]	Pavón S.; Lapo B.; Fortuny A.; Sastre A.M.; Bertau M.	Recycling of rare earths from fluorescent lamp waste by the integration of solid-state chlorination, leaching and solvent extraction processes	2021
[75]	Pavón S.; Lorenz T.; Fortuny A.; Sastre A.M.; Bertau M.	Rare earth elements recovery from secondary wastes by solid-state chlorination and selective organic leaching	2021
[76]	Pietrelli L.; Bellomo B.; Fontana D.; Montereali M.R	Rare earths recovery from NiMH spent batteries	2002
[77]	Prodius D.; Gandha K.; Mudring A.-V.; Nlebedim I.C.	Sustainable Urban Mining of Critical Elements from Magnet and Electronic Wastes	2020
[78]	Rinne M.; Elomaa H.; Porvali A.; Lundström M.	Simulation-based life cycle assessment for hydrometallurgical recycling of mixed LIB and NiMH waste	2021
[30]	Romano P.; Rahmati S.; Adavodi R.; Clementini G.; Gallo F.; Vegliò F.	Study of the kinetics and mechanisms of rare earth elements leaching from end-of-life NdFeB magnets through Hydro-Nd process	2025
[79]	Sawada T.; Asada M.; Serizawa T.	Selective Rare Earth Recovery Employing Filamentous Viruses with Chemically Conjugated Peptides	2016
[80]	Shi J.; Chen D.; Chen M.; Qiu Y.; Dong J.; Hou C.; Zhang F.; Li J.	Sulfation roasting for rare earth recovery from NdFeB scrap: Kinetics, thermodynamics, and phase transformation	2025
[12]	Shukla N.; Dhawan N.	Processing End-of-Life Tube Lights for Recovery of Rare Earth Oxides	2021
[39]	Shukla N.; Dhawan N.	Evaluation of Baking Process for Rare-Earth Recovery from Discarded Tube Lights Phosphor	2022

Table A1. *Cont.*

Ref.	Authors	Title	Year
[48]	Song H.; Zhu H.; Wang R.; Wen S.; Yan C.; Cong W.	A novel adsorptive membrane for rare earth recovery prepared by facile UV grafting using 3,3′, 4,4′-benzophenone tetracarboxylic acid (BTA)	2025
[81]	Su X.; Guo X.; Zhao Z.; Dong Y.; Wang Y.; Li F.; Sun X.	An efficient and sustainable [P6,6,6,14]2[BDOAC] ionic liquid based extraction–precipitation strategy for rare earth recovery	2018
[41]	Tian Z.; Zhang Q.; Wu Y.; Yin X.; Liu X.-M.; Wang H.; Pang W.	Alkali Fusion Deconstruction and Rare-Earth Recovery from Hazardous Spent Fluorescent Lamp Phosphors: Experimental and Theoretical Calculations	2025
[82]	Van Loy S.; Binnemans K.; Van Gerven T.	Mechanochemical-Assisted Leaching of Lamp Phosphors: A Green Engineering Approach for Rare-Earth Recovery	2018
[24]	Walton A.; Williams A.	Rare earth recovery	2011
[83]	Wang Z.; Liu C.; Li Y.; Zeng J.; Luo W.; Wang X.	Thermal evolution of mercury from waste rare earth phosphor: Effect of thermal treatment conditions and kinetic analysis	2024
[84]	Wu S.; Bie C.; Gao Y.; Sun X.	A novel bifunctional ionic liquid [N1888][OOB] for the separation of rare earth and transition metal in NdFeB magnet	2024
[85]	Xu B.; Shanshan E; Liu J.; Niu B.; Qin Y.	Machine learning-guided rare earth recovery from NdFeB magnet waste: Model development, parameter influence analysis and experimental validation	2025
[86]	Yang D.; Gao S.; Hong J.; Ye L.; Ma X.; Qi C.; Li X.	Life cycle assessment of rare earths recovery from waste fluorescent powders–A case study in China	2019
[87]	Yu M.; Huang G.; Zhang T.	Kinetic Mechanisms and Efficient Leaching of Praseodymium, Neodymium, Fluorine, and Lithium from Molten-Salt Slag via Atmospheric Alkaline Leaching	2025
[88]	Yurramendi L.; Gijsemans L.; Forte F.; Aldana J.L.; del Río C.; Binnemans K.	Enhancing rare-earth recovery from lamp phosphor waste	2019

References

1. Han, Y.H.; Cui, X.W.; Zhang, Y.; Zhang, H.; Chen, Z. Environmental Impacts of Rare Earth Elements Mining and Strategies for Sustainable Management: A Comprehensive Review. *J. Hazard Mater.* **2025**, *500*, 140400. [CrossRef] [PubMed]
2. Septiarani, A.; Wijayanti, R.; Rodliyah, I.; Hidayat, K.N.; Purnama, A.B.; Dayyan, D.Z.; Rochani, S.; Andriani, A.; Torabi, S.A.; Sariman; et al. Extraction of Rare Earth Elements from Ion-Adsorption Clay Deposit of Keposang Toboali, South Bangka, Indonesia: Mineralogical Analysis and Diagnostic Leaching. *Hydrometallurgy* **2026**, *239*, 106607. [CrossRef]
3. International Energy Agency (IEA). *The Role of Critical Minerals in Clean Energy Transitions*; World Energy Outlook Special Report: Paris, France, 2021.
4. Carrara, S.; Bobba, S.; Blagoeva, D.; Alves Dias, P.; Black, C. *Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU—Publications Office of the EU*; Publications Office of the European Union: Luxembourg, 2023.
5. Binnemans, K.; Jones, P.T.; Blanpain, B.; Van Gerven, T.; Pontikes, Y. Towards Zero-Waste Valorisation of Rare-Earth-Containing Industrial Process Residues: A Critical Review. *J. Clean. Prod.* **2015**, *99*, 17–38. [CrossRef]
6. European Commission. *Regulation of The European Parliament and of the Council*; European Commission: Brussels, Belgium, 2023.
7. European Commission. Communication from the Commission to the European, the Council, the European Economic and Social Committee and the Committee of the Regions Tackling the Challenges in Commodity Markets and on Raw Materials. 2011. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0025&utmpt.com (accessed on 15 June 2025).
8. Ramprasad, C.; Gwenzi, W.; Chaukura, N.; Izyan Wan Azelee, N.; Upamali Rajapaksha, A.; Naushad, M.; Rangabhashiyam, S. Strategies and Options for the Sustainable Recovery of Rare Earth Elements from Electrical and Electronic Waste. *Chem. Eng. J.* **2022**, *42*, 135992. [CrossRef]
9. Elwert, T.; Goldmann, D.; Römer, F.; Buchert, M.; Merz, C.; Schueler, D.; Sutter, J. Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles. *Recycling* **2016**, *1*, 25–60. [CrossRef]

10. United States Department of Energy. *Critical Materials Rare Earths Supply Chain: A Situational White Paper*; DOE: Washington, DC, USA, 2020.
11. Jha, M.K.; Kumari, A.; Panda, R.; Rajesh Kumar, J.; Yoo, K.; Lee, J.Y. Review on Hydrometallurgical Recovery of Rare Earth Metals. *Hydrometallurgy* **2016**, *165*, 2–26. [CrossRef]
12. Shukla, N.; Dhawan, N. Processing End-of-Life Tube Lights for Recovery of Rare Earth Oxides. *JOM* **2021**, *73*, 1090–1102. [CrossRef]
13. Dhawan, N.; Tanvar, H. A Critical Review of End-of-Life Fluorescent Lamps Recycling for Recovery of Rare Earth Values. *Sustain. Mater. Technol.* **2022**, *32*, e00401. [CrossRef]
14. Lukowiak, A.; Zur, L.; Tomala, R.; LamTran, T.N.; Bouajaj, A.; Strek, W.; Righini, G.C.; Wickleder, M.; Ferrari, M. Rare Earth Elements and Urban Mines: Critical Strategies for Sustainable Development. *Ceram. Int.* **2020**, *46*, 26247–26250. [CrossRef]
15. Seuring, S.; Gold, S. Conducting Content-Analysis Based Literature Reviews in Supply Chain Management. *Supply Chain. Manag. Int. J.* **2012**, *17*, 544–555. [CrossRef]
16. Mohsin, A.K.M.; Valentin, S.; Franz, A.; Plasch, M.; Gerschberger, M. Examining the Evolution of Sustainable Supply Chain Management: A Systematic Review and Bibliometric Analysis. *Sustain. Dev.* **2025**, *33*, 8213–8238. [CrossRef]
17. Mura, R.; Di Flauro, S.; Fratocchi, L. Collaboration Between Universities and Micro, Small and Medium Firms: A Structured Literature Review. *Ind. High. Educ.* **2025**, 1–32. [CrossRef]
18. Asgari, K.; Huang, Q.; Honaker, R.; Sabolsky, E. Investigating the Effect of Microwave Pretreatment on Bastnasite Grinding for Comminution Energy Reduction and Rare Earth Recovery. *Processes* **2024**, *12*, 2468. [CrossRef]
19. Allaedini, G.; Zhang, P. Treatment of Phosphoric Acid Sludge for Rare Earths Recovery II: Effect of Sonication and Flocculant Solution Temperature on Settling Rate. *Sep. Sci. Technol.* **2019**, *54*, 1842–1852. [CrossRef]
20. Alcaraz, L.; Saquinga, D.N.; Alguacil, F.J.; Escudero, E.; López, F.A. Application of Activated Carbon Obtained from Spent Coffee Ground Wastes to Effective Terbium Recovery from Liquid Solutions. *Metals* **2021**, *11*, 630. [CrossRef]
21. Wang, F.; Zhi, W.; Malfliet, A.; Blanpain, B.; Guo, M. Experimental Investigation of the Phase Relations in the $SiO_2Dy_2O_3CaO$ Ternary System. *Ceram. Int.* **2020**, *46*, 23534–23543. [CrossRef]
22. *ISO 16290:2013*; Space Systems—Definition of the Technology Readiness Levels (TRLs) and Their Criteria of Assessment. International Organization for Standardization: Geneva, Switzerland, 2013. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:16290:ed-1:v1:en (accessed on 4 December 2025).
23. Walton, A.; Williams, A. Rare Earth Recovery. *Mater. World* **2011**, *19*, 24–26.
24. Taglieri, L.; Fratocchi, L. Made in Europe Recovery of Rare Earth Elements: Is a Circular and Sustainable Value Chain Really Possible? *IFAC-PapersOnLine* **2025**, *59*, 1510–1515. [CrossRef]
25. Orlova, S.; Rassõlkin, A. Permanent Magnets in Sustainable Energy: Comparative Life Cycle Analysis. *Energies* **2024**, *17*, 6384. [CrossRef]
26. Taglieri, L.; Spera, A.; Gallifuoco, A. Green Recovery of Platform Chemicals from Hydrothermal Carbonization Process Water. *Bioresour. Technol. Rep.* **2024**, *26*, 101815. [CrossRef]
27. Peelman, S.; Kooijman, D.; Sietsma, J.; Yang, Y. Hydrometallurgical Recovery of Rare Earth Elements from Mine Tailings and WEEE. *J. Sustain. Metall.* **2018**, *4*, 367–377. [CrossRef]
28. Romano, P.; Birloaga, I.; Vegliò, F. Recovery of Platinum and Palladium from Spent Automotive Catalysts: Study of a New Leaching System Using a Complete Factorial Design. *Minerals* **2023**, *13*, 479. [CrossRef]
29. Romano, P.; Rahmati, S.; Adavodi, R.; Clementini, G.; Gallo, F.; Vegliò, F. Study of the Kinetics and Mechanisms of Rare Earth Elements Leaching from End-of-Life NdFeB Magnets through Hydro-Nd Process. *Sep. Purif. Technol.* **2025**, *356*, 129850. [CrossRef]
30. Habashi, F. Fire and the Art of metals A Short History of Pyrometallurgy. In *VII International Conference on Molten Slags, Fluxes and Salts, The South African Institute of Mining and Metallurgy*; The South African Institute of Mining and Metallurgy: Gautengt, South Africa, 2004.
31. Schippers, A.; Hedrich, S.; Vasters, J.; Drobe, M.; Sand, W.; Willscher, S. Biomining: Metal Recovery from Ores with Microorganisms. *Adv. Biochem. Eng. Biotechnol.* **2013**, *141*, 1–47. [CrossRef]
32. Biswal, B.K.; Balasubramanian, R. Recovery of Valuable Metals from Spent Lithium-Ion Batteries Using Microbial Agents for Bioleaching: A Review. *Front. Microbiol.* **2023**, *14*, 1197081. [CrossRef] [PubMed]
33. Orefice, M.; Van den Bulck, A.; Blanpain, B.; Binnemans, K. Selective Roasting of Nd–Fe–B Permanent Magnets as a Pretreatment Step for Intensified Leaching with an Ionic Liquid. *J. Sustain. Metall.* **2020**, *6*, 91–102. [CrossRef]
34. Ou, Z.; Li, J.; Wang, Z. Application of Mechanochemistry to Metal Recovery from Second-Hand Resources: A Technical Overview. *Env. Sci. Process. Impacts* **2015**, *17*, 1522–1530. [CrossRef]
35. Innocenzi, V.; Ippolito, N.M.; Pietrelli, L.; Centofanti, M.; Piga, L.; Vegliò, F. Application of Solvent Extraction Operation to Recover Rare Earths from Fluorescent Lamps. *J. Clean. Prod.* **2018**, *172*, 2840–2852. [CrossRef]

36. Ippolito, N.M.; Amato, A.; Innocenzi, V.; Ferella, F.; Zueva, S.; Beolchini, F.; Vegliò, F. Integrating Life Cycle Assessment and Life Cycle Costing of Fluorescent Spent Lamps Recycling by Hydrometallurgical Processes Aimed at the Rare Earths Recovery. *J. Environ. Chem. Eng.* **2022**, *10*, 107064. [CrossRef]
37. Abrahami, S.T.; Xiao, Y.; Yang, Y. Rare-Earth Elements Recovery from Post-Consumer Hard-Disc Drives. *Trans. Inst. Min. Metall. Sect. C Miner. Process. Extr. Metall.* **2015**, *124*, 106–115. [CrossRef]
38. Meng, X.; Zhao, H.; Zhao, Y.; Shen, L.; Gu, G.; Qiu, G. Effective Recovery of Rare Earth from (Bio)Leaching Solution through Precipitation of Rare Earth-Citrate Complex. *Water Res.* **2023**, *233*, 119752. [CrossRef]
39. Shukla, N.; Dhawan, N. Evaluation of Baking Process for Rare-Earth Recovery from Discarded Tube Lights Phosphor. *Min. Metall. Explor.* **2022**, *39*, 1571–1586. [CrossRef]
40. Lin, J.; Kou, J.; Wen, X.; Xu, H. Migration and Enrichment of Rare Earth Elements in the Flotation Process of Rare Earth-Bearing Collophanite. *Separations* **2025**, *12*, 90. [CrossRef]
41. Tian, Z.; Zhang, Q.; Wu, Y.; Yin, X.; Liu, X.-M.; Wang, H.; Pang, W. Alkali Fusion Deconstruction and Rare-Earth Recovery from Hazardous Spent Fluorescent Lamp Phosphors: Experimental and Theoretical Calculations. *ACS Sustain. Chem. Eng.* **2025**, *13*, 1894–1905. [CrossRef]
42. Zhong, X.; Qing, J.; Deng, S.; Du, J.; Zeng, L.; Li, Q.; Zhang, G.; Wu, S. Complete Recovery of Rare Earths from Waste LYSO Crystals by Thermal Shock Treatment and Reinforcement Decomposition. *J. Environ. Chem. Eng.* **2024**, *12*, 113659. [CrossRef]
43. Romano, P.; Ippolito, N.M.; Vegliò, F. Chemical Characterization of an ARDUINO® Board and Its Surface Mount Devices for the Evaluation of Their Intrinsic Economic Value. *Processes* **2023**, *11*, 1911. [CrossRef]
44. Wu, Y.; Song, M.; Zhang, Q.; Wang, W. Review of Rare-Earths Recovery from Polishing Powder Waste. *Resour. Conserv. Recycl.* **2021**, *171*, 105660. [CrossRef]
45. Opare, E.O.; Struhs, E.; Mirkouei, A. A Comparative State-of-Technology Review and Future Directions for Rare Earth Element Separation. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110917. [CrossRef]
46. Lu, G.; Liang, H. Review and Test on Rare Earths Recovery from Polishing Powder Waste. *Heliyon* **2024**, *10*, e40785. [CrossRef]
47. Artiushenko, O.; da Silva, R.F.; Zaitsev, V. Recent Advances in Functional Materials for Rare Earth Recovery: A Review. *Sustain. Mater. Technol.* **2023**, *37*, e00681. [CrossRef]
48. Song, H.; Zhu, H.; Wang, R.; Wen, S.; Yan, C.; Cong, W. A Novel Adsorptive Membrane for Rare Earth Recovery Prepared by Facile UV Grafting Using 3,3′, 4,4′-Benzophenone Tetracarboxylic Acid (BTA). *Chem. Eng. Sci.* **2025**, *302*, 120889. [CrossRef]
49. Azimi, G. Technological Advancements in Rare Earth Elements Recovery from Ionic Clays: A Comprehensive Review. *Hydrometallurgy* **2025**, *231*, 106414. [CrossRef]
50. Kitagawa, J.; Uemura, R. Rare Earth Extraction from NdFeB Magnet Using a Closed-Loop Acid Process. *Sci. Rep.* **2017**, *7*, 8039. [CrossRef]
51. Dupont, D.; Binnemans, K. Recycling of Rare Earths from NdFeB Magnets Using a Combined Leaching/Extraction System Based on the Acidity and Thermomorphism of the Ionic Liquid [Hbet][Tf2N]. *Green Chem.* **2015**, *17*, 2150–2163. [CrossRef]
52. Roshanak, R.A.; Taglieri, L.; Romano, P.; Ferella, F.; Vegliò, F. Exploring Hydrothermal Leaching for Selective Metal Recovery from Spent DeNOx Catalysts. In Proceedings of the GRICU 2025 Congress & GRICU/NEST Doctoral School + CAPE Forum, Ischia, Italy, 17–20 September 2025.
53. Li, X.; Li, Z.; Binnemans, K. Closed-Loop Process for Recovery of Metals from NdFeB Magnets Using a Trichloride Ionic Liquid. *Sep. Purif. Technol.* **2021**, *275*, 119158. [CrossRef]
54. European Commission. Commission Selects 47 Strategic Projects to Secure Diversify Access to Raw Materials in the EU. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_25_864 (accessed on 15 June 2025).
55. Bandara, H.D.; Field, K.D.; Emmert, M.H. Rare earth recovery from end-of-life motors employing green chemistry design principles. *Green Chem.* **2016**, *18*, 753–759. [CrossRef]
56. Brewer, A.; Dohnalkova, A.; Shutthanandan, V.; Kovarik, L.; Chang, E.; Sawvel, A.M.; Mason, H.E.; Reed, D.; Ye, C.; Hynes, W.F.; et al. Microbe Encapsulation for Selective Rare-Earth Recovery from Electronic Waste Leachates. *Environ. Sci. Technol.* **2019**, *53*, 13888–13897. [CrossRef] [PubMed]
57. Dasgupta, K.; Vijayalakshmi, R.; Anitha, M. Recovery of Nd(III) in coexistence with Fe(III) ions from aqueous phase using functionalized multiwalled carbon nanotubes: An environmental benign approach. *J. Environ. Chem. Eng.* **2016**, *4*, 2103–2113. [CrossRef]
58. Innocenzi, V.; Ippolito, N.M.; De Michelis, I.; Medici, F.; Vegliò, F. A hydrometallurgical process for the recovery of terbium from fluorescent lamps: Experimental design, optimization of acid leaching process and process analysis. *J. Environ. Manag.* **2016**, *184*, 552–559. [CrossRef]
59. Innocenzi, V.; Vegliò, F. Recovery of rare earths and base metals from spent nickel–metal hydride batteries by sequential sulphuric acid leaching and selective precipitations. *J. Power Sources* **2012**, *211*, 184–191. [CrossRef]
60. Ippolito, N.M.; Ferella, F.; Innocenzi, V.; Trapasso, F.; Passeri, D.; Belardi, G.; Vegliò, F. Effect of mechanical activation on terbium dissolution from waste fluorescent powders. *Miner. Eng.* **2021**, *167*, 106906. [CrossRef]

61. Itoh, M.; Miura, K.; Machida, K. Novel rare earth recovery process on Nd–Fe–B magnet scrap by selective chlorination using NH_4Cl. *J. Alloys Compd.* **2009**, *477*, 484–487. [CrossRef]
62. Jiang, Y.; Deng, Y.; Xin, W. Oxidative roasting–selective pressure leaching process for rare earth recovery from NdFeB magnet scrap. *Trans. Indian Inst. Met.* **2020**, *73*, 703–711. [CrossRef]
63. Klemettinen, A.; Adamski, Z.; Leśniewicz, A.; Rycerz, L. Semicontinuous Process of Rare Earths Recovery from End-of-Life NdFeB Magnets on a Large Laboratory Scale. *Minerals* **2023**, *13*, 862. [CrossRef]
64. Korkmaz, K.; Alemrajabi, M.; Rasmuson, Å.; Forsberg, K. Recoveries of valuable metals from spent nickel metal hydride vehicle batteries via sulfation selective roasting, and water leaching. *J. Sustain. Metall.* **2018**, *4*, 313–325. [CrossRef]
65. Korkmaz, K.; Alemrajabi, M.; Rasmuson, Å.C.; Forsberg, K.M. Separation of valuable elements from NiMH battery leach liquor via antisolvent precipitation. *Sep. Purif. Technol.* **2020**, *234*, 115812. [CrossRef]
66. Li, L.; Xu, S.; Ju, Z.; Wu, F. Recovery of Ni, Co and rare earths from spent Ni–metal hydride batteries and preparation of spherical $Ni(OH)_2$. *Hydrometallurgy* **2009**, *100*, 41–46. [CrossRef]
67. Liu, C.; Luo, W.; Li, Y.; Wang, Z.; Xu, S.; Wang, X. Extraction of rare earth Eu from waste blue phosphor strengthened by microwave alkali roasting. *J. Environ. Manag.* **2024**, *362*, 121303. [CrossRef]
68. Liu, C.; Yan, Q.; Zhang, X.; Lei, L.; Xiao, C. A one-pot process based on P44414Cl–HCl aqueous biphasic system for recovering rare earth elements from NdFeB permanent magnet. *Chin. Chem. Lett.* **2022**, *33*, 953–956. [CrossRef]
69. Lorenz, T.; Bertau, M. Recycling of rare earth elements from FeNdB magnets via solid-state chlorination. *J. Clean. Prod.* **2019**, *215*, 131–143. [CrossRef]
70. Nogueira, M.; Matos, I.; Bernardo, M.; Pinto, F.; Fonseca, I.; Lapa, N. Recovery of Nd^{3+} and Dy^{3+} from E-Waste Using Adsorbents from Spent Tyre Rubbers: Batch and Column Dynamic Assays. *Molecules* **2025**, *30*, 92. [CrossRef]
71. Onoda, H.; Iinuma, A. Selective preparation of neodymium phosphates from iron mixed solution by two-step precipitation. *J. Environ. Chem. Eng.* **2020**, *8*, 104083. [CrossRef]
72. Onoda, H.; Iinuma, A. Effects of dissolution conditions on the recovery of neodymium phosphate from waste magnets. *J. Mater. Sci. Eng. B* **2022**, *12*, 16–22. [CrossRef]
73. Onoda, H.; Iinuma, A. Selective formation of neodymium phosphate from iron–neodymium magnet waste. *Cerâmica* **2022**, *68*, 703–711. [CrossRef]
74. Pavón, S.; Lapo, B.; Fortuny, A.; Sastre, A.M.; Bertau, M. Recycling of rare earths from fluorescent lamp waste by the integration of solid-state chlorination, leaching and solvent extraction processes. *Sep. Purif. Technol.* **2021**, *272*, 118879. [CrossRef]
75. Pavón, S.; Lorenz, T.; Fortuny, A.; Sastre, A.M.; Bertau, M. Rare earth elements recovery from secondary wastes by solid-state chlorination and selective organic leaching. *Waste Manag.* **2021**, *122*, 55–63. [CrossRef]
76. Pietrelli, L.; Bellomo, B.; Fontana, D.; Montereali, M.R. Rare earths recovery from NiMH spent batteries. *Hydrometallurgy* **2002**, *66*, 135–139. [CrossRef]
77. Prodius, D.; Gandha, K.; Mudring, A.-V.; Nlebedim, I.C. Sustainable urban mining of critical elements from magnet and electronic wastes. *ACS Sustain. Chem. Eng.* **2020**, *8*, 1455–1463. [CrossRef]
78. Rinne, M.; Elomaa, H.; Porvali, A.; Lundström, M. Simulation-based life cycle assessment for hydrometallurgical recycling of mixed LIB and NiMH waste. *Resour. Conserv. Recycl.* **2021**, *170*, 105586. [CrossRef]
79. Sawada, T.; Asada, M.; Serizawa, T. Selective rare earth recovery employing filamentous viruses with chemically conjugated peptides. *ChemistrySelect* **2016**, *1*, 2712–2716. [CrossRef]
80. Shi, J.; Chen, D.; Chen, M.; Qiu, Y.; Dong, J.; Hou, C.; Zhang, F.; Li, J. Sulfation roasting for rare earth recovery from NdFeB scrap: Kinetics, thermodynamics, and phase transformation. *Process Saf. Environ. Prot.* **2025**, *195*, 106804. [CrossRef]
81. Su, X.; Guo, X.; Zhao, Z.; Dong, Y.; Wang, Y.; Li, F.; Sun, X. An efficient and sustainable $[P6,6,6,14]_2$[BDOAC] ionic liquid based extraction–precipitation strategy for rare earth recovery. *Chem. Eng. Res. Des.* **2018**, *136*, 786–794. [CrossRef]
82. Van Loy, S.; Binnemans, K.; Van Gerven, T. Mechanochemical-assisted leaching of lamp phosphors: A green engineering approach for rare-earth recovery. *Engineering* **2018**, *4*, 398–405. [CrossRef]
83. Wang, Z.; Liu, C.; Li, Y.; Zeng, J.; Luo, W.; Wang, X. Thermal evolution of mercury from waste rare earth phosphor: Effect of thermal treatment conditions and kinetic analysis. *J. Environ. Chem. Eng.* **2024**, *12*, 113908. [CrossRef]
84. Wu, S.; Bie, C.; Gao, Y.; Sun, X. A novel bifunctional ionic liquid [N1888][OOB] for the separation of rare earth and transition metal in NdFeB magnet. *Mater. Today Sustain.* **2024**, *26*, 100713. [CrossRef]
85. Xu, B.; E, S.; Liu, J.; Niu, B.; Qin, Y. Machine learning-guided rare earth recovery from NdFeB magnet waste: Model development, parameter influence analysis and experimental validation. *J. Environ. Manag.* **2025**, *384*, 125578. [CrossRef] [PubMed]
86. Yang, D.; Gao, S.; Hong, J.; Ye, L.; Ma, X.; Qi, C.; Li, X. Life cycle assessment of rare earths recovery from waste fluorescent powders—A case study in China. *Waste Manag.* **2019**, *99*, 60–70. [CrossRef]

87. Yu, M.; Huang, G.; Zhang, T. Kinetic Mechanisms and Efficient Leaching of Praseodymium, Neodymium, Fluorine, and Lithium from Molten-Salt Slag via Atmospheric Alkaline Leaching. *Processes* **2025**, *13*, 1025. [CrossRef]
88. Yurramendi, L.; Gijsemans, L.; Forte, F.; Aldana, J.L.; del Río, C.; Binnemans, K. Enhancing rare-earth recovery from lamp phosphor waste. *Hydrometallurgy* **2019**, *187*, 38–44. [CrossRef]

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