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Recovery of Rare Earth Elements from Hard Disk Drives: Technologies, Challenges, and Circular Economy Perspectives

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ABSTRACT **Review Article**

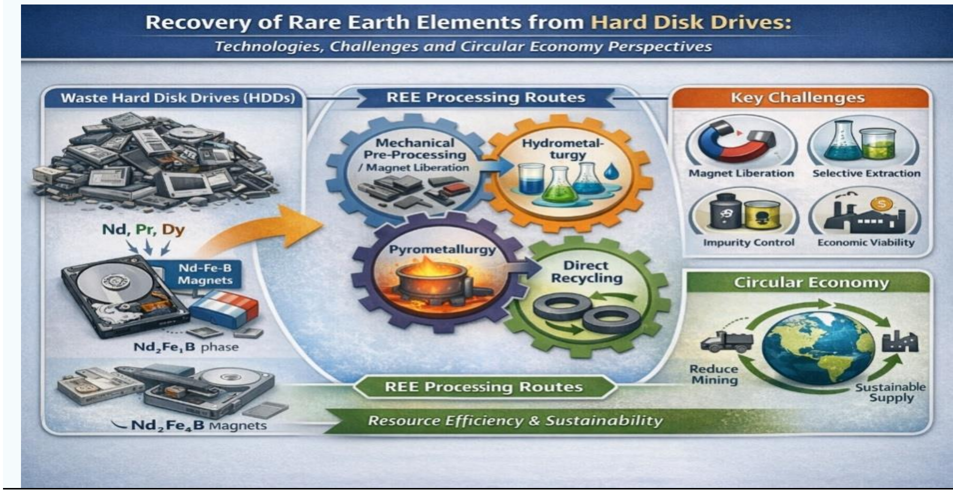
Rare earth elements (REEs), especially neodymium (Nd), praseodymium (Pr), and dysprosium (Dy), are crucial for modern technologies because they are necessary for high-performance permanent magnets used in electronics, renewable energy systems, and electric vehicles. The rapid expansion of digital technologies has led to a significant increase in electronic waste (e-waste), which presents both environmental challenges and opportunities for resource recovery. Hard disk drives (HDDs), commonly used for data storage, contain NdFeB permanent magnets that serve as a valuable secondary source of REEs within the emerging field of urban mining. Efforts to recover REEs from HDDs are gaining importance in both research and industry, with various methods being explored, including mechanical dismantling, pyrometallurgical processing, hydrometallurgical leaching and separation, and direct magnet-to-magnet recycling. Although there are promising developments, several technical and economic barriers remain, such as efficient magnet separation, selective extraction of rare earths, impurity control, process scalability, and environmental concerns. This critical review discusses current technologies for REE recovery from HDDs, comparing different processing approaches and evaluating their benefits, limitations, and technological readiness. Special emphasis is placed on integrating recycling into circular economy models, highlighting opportunities for resource efficiency, reducing primary mining, and ensuring a sustainable supply of critical materials. The review also identifies key knowledge gaps and research priorities needed to enable large-scale industrial recycling of HDDs.

Keywords: Rare earth elements, NdFeB magnets, Hard disk drive recycling, Urban mining, Hydrometallurgy, Magnet-to-magnet recycling, Circular economy.

Highlights

- Hard disk drives (HDDs) represent an important secondary source of rare earth elements, particularly Nd, Pr, and Dy contained in NdFeB permanent magnets.
- Multiple recycling routes have been developed for REE recovery from HDDs, including mechanical separation, hydrometallurgical extraction, pyrometallurgical processing, and direct magnet-to-magnet recycling.
- Key challenges include efficient magnet liberation, selective separation of rare earth elements, impurity control, and the economic viability of large-scale recycling processes.
- Integrating HDD recycling into circular economy strategies can reduce dependence on primary mining and contribute to a more sustainable supply of critical materials.

Graphical Abstract



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Introduction

Rare earth elements (REEs) are vital for high-performance technologies due to their unique magnetic and electronic properties, influencing energy, electronics, and manufacturing choices. Critical REEs such as Nd, Pr, and Dy are key to permanent magnets. However, REE supply faces price volatility, geopolitical risks, and environmental issues, prompting interest in secondary sources and recycling.

NdFeB magnets dominate REE applications in high-efficiency devices. Demand from electrification, automation, and renewables is strong, but the supply chain faces disruptions and quality issues (Binnemans & Jones, 2022; Binnemans et al., 2020). Recycling is often proposed as a solution, yet many methods still struggle with selectivity, impurities, and economics in real-world settings (Golev et al., 2021; Rademaker et al., 2020). A critical review must weigh technical feasibility against industrial practicality.

Electronic waste (e-waste) is a practical entry point for urban mining because it aggregates metals in accessible logistics networks. However, e-waste is heterogeneous, and REEs occur in small mass fractions and in components that are not always designed for recovery (Akcil et al., 2021; Buchert et al., 2020). Collection, dismantling, and preprocessing largely determine whether downstream separation routes can be efficient and low-impact (Cossu & Williams, 2020; Cucchiella et al., 2020). This is especially true for permanent magnets, where mixing with steel, coatings, adhesives, and polymeric parts can amplify reagent demand and contaminate products (Chen, Li, & Xu, 2021).

Hard disk drives (HDDs) are a significant component of e-waste and contain NdFeB magnets with high REE content. They are an attractive “urban mine," but recovery depends on dismantling, magnet extraction, and controlling oxidation and contamination (Frost et al., 2020; München et al., 2021). Circularity claims are sensitive to collection rates, design variability, and material flow uncertainties, which must be explicitly addressed (Walzberg et al., 2022).

The rare earth recycling's economic importance is tied to the rapid growth of the rare earth magnet market. Estimated at USD 3.95 billion in 2024, it is projected to reach USD 6.28 billion by 2030. Meanwhile, the magnet market surpassed USD 20 billion in 2024 and is expected to grow further driven by demand from electric vehicles, wind energy, and electronics (Grand View Research, 2024; Marketsand Markets, 2025).

The growth of low-carbon technologies has raised demand for rare earths such as neodymium and praseodymium, which are used in NdFeB magnets. Understanding the link between the rare earth market and magnet demand is key for recycling potential. Market forecasts are shown in Figure 1.

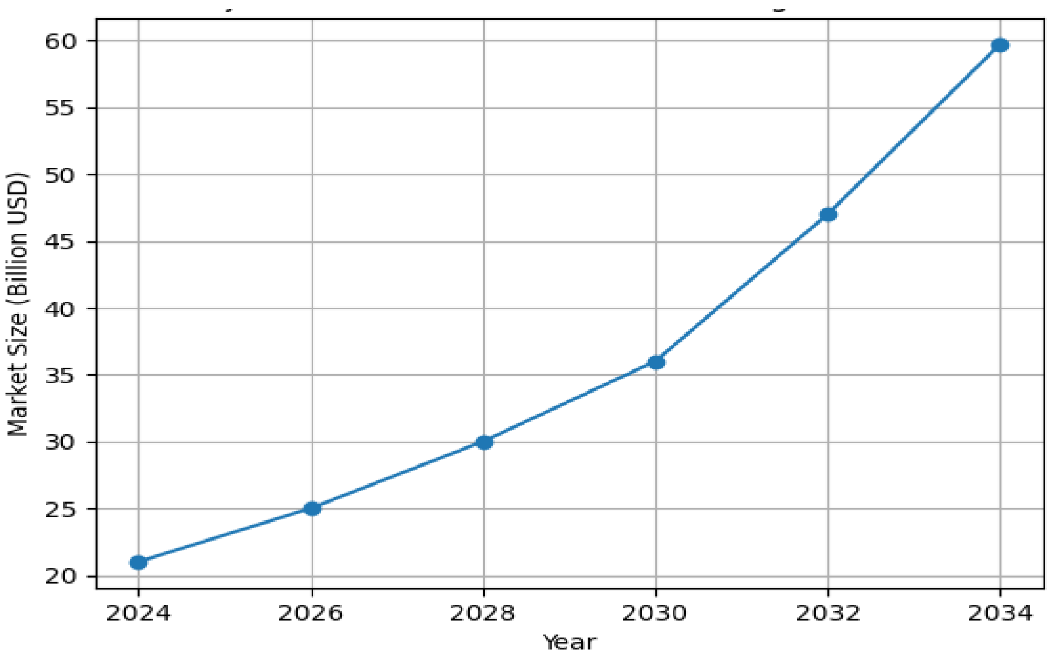

Figure 1. Global rare earth magnet market growth and projected demand for NdFeB magnets. Adapted from MarketsandMarkets (2025) and Grand View Research (2024).

Figure 1 shows the projected growth of the rare earth magnet market compared to the overall rare earth elements market. The rapid expansion of NdFeB magnets reflects rising demand from electric vehicles, renewable energy, and advanced electronics, which need high-performance magnets with neodymium, praseodymium, and dysprosium.

The figure highlights a challenge in the rare earth supply chain: demand for magnet-grade elements outpaces production, heightening supply risks and emphasizing secondary resources such as electronic waste (Balaram, 2021; Binnemans et al., 2020; Golev et al., 2021). In this context, recycling NdFeB magnets from end-of-life electronics, including hard disk drives, is increasingly considered a complementary source of rare earth supply.

This review evaluates technologies for recovering REEs from HDD-derived NdFeB magnets, including pre-treatment, magnet separation, hydrometallurgical and pyrometallurgical routes, and direct "magnet-to-magnet" recycling. It aims to identify routes near industrial deployment, remaining barriers, and unsupported claims under scale-up constraints. The analysis highlights selectivity for Nd–Pr–Dy, iron management, reagent and energy use, and circular economy implications (Binnemans et al., 2020; Ganguli & Cook, 2020; Ramprasad et al., 2022).

The next section explains the review methodology, including search strategy, screening, and inclusion criteria to build the evidence base and prevent orphan claims (Page et al., 2021).

Methodology

This review uses a structured screening approach to reduce bias and trace sources. It aims to highlight studies on recovering REEs from HDD magnets and NdFeB recycling, prioritizing relevance and clarity over volume.

Search Strategy and Reporting Guideline

The literature search and screening followed PRISMA 2020 guidelines (Page et al., 2021), which structured the identification, screening, and eligibility stages, improving transparency and reducing bias.

Searches in Scopus, Web of Science, and Google Scholar covered publications from 2020 to 2026, reflecting the rapid development of recycling technologies for NdFeB magnets.

Keywords were combined with Boolean operators. Typical search strings included:

"rare earth recycling" AND NdFeB, "hard disk drive magnet recycling", "NdFeB hydrometallurgy", "rare earth recovery electronic waste", "magnet-to-magnet recycling"

The search included terms on pre-treatment, hydrogen decrepitation, hydrometallurgy, pyrometallurgy, and recycling routes to cover all technological approaches.

The selection process followed PRISMA 2020 guidelines for systematic reviews. Publications on rare earth recovery from NdFeB magnets, HDD recycling, and electronic waste were found through database searches and screened based on criteria. The workflow is summarized in Figure 2.

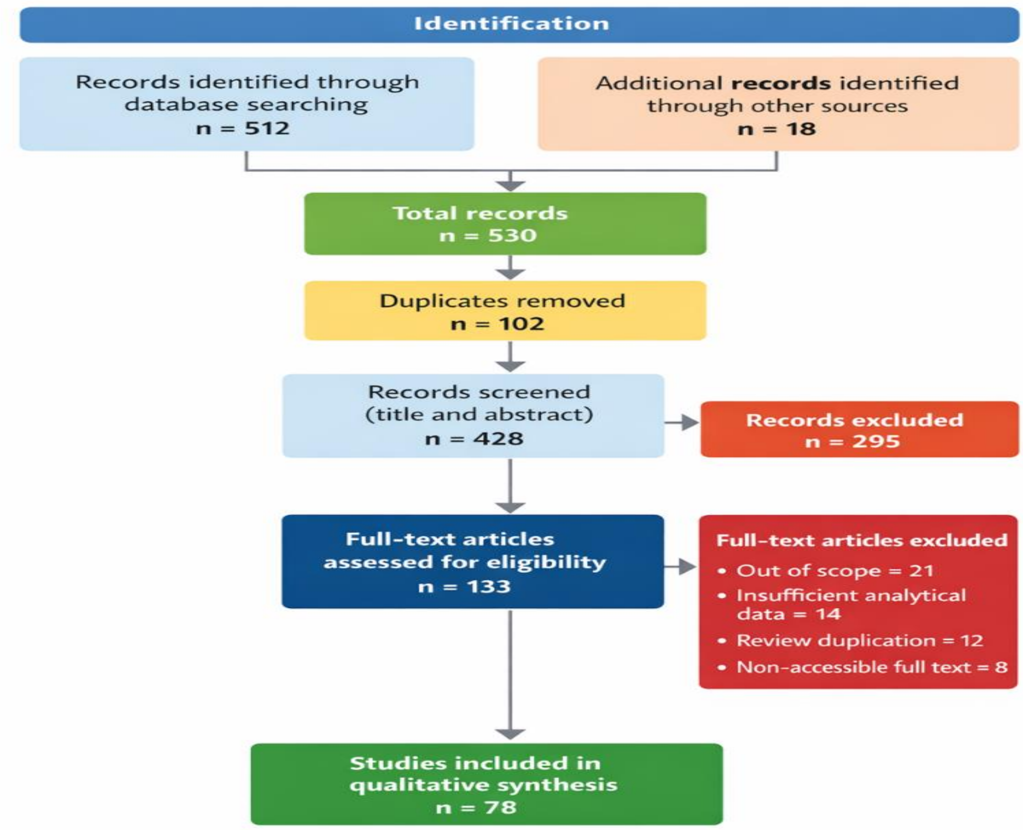

Figure 2. PRISMA flow diagram describing the literature screening process used in this review. Adapted from Page et al. (2021).

Figure 2 summarizes the literature selection workflow. Records from database searches were screened to remove duplicates and irrelevant publications. Full-text articles were then assessed based on the inclusion criteria for this review. After screening and eligibility checks, 78 references remained and were analyzed in the final dataset.

After initial search, duplicate records were removed. Titles and abstracts were reviewed for publications recovery, the recovery of rare earths from permanent magnets or similar e-waste. Full texts were analyzed for relevance, transparency, and suitability for NdFeB recycling.

Inclusion and Exclusion Criteria

The review focuses on the recovery of rare earths from HDD magnets and NdFeB waste. Studies on general rare-earth extraction from ores or unrelated waste streams were excluded unless they directly contributed to magnet recycling technology.

The main inclusion criteria were:

- Studies on recycling or recovery of rare earth elements from NdFeB magnets
- Research on electronic waste streams that contain permanent magnets
- Articles covering hydrometallurgical, pyrometallurgical, or direct recycling methods
- Publications reporting experimental results, process design, or industrial evaluations

The exclusion criteria included:

- Studies focused solely on primary rare earth mining
- Articles without experimental or technological relevance
- Publications lacking sufficient methodological detail

This approach focused the review on relevant process routes, avoiding peripheral topics. Similar criteria have been used in previous studies on rare earth recycling and e-waste (Akcil et al., 2021; Ramprasad et al., 2022; Hamzat et al., 2025).

While PRISMA enhances transparency, biases remain due to database coverage, keyword choice, and language. These limitations are acknowledged in interpreting the literature.

The next section looks at the structure and materials of hard disk drives, focusing on the location, composition, and mass fraction of NdFeB magnets. Understanding these helps assess the feasibility and efficiency of recycling.

Structure and Composition of Hard Disk Drives

Understanding HDDs' structure is key to assessing their potential as REE sources. They contain metal-rich parts, but REEs are mainly in the actuator system's permanent magnets, often NdFeB alloys containing neodymium, praseodymium, and sometimes dysprosium.

Because these magnets constitute the primary reservoir of REEs in HDDs, dismantling and targeted component separation are critical steps in any recycling strategy. If HDDs are shredded without prior magnet extraction, rare earth elements become diluted in mixed metal fractions, significantly reducing recovery efficiency (Burkhardt et al., 2024; Frost et al., 2020; München et al., 2021).

Components of HDD

A traditional HDD consists of mechanical, magnetic, and electronic parts enclosed within a sealed casing. The main components include:

- outer enclosure (aluminum or steel),
- magnetic platters,
- spindle motor,
- actuator arm,
- read–write head assembly,
- printed circuit board,
- permanent magnets.

The actuator assembly is key for rare earth recovery as it contains NdFeB magnets that position the read–write head.

Hard disk drives (HDDs) have components made of metals, polymers, and electronic materials recoverable through recycling. The actuator assembly has Nd–Fe–B permanent magnets, an important secondary REE source, especially neodymium and praseodymium. Figure 3 shows a disassembled HDD with NdFeB magnets in the actuator, visualizing key components for REE recovery.

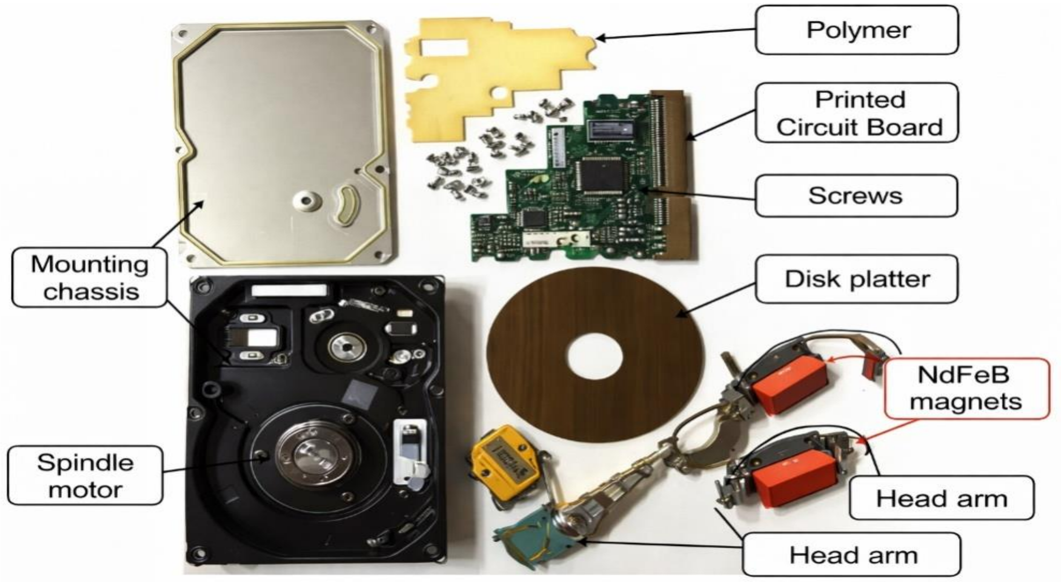

Figure 3. Location of NdFeB permanent magnets in the actuator assembly of a typical hard disk drive. Adapted from Frost et al. (2020) and München et al. (2021).

The actuator system features two curved NdFeB magnets around a copper voice coil, creating a magnetic field for precise head positioning. Although small, these magnets contain most of the rare-earth elements used in HDDs.

Studies show that selective extraction of actinides boosts rare-earth recovery. Manual disassembly yields high recovery but is labor-intensive; automated methods are being developed to increase throughput (Burkhardt et al., 2024).

Rare Earth Magnets in Actuator Systems

The voice coil actuator uses high-energy permanent magnets to provide rapid and precise movement of the read–write head. NdFeB magnets are widely used because they exhibit the highest magnetic energy density among commercially available permanent magnet materials.

From a recycling perspective, these magnets represent the most valuable component of HDD waste streams. However, their recovery depends on efficient separation from the surrounding steel structures and electronic components. Mechanical damage, excessive heating, or oxidation during dismantling may degrade magnet properties and complicate downstream recycling routes (Frost et al., 2020).

Consequently, the development of efficient dismantling processes has become a key research area in rare earth recycling from electronic waste.

Composition of NdFeB Magnets

NdFeB magnets consist of an iron-rich matrix containing rare earth elements and small amounts of boron. Praseodymium and dysprosium are often added to improve magnetic performance and thermal stability. Although the exact composition varies among magnet grades and manufacturers, typical ranges reported in the literature are relatively consistent (Binnemans et al., 2020; Tunsu et al., 2020; Zhang, Gu, et al., 2020).

NdFeB magnets mainly contain rare earths and iron, used in electronics, motors, and data storage. Their element proportions vary by grade and desired magnetic properties. Neodymium and praseodymium are the main rare earths, with dysprosium added for thermal stability and coercivity. Table 1 shows typical compositions.

Table 1. Typical composition range of NdFeB permanent magnets.Adapted from Binnemans et al. (2020), Tunsu et al. (2020), and Zhang, Gu, et al. (2020

Element	wt%
Nd	20–30
Pr	2–6
Dy	1–5
Fe	60–70
B	~1

The values presented in Table 1 represent typical composition ranges rather than fixed compositions. The proportion of dysprosium, for example, depends on the temperature resistance required for the magnet application. These variations influence recycling strategies because Dy-containing magnets require different separation considerations magnets.

Mass Fraction of Rare Earth Elements in HDDs

Although NdFeB magnets contain high concentrations of rare earth elements, their contribution to the total mass of an HDD is relatively small. Magnets typically represent only a few percent of the device's weight, yet they contain the majority of the recoverable rare earth content.

Estimates of material distribution in HDDs indicate that efficient magnet extraction is essential for maximizing recovery potential. If magnets remain mixed with steel scrap during shredding, rare earth elements become diluted and difficult to recover economically (München et al., 2021).

Life cycle assessments also show that pre-treatment steps such as dismantling and magnet separation significantly influence the environmental performance of recycling systems. Efficient recovery at this stage reduces chemical consumption and improves downstream process efficiency (Walzberg et al., 2022; Frost et al., 2021).

The structure of HDDs presents a key challenge for rare earth recycling: valuable materials are concentrated in small, specific parts, requiring targeted dismantling and integrated processing.

The next section examines global HDD waste and the resource value of rare earth elements in these devices, providing data to evaluate HDD recycling's industrial significance.

Global Generation of HDD Waste and Resource Potential

Electronic waste (e-waste) has become one of the fastest-growing waste streams worldwide. The rapid expansion of digital infrastructure, short product lifetimes, and frequent device replacement have significantly increased the volume of discarded electronic equipment. Within this context, hard disk drives (HDDs) are a relevant yet often overlooked source of rare earth elements (REEs), primarily present in NdFeB permanent magnets used in actuator systems.

Although HDDs account for only a fraction of total electronic waste, their magnets contain relatively high concentrations of neodymium, praseodymium, and dysprosium. These elements are essential for advanced technologies such as electric vehicles, wind turbines, robotics, and consumer electronics. Consequently, the recovery of REEs from HDD waste has attracted growing attention within the framework of **urban mining and circular economy strategies**.

Global Electronic Waste Generation

Global electronic waste generation has increased steadily over the last decade. Recent assessments estimate that worldwide e-waste production exceeds **50 million tonnes per year**, with projections indicating continued growth as digital technologies expand (Buchert et al., 2020; Cucchiella et al., 2020).

Despite the presence of valuable metals in electronic devices, recycling rates remain relatively low for many critical materials. Complex product design, inadequate collection systems, and technological limitations in material separation contribute to inefficient resource recovery from electronic waste streams (Cossu & Williams, 2020).

Electronic waste is seen as an urban mine for valuable metals, especially rare earth elements, which are geographically concentrated and vulnerable to supply disruptions (Chen, Li, & Xu, 2021).

Electronic waste contains valuable materials such as critical metals, precious metals, and rare earth elements across various components. Recovery is increasingly important due to the rapid growth of e-waste and the strategic value of these metals. Figure 4 shows electronic devices as secondary sources for critical metals and links rising e-waste to potential material recovery.

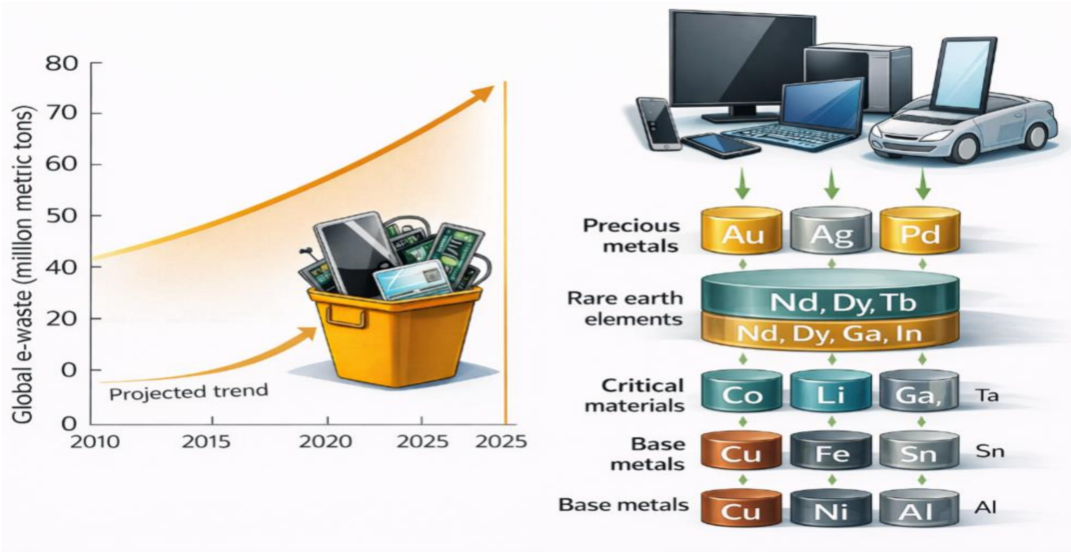

Figure 4. Global electronic waste generation and conceptual representation of electronic devices as secondary resources for critical metals. Adapted from Cucchiella et al. (2020) and Cossu and Williams (2020).

As shown in Figure 4, the rise in electronic waste creates opportunities to recover valuable materials like copper, gold, silver, cobalt, and rare earths from devices such as computers and smartphones. These metals are mainly in circuit boards, magnets, batteries, and electronics. E-waste is becoming a vital secondary resource for critical metals, supporting resource efficiency, and a circular economy while reducing reliance on primary mining.

HDD Disposal Trends

While solid-state storage is replacing HDDs in some areas, many HDDs still operate in personal computers, data centers, and industrial systems. When they reach the end of their life, large amounts of HDD waste enter the recycling stream.

HDDs are typically replaced after three to five years, especially in high-performance settings, leading to a steady disposal of units (Walzberg et al., 2022).

Many HDDs are stored temporarily after use, as data security concerns and recycling uncertainties delay their return to recovery systems (Frost et al., 2020).

Material flow analyses show the global increase in end-of-life HDD units, making HDD waste a growing source of rare earth elements (München et al., 2021).

Estimated REE Resource Potential

Although each HDD contains small amounts of rare earth elements, the cumulative potential is significant when many devices are considered. Studies using device production stats and magnet data estimate the total rare earth in HDD waste.

These analyses indicate discarded HDDs could be a secondary resource for neodymium and praseodymium if collection and recycling are efficient (München et al., 2021).

Comparative assessments indicate that urban mining could meet future rare-earth demand, primarily for magnets, but success hinges on the efficiency of collection and pre-treatment (Rademaker et al., 2020; Golev et al., 2021).

Hard disk drives (HDDs) are an important secondary source of rare earth elements, containing NdFeB magnets , which use neodymium and other elements such as dysprosium to achieve high magnetic performance. Estimating these materials per device helps resources. Table 2 summarizes typical HDD mass, magnet mass, and rare-earth element content from rare-earth element content reported in the literature.

Table 2. Estimated rare earth element content in HDD waste streams. Adapted from München et al. (2021), Nansai et al. (2021), and Rademaker et al. (2020)

Parameter	Typical range
Average HDD mass	0.5–0.7 kg
NdFeB magnet mass per HDD	10–30 g
Rare earth content in magnets	25–35 wt%
Nd content per HDD	~3–7 g
Dy content per HDD	~0.1–0.5 g

Table 2 summarizes typical estimates of rare earth content in HDD magnets. While individual devices contain only a few grams of rare earth elements, the aggregated resource potential becomes significant when millions of units are processed.

However, these estimates are subject to uncertainty in product lifetime, collection efficiency, and device storage. Many HDDs sit unused in households or data centers for extended periods before being recycled, delaying material recovery (Nansai et al., 2021).

HDD waste is a concentrated but dispersed resource. Effective recovery needs efficient collection and targeted processing to isolate NdFeB magnets.

The next section covers pre-treatment and magnet separation, the crucial initial step in recovering rare earths from HDD waste. These steps affect magnet purity and impact downstream recycling efficiency.

Pre-treatment and Magnet Separation

Pre-treatment is the initial step in recycling rare earths from hard disk drives, focusing on isolating NdFeB magnets prior to chemical or metallurgical processing. This step enhances the concentration of rare earths and reduces contamination risks.

HDDs have many metallic and electronic components, but few contain rare-earth elements. Therefore, separating magnets is crucial to prevent the rare-earth content in mixed scrap. This step greatly affects the success of later recovery processes.

Multiple methods exist for HDD magnet extraction, such as manual dismantling, automated systems, demagnetization, and mechanical processing. Each has pros and cons regarding cost, efficiency, and material purity.

Manual Dismantling

Manual dismantling is the common method for extracting NdFeB magnets from HDDs in labs and small-scale recycling. It involves opening the HDD, removing the actuator, and manually extracting the magnets.

Manual extraction precisely separates magnet components, reducing contamination from steel or electronics, and often yields high-purity magnet fractions for recycling or chemical recovery (Frost et al., 2020).

Manual dismantling requires significant labor and is hard to scale for large waste volumes. Its economic viability depends on labor costs and device complexity. In industrial recycling, it usually targets high-value components or small waste streams (Walzberg et al., 2022).

Automated Dismantling

Automated dismantling systems aim to improve HDD processing efficiency by using robotic manipulation, mechanical cutting, and sorting to remove magnets from actuator assemblies.

Automated dismantling offers advantages over manual extraction, including higher-volume processing, reduced reliance on manual labor, and standardized procedures that improve consistency (Burkhardt et al., 2024).

Despite advantages, automation faces challenges. HDD designs differ, hindering universal dismantling. Automated extraction risks damage or contamination if not precisely controlled.

Recovering rare earths from NdFeB magnets involves direct recycling, hydrometallurgy, and pyrometallurgy, each with advantages and limitations in terms of complexity, energy use, environmental impact, and recovery efficiency. Understanding these methods is key to designing efficient recycling systems for end-of-life electronics. Figure 5 summarizes the main routes.

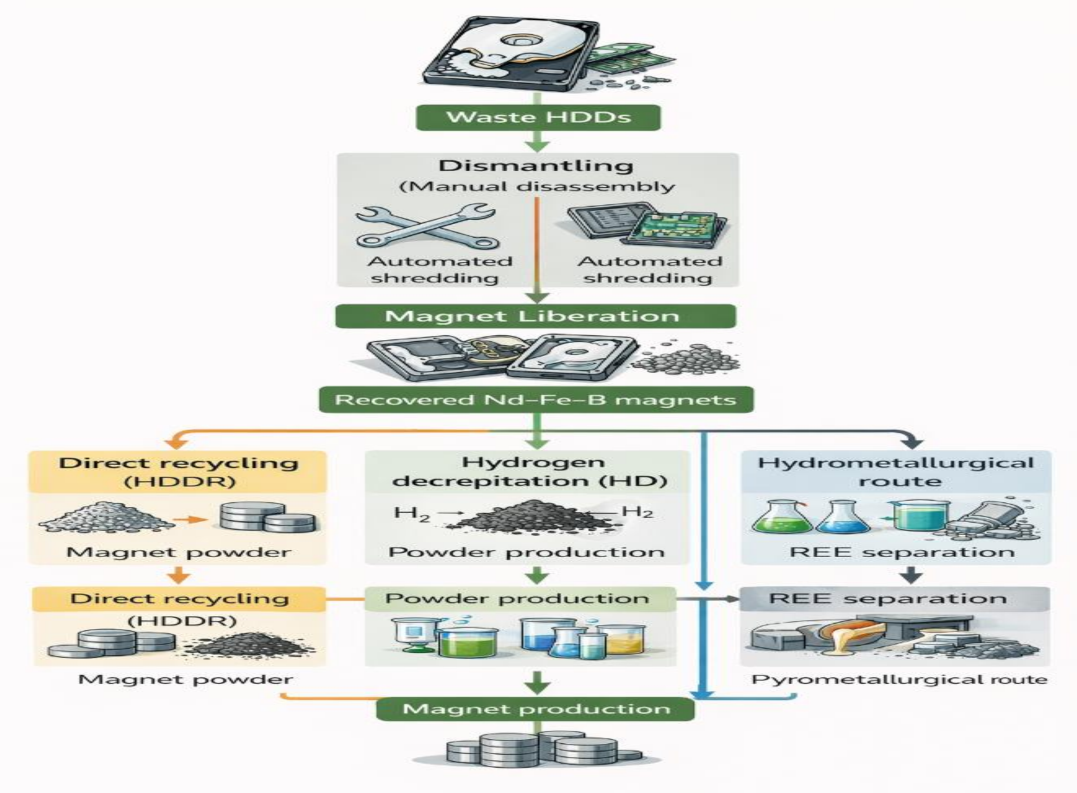

Figure 5. Schematic comparison of manual and automated dismantling routes for magnet extraction from HDDs. Adapted from Frost et al. (2020), Walzberg et al. (2022), and Burkhardt et al. (2024).

Figure 5 shows NdFeB magnet recycling methods. Direct recycling preserves the magnetic phase through hydrogen decrepitation, sintering, or melt spinning. Hydrometallurgical processes recover rare-earth elements such as neodymium and dysprosium through leaching, solvent extraction, and precipitation. Pyrometallurgical methods use high-temperature treatments such as roasting, smelting, or reduction to separate rare earths. The method chosen depends on feed composition, scale, costs, and environmental factors.

Demagnetization Techniques

After extraction from the HDD structure, NdFeB magnets are typically demagnetized prior to processing. Strong magnetic fields can disrupt mechanical separation and handling, especially when magnets attract metallic particles or surfaces.

Demagnetization is achieved by thermal treatment, heating magnets above their Curie temperature, or by alternative methods like applying alternating magnetic fields or mechanical disruption (Tunsu et al., 2020).

Thermal demagnetization is effective but requires careful temperature control to prevent material degradation, as excessive heat can alter the magnetic microstructure and affect recycling (Binnemans et al., 2020).

Recent studies explore low-energy demagnetization methods to reduce thermal damage and boost efficiency (Kaya, 2024).

Mechanical Processing

Mechanical processing, used after magnet extraction and demagnetization, prepares material for recovery through crushing, milling, and separation.

Fragmentation increases surface area, enhancing chemical leaching and metallurgical efficiency, and releases magnet particles from coatings, adhesives, and substrates (Karal et al., 2021).

Additional techniques, such as magnetic separation, sieving, and density-based separation, remove impurities such as steel fragments, aluminum, and polymer residues, thereby improving feed purity.

After extracting NdFeB magnets from HDDs, mechanical steps are used to reduce size, remove coatings or metals, and produce a uniform feed for hydrometallurgical or pyrometallurgical recycling. These steps also aid in separating ferrous materials and enhancing the recovery of rare-earth elements. Figure 6 shows these mechanical processing steps.

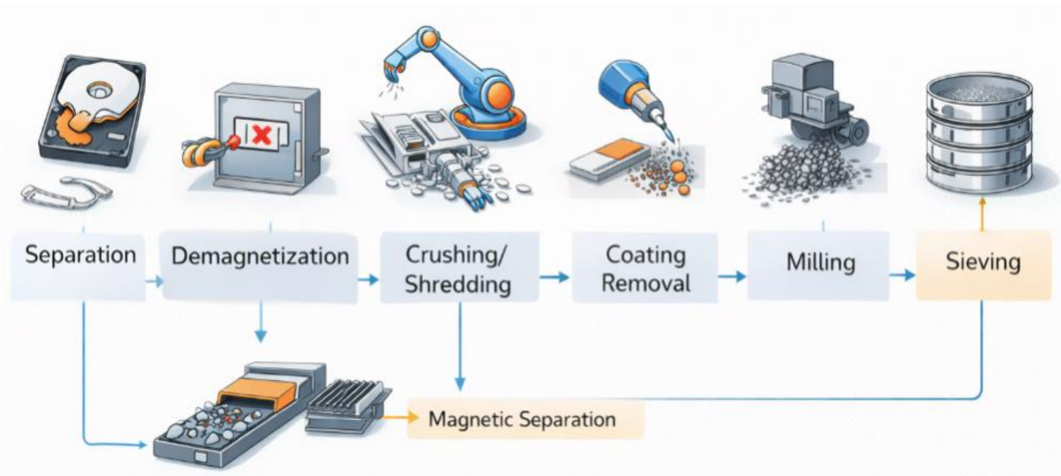

Figure 6. Typical mechanical processing steps applied to NdFeB magnets after extraction from HDDs. Adapted from Karal et al. (2021), Friebe et al. (2025), and Fironda et al. (2025).

Mechanical processing of NdFeB magnets involves sequential steps: magnet separation, demagnetization, crushing, milling, and sometimes coating removal, magnetic separation, and sieving. These pre-treatments are crucial for preparing waste for recycling and aiding the efficient recovery of rare-earth elements such as neodymium and dysprosium.

Mechanical processing improves material preparation, but excessive grinding produces powders that are difficult to handle and prone to oxidation. Process design must balance efficiency and safety.

Pre-treatment and magnetic separation are vital for recycling rare-earth elements from HDD waste, thereby improving NdFeB magnet recovery. The next section discusses hydrometallurgical recovery for extracting rare earths.

Hydrometallurgical Recovery Processes

Hydrometallurgical processing is one of the most widely investigated approaches for recovering rare earth elements (REEs) from NdFeB magnets. These routes typically involve the chemical dissolution of magnet alloys, followed by the separation and purification of rare-earth ions from solution. Compared with high-temperature processes, hydrometallurgical systems operate at moderate temperatures and allow flexible control of solution chemistry.

NdFeB magnets contain iron, and during dissolution, iron and REEs form complex solutions requiring multiple purification steps. Hydrometallurgical flowsheets mainly aim to efficiently separate REEs from iron-rich solutions, reducing reagent use and waste (Binnemans et al., 2020).

Hydrometallurgical processing efficiently recovers rare earths from NdFeB magnets through selective chemical treatments under moderate conditions. These involve dissolving the rare earths and separating them from iron and other components, with precise control of leaching and separation essential for high recovery and purity. Figure 7 illustrates a typical process flow.

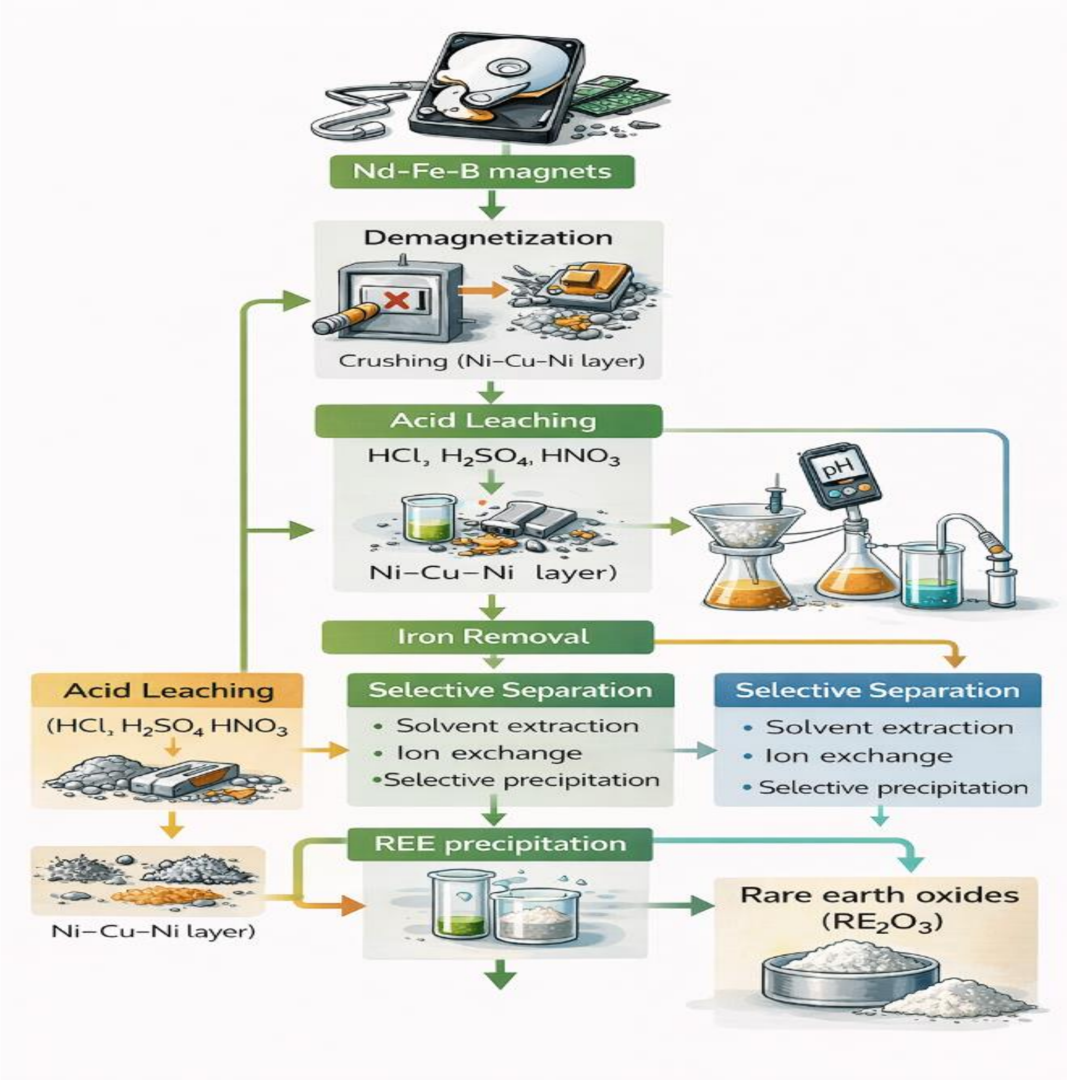

Figure 7. Hydrometallurgical flowsheet for rare earth recovery from NdFeB magnets. Typical steps include magnet pre-treatment, acid leaching, iron removal, selective separation of rare earth elements, and final recovery as oxides or salts. Adapted from Binnemans et al. (2020), Liu, Wang, and Zhang (2020), and Zhao, Chen, and Li (2023).

Figure 7 depicts a hydrometallurgical process for NdFeB recycling: the magnet material dissolves in acid, forming a leachate containing rare earths and iron. Then, iron is removed, rare earths are separated, purified, and recovered.

Acid Leaching Systems

Acid leaching is usually the initial step in recovering rare earths from NdFeB magnets. Mineral acids such as HCl and H_2SO_4 are used because they dissolve rare-earth elements and the iron matrix.

Hydrochloric acid leaching is popular due to its fast dissolution and compatibility with separation processes. Optimized conditions have achieved over 95% dissolution efficiency for rare earth elements (Liu, Wang, & Zhang, 2020).

Sulfuric acid systems are often used, achieving high dissolution yields but potentially complicating purification due to iron sulfate species (Zhang, Gu, et al., 2020).

Recent research explores improved leaching systems using oxidizing agents, temperature control, and optimized acid concentrations to enhance dissolution and reduce processing time (Zhu, Cheng, & Wang, 2021; Cheng et al., 2025).

Table 3 summarizes representative leaching systems reported in the literature. Although high rare earth dissolution efficiencies are frequently achieved, these systems also dissolve large amounts of iron, which must be removed during subsequent purification stages

Table 3. Summary of hydrometallurgical leaching systems applied to NdFeB magnet recycling. Adapted from Liu, Wang, and Zhang (2020), Zhang, Gu, et al. (2020), and Zhu, Cheng, and Wang (2021).

Process	Reagent	Typical REE recovery
HCl leaching	Hydrochloric acid	>95%
H_2SO_4 leaching	Sulfuric acid	90–98%
Oxidative leaching	Acid + oxidant	>95%

Selective Precipitation

Selective precipitation separates iron and rare earths from leach solutions by exploiting differences in their precipitation behavior under controlled pH conditions.

Iron is usually removed first by precipitating hydroxides via pH adjustment, leaving rare earth elements soluble for partial purification (Zhao, Chen, & Li, 2023).

Rare earth elements can be precipitated as oxalates, carbonates, or fluorides. Oxalate precipitation is common because it yields pure intermediates for conversion to oxides via calcination (Emil-Kaya et al., 2023).

Recent studies explore hybrid precipitation strategies to boost separation efficiency and cut reagent use (El Maangar et al., 2024).

Solvent Extraction

Solvent extraction is common in primary rare earth processing and recycling NdFeB magnet leachates, transferring rare earth ions from water to organic phase with selective extractants.

Common extractants such as D2EHPA and PC88A can selectively extract rare earths from iron solutions under controlled pH (Zhu, Cheng, & Li, 2022).

Because rare earth elements have similar chemical properties, multistage extraction circuits are often needed, which increases process complexity and reagent use (Zhang, Chen, & Li, 2023).

Recent research aims to improve extraction selectivity and reduce environmental impact by developing novel extractants and optimized extraction systems (Rahmati et al., 2025).

Ion Exchange and Adsorption

Ion exchange and adsorption are alternative methods for separating rare earths from leach solutions, relying on selective binding to functionalized materials such as ion-exchange resins or adsorbents.

Ion exchange resins selectively capture rare-earth ions from acidic solutions and can be recovered via controlled elution with suitable reagents (Zhao, Wang, & Zhang, 2021).

Recent studies have also explored biosorption and bio-based materials designed to improve environmental performance while maintaining efficient metal recovery (Amato et al., 2021).

Hybrid methods that combine hydrometallurgical leaching and adsorption improve separation selectivity and reduce chemical use (Magrini et al., 2022; Inman et al., 2021).

Purification and REE Recovery

The final hydrometallurgical stage involves purifying and recovering rare earths, which are usually obtained as oxalates, hydroxides, or carbonates after removing impurities like iron.

Intermediate compounds are calcined to produce rare-earth oxides, the most common products in rare-earth supply chains.

Hydrometallurgical routes are flexible for treating complex electronic waste but face challenges, including increased reagent use due to iron co-dissolution and the need for careful recycling of waste and reagents for industrial use.

Hydrometallurgy is highly adaptable for NdFeB magnet recycling. Effective process design must address iron removal, reagent efficiency, and environmental impacts for large-scale use (Binnemans et al., 2020; Liu, Wang, & Zhang, 2020; Zhao, Chen, & Li, 2023; Rahmati et al., 2025).

The next section explores pyrometallurgical routes for rare-earth recovery, which involve high-temperature treatment and separation.

Pyrometallurgical Processing

Pyrometallurgical routes are a strong alternative for treating NdFeB magnets and scrap, using high temperatures to melt or oxidize the alloys for rare-earth separation. They tolerate feed heterogeneity better than hydrometallurgy but often face issues with energy use and product quality.

Many pyrometallurgical flowsheets do not directly produce separated Nd–Pr–Dy products. Instead, they generate intermediate alloys, slags, or oxidized phases that require further separation, thereby impacting the true process boundary and overall circular-economy performance (Binnemans et al., 2020; Ramprasad et al., 2022).

Direct Melting Routes

Direct melting involves heating NdFeB magnets to melt and separate into metal-rich and oxide phases, depending on atmosphere and additives. Its appeal lies in operational simplicity and tolerance to contaminated feeds. However, the strong oxygen affinity of rare earth elements influences oxidation and partitioning behavior.

Studies show that rare-earth elements concentrate in oxidized phases during melting, while iron remains mostly metallic, aiding separation. Effectiveness varies with temperature, oxygen, and slag chemistry (Stopic et al., 2022). Direct melting risks losses via volatilization, entrainment, or oxidation if furnace conditions are not well-controlled (Buzatu et al., 2021).

Alloying Approaches

Alloying routes convert NdFeB magnets into easier-to-handle alloys, often using additives to alter phase equilibria and partitioning, rather than immediately isolating REEs.

This strategy appeals to integrating magnet recycling into existing metallurgical systems, but often produces diluted REE concentrations and needs a clear upgrading method. Without refinement, alloying leads to downcycling rather than circular recovery (Bian et al., 2022; Binnemans et al., 2020).

Pyrometallurgical processing offers an alternative for recycling NdFeB magnets, especially with large volumes of mixed electronic waste or integration with existing metallurgical infrastructure. These high-temperature processes separate rare earth elements from iron and other components via phase partitioning or alloying. Compared to hydrometallurgical methods, pyrometallurgy may be more robust and tolerant to impurities. Figure 8 shows simplified routes for NdFeB magnet recycling.

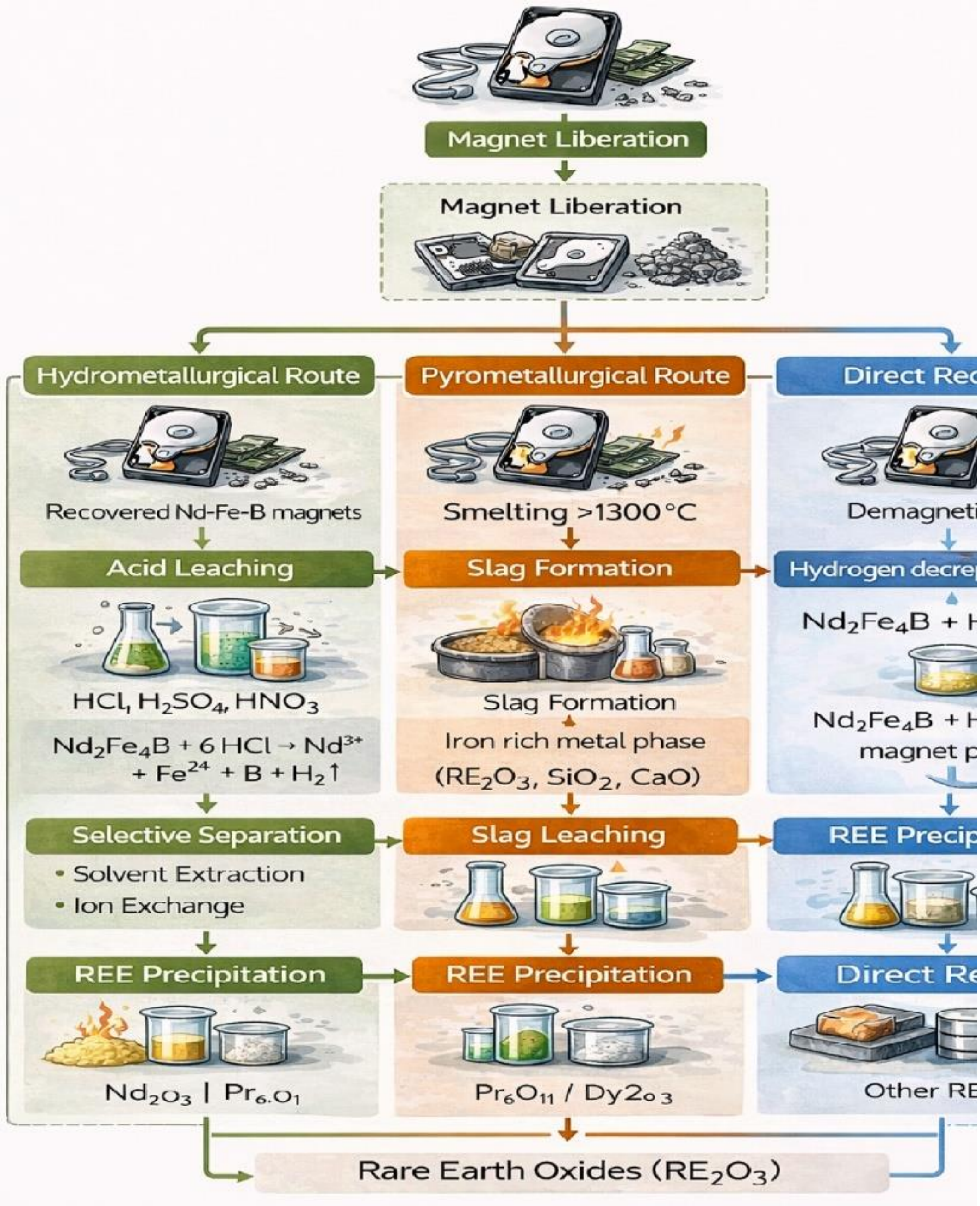

Figure 8. Simplified pyrometallurgical routes for NdFeB magnet recycling. Adapted from Bian et al. (2022), Stopic et al. (2022), and Buzatu et al. (2021).

Figure 8 shows pyrometallurgical recycling routes for NdFeB magnets, which involve high-temperature steps that separate rare-earth elements from iron and other components. The direct melting and oxidation process melts NdFeB scrap, oxidizes it, and separates the rare earths into slag or oxide phases, leaving iron metallic. Alloying routes add metallic elements to produce an intermediate alloy, which is later refined to recover the rare earths. These methods are advantageous for large or complex waste streams where mechanical or hydrometallurgical processes are difficult.

Metallurgical Refining

Metallurgical refining upgrades pyrometallurgical intermediates into rare-earth products or high-grade alloys via oxidation–reduction, slag engineering, or phase separation, followed by secondary processing.

Pyrometallurgy produces mixed rare earth oxides or slags, not pure Nd–Pr–Dy. Extracting pure REOs or REEs requires extra hydrometallurgical steps. It mainly pre-concentrates rather than fully recycles (Ramprasad et al., 2022).

From a critical review perspective, studies should be assessed on how clearly they define the final product and whether they quantify recoveries throughout the entire chain, including losses during refining and purification (Binnemans et al., 2020).

Advantages and Limitations

Pyrometallurgical routes are often described as robust, but that robustness comes with a cost. Their main advantages are:

- **Tolerance to mixed feeds** and incomplete dismantling.
- **High throughput potential** using established furnace technologies.
- **Potential to integrate** with existing metallurgical operations.

Their main limitations are also consistent across studies:

- **High energy demand**, especially for melting and controlled oxidation steps (Bian et al., 2022; Stopic et al., 2022).
- **Lower selectivity**, since many routes produce mixed REE phases rather than separated products (Binnemans et al., 2020).
- **Process boundary issues**, because additional refining is often required and is sometimes excluded from reported metrics (Ramprasad et al., 2022).

Pyrometallurgy is best used intentionally as a conditioning or pre-concentration step to improve downstream separation. If used alone, it should be evaluated based on full-chain recovery, product specs, and total energy and emissions.

The next section examines direct recycling and magnet-to-magnet processes that preserve magnet value by avoiding full dissolution or high-temperature steps.

Direct Recycling and Magnet-to-Magnet Processes

Direct recycling recovers value from NdFeB magnets without full chemical or high-temperature processing. Instead of isolating rare earth elements, it maintains the magnetic phase and reuses it in manufacturing. These methods are called magnet-to-magnet recycling.

Direct recycling reduces energy and reagent use compared to hydrometallurgical or pyrometallurgical, but requires clean feedstocks and careful control of contamination, relying on effective pre-treatment and separation (Tunsu et al., 2020; Binnemans & Jones, 2022).

Hydrogen Decrepitation

Hydrogen decrepitation (HD) is one of the most widely investigated techniques for the direct recycling of NdFeB magnets. In this process, magnets are exposed to hydrogen gas under controlled pressure and temperature. Hydrogen diffuses into the Nd-rich grain boundary phases and causes expansion of the crystal lattice. This leads to spontaneous fragmentation of the magnet into fine powder.

The main benefit of hydrogen decrepitation is that it breaks the magnet into powder without extensive mechanical grinding. This reduces oxidation and preserves much of the original magnetic microstructure. The resulting powder can then be processed further for magnet regeneration or alloy modification (Habibzadeh et al., 2023).

Recent studies have investigated optimized hydrogen treatment conditions to improve powder quality and minimize contamination during decrepitation (Habibzadeh et al., 2024). Variations of the process also integrate hydrogenation with controlled heat treatment to improve phase stability during subsequent processing (Kaya, 2024).

Hydrogen decrepitation (HD) is an effective pre-treatment for NdFeB magnet recycling, causing magnet fragmentation by hydrogen gas penetrating Nd-rich phases, forming hydrides, internal stresses that fracture the magnet into powder, aiding separation. Figure 9 shows this process.

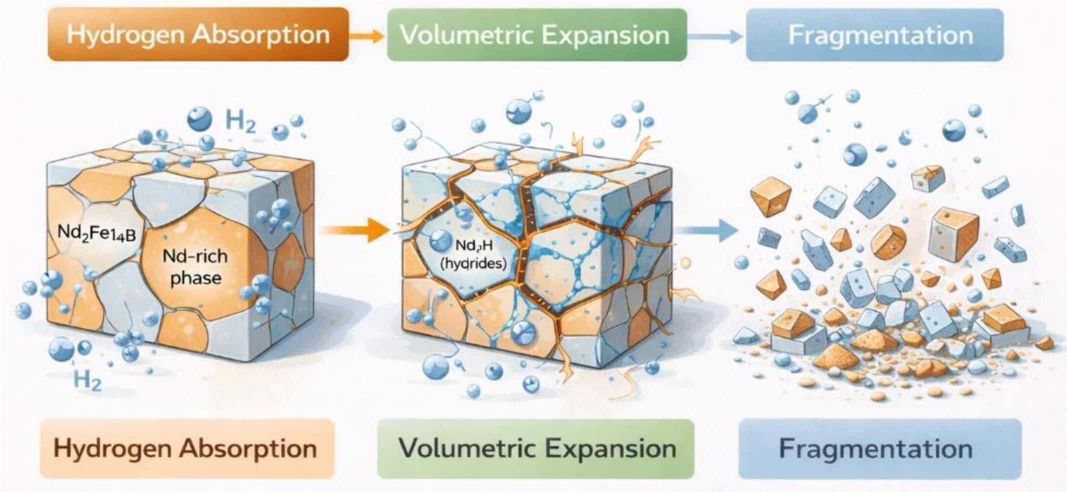

Figure 9. Hydrogen decrepitation mechanism applied to NdFeB magnet recycling. Hydrogen penetrates Nd-rich phases, causing volumetric expansion and fragmentation of the magnet into powder suitable for further processing. Adapted from Habibzadeh et al. (2023) and Kaya (2024).

Hydrogen decrepitation occurs when hydrogen diffuses into Nd-rich grain boundary phases of NdFeB magnets, reacting to form rare-earth hydrides. This causes volumetric expansion, generating stresses that make the magnet fracture into fine particles. These powders can be separated and recycled via hydrometallurgical or pyrometallurgical methods. Because it operates at low temperatures and uses limited mechanical energy, hydrogen decrepitation is an efficient, scalable pre-treatment for rare-earth magnet recycling.

Powder Processing Routes

After hydrogen decrepitation, the powder can be processed using powder metallurgy methods—such as classification, additive adjustment, compaction, and sintering—to manufacture primary magnets.

Powder processing allows modification of the chemical composition or particle size before magnet regeneration, adding rare-earth elements or alloying components to offset changes from recycling (Tunsu et al., 2020).

Powder processing requires strict oxygen control because NdFeB powders are highly reactive. Excessive oxidation reduces magnetic performance and affects magnet quality.

Re-Sintering of Magnets

Re-sintering is the final stage in many magnet recycling processes, where, after powder preparation, the material is compacted and sintered at high temperatures to form new NdFeB magnets.

Success depends on powder purity and particle size. Low contamination enables regenerated magnets to match the magnetic properties of primary magnets (Binnemans & Jones, 2022).

Recent research explores hybrid methods blending recycled powders with virgin materials to sustain performance and boost recycled content (Ullah et al., 2026).

Industrial Implementations

Although many magnet-to-magnet recycling technologies are still under development, several pilot-scale and industrial initiatives have been reported. These initiatives aim to integrate hydrogen decrepitation and powder processing into industrial magnet supply chains.

Industrial implementation requires reliable sources of magnet scrap, consistent feedstock quality, and well-controlled processing environments. Without these conditions, maintaining magnet performance and reproducibility becomes difficult (Kaya, 2024).

Table 4 summarizes magnet-to-magnet recycling methods that preserve magnet phase rather than separating rare-earth elements, unlike chemical recycling.

Table 4. Comparison of magnet-to-magnet recycling processes for NdFeB magnets. Adapted from Tunsu et al. (2020), Binnemans and Jones (2022), and Ullah et al. (2026)

Process	Main principle	Key advantage	Main limitation
Hydrogen decrepitation	Hydrogen-induced fragmentation	Low mechanical energy	Sensitive to contamination
Powder metallurgy recycling	Reuse of magnet powder	Preserves magnetic phase	Requires strict oxidation control
Re-sintering routes	Re-forming magnets from recycled powder	High material recovery	Requires high-quality feedstock

From a critical perspective, direct recycling reduces energy and chemical use but relies on reliable magnet separation and consistent feedstock. Mixed waste streams need extensive pre-processing before direct recycling is feasible.

Thus, direct recycling is a complementary approach rather than a universal solution for rare-earth recovery.

The next section compares environmental and economic assessments of rare earth recycling methods, including hydrometallurgical, pyrometallurgical, and direct recycling processes.

Environmental and Economic Assessment

Evaluating rare-earth recovery from hard disk drives needs environmental and economic analysis. Recycling methods should be judged based on metal recovery, energy use, greenhouse gas emissions, and cost, to determine whether recycling can supplement primary mining.

Environmental assessments often use life cycle analysis (LCA) to evaluate impacts across the whole process chain. Economic assessments focus on process costs, market value of recovered materials, and the scale needed for industrial viability.

Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is used to evaluate the environmental performance of rare-earth recycling systems by comparing recycling routes with primary mining across stages such as collection, dismantling, processing, and recovery.

Several studies show that recycling NdFeB magnets reduces environmental impacts compared with primary rare-earth production, which requires substantial energy and chemicals, especially during ore separation (Frost et al., 2021).

LCA results show that recycling's environmental performance depends heavily on upstream steps such as collection and dismantling. Poor magnet recovery can dilute rare-earth elements in scrap, thereby lowering recycling benefits (Walzberg et al., 2022).

Some studies highlight that hydrometallurgical recycling can cause environmental impacts related to reagent use and waste management, which must be considered in the overall environmental assessment (Ramprasad et al., 2022).

Hydrogen decrepitation (HD) is an effective pre-treatment for NdFeB magnet recycling, causing the magnet to fracture into powder as hydrogen gas penetrates the Nd-rich phases, forms hydrides, expands, and induces internal stresses. Figure 10 shows this mechanism.

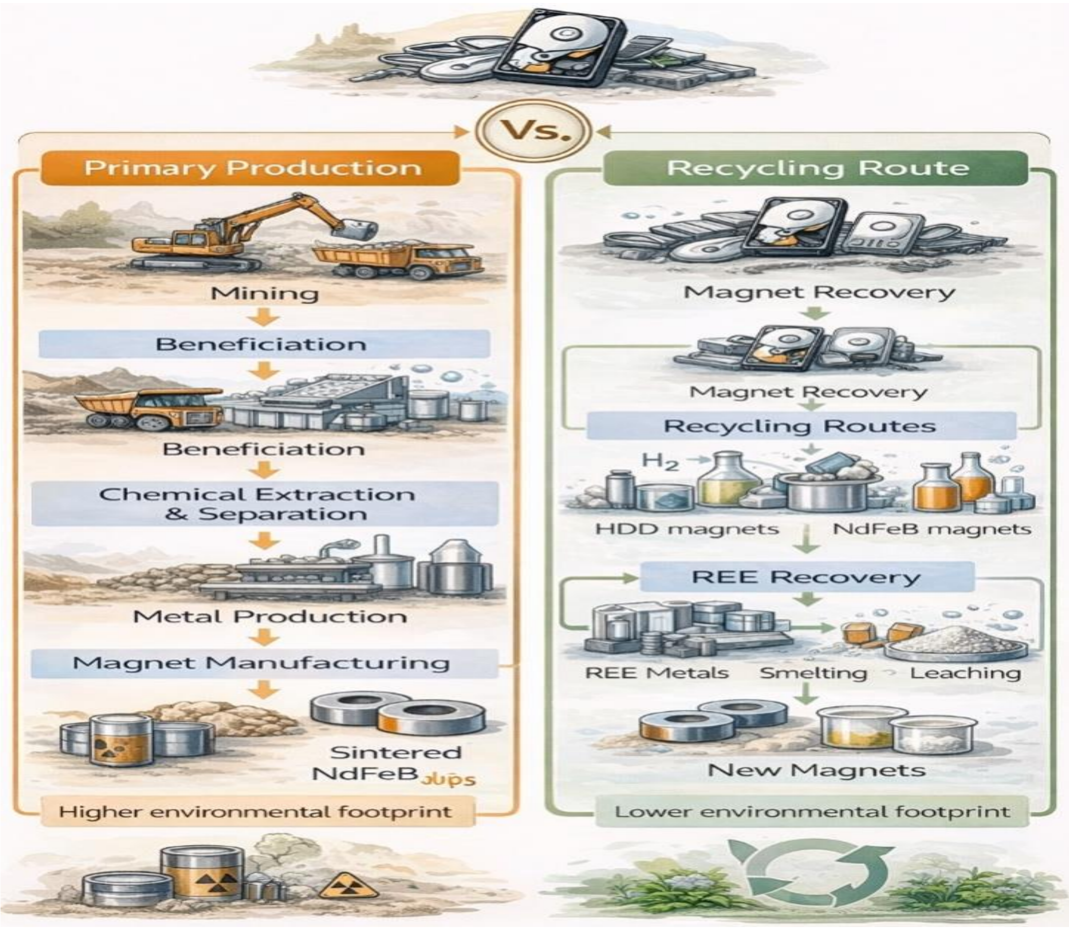

Figure 10. Conceptual life cycle comparison between primary rare earth mining and HDD magnet recycling. The comparison includes raw material extraction, processing stages, and final product recovery. Adapted from Frost et al. (2021) and Walzberg et al. (2022).

Hydrogen decrepitation in NdFeB magnets occurs when hydrogen diffuses into the Nd-rich grain-boundary phases, forming rare-earth hydrides that lead to volumetric expansion and internal stresses. These stresses cause the magnets to fracture into fine particles, which can be easily separated for recycling. Since it operates at low temperatures with minimal mechanical energy input, hydrogen decrepitation is an efficient, scalable pre-treatment for rare-earth magnet recycling.

Energy Consumption

Energy demand is key in assessing recycling methods, with significant variations based on process design and operation.

Pyrometallurgical routes demand higher energy due to high-temperature melting and refining, with furnace operation and temperature control being major costs (Bian et al., 2022).

Hydrometallurgical processes run at lower temperatures but need energy for grinding, pumping, reagent production, and solution treatment. Total energy use depends on purification stages and separation complexity (Stopic et al., 2022).

Direct recycling methods like hydrogen decrepitation typically use less energy since they skip high temperatures and extensive chemicals.

CO_2 Emissions

Carbon emissions are tied to process energy demand. The carbon footprint of rare earth recycling heavily depends on the process's energy intensity and the electricity mix used.

High-temperature pyrometallurgical processes emit significant CO_2 due to furnace energy use, while hydrometallurgical and recycling methods may lower emissions if reagent production and waste are well managed (Zhao, Zhang, & Wang, 2024).

Comparative analyses show recycling NdFeB magnets can cut greenhouse gases compared to mining, but benefits depend on efficient collection and processing (Ramprasad et al., 2022).

Economic Feasibility

The viability of rare earth recycling depends on feedstock availability, infrastructure, processing costs, and market prices.

Rare earth mining benefits from economies of scale and supply chains, while recycling relies on dispersed waste streams and complex dismantling, raising costs (Rademaker et al., 2020).

Material flow analyses show recycling's economic potential relies heavily on device collection and magnet extraction efficiency. Many HDDs outside formal recycling limits rare-earth feedstock (Nansai et al., 2021).

The circular economy framework adds considerations. Increased recycling doesn't automatically lessen resource extraction if demand grows, due to the rebound effect, which can limit the long-term impacts of circular strategies (Zink & Geyer, 2021).

Table 5 highlights differences between primary rare earth mining and recycling. Recycling provides environmental benefits, but economic feasibility depends on collection, process efficiency, and demand.

Table 5. Comparison of the environmental and economic aspects of primary rare-earth mining and HDD magnet recycling. Adapted from Rademaker et al. (2020), Nansai et al. (2021), and Golev et al. (2021)

Parameter	Primary mining	HDD recycling
Resource source	Natural ores	Electronic waste
Energy demand	High (mining + processing)	Moderate to high (depending on process)
CO_2 emissions	High	Lower in optimized systems
Supply security	Geographically concentrated	Distributed secondary resource
Economic scale	Large industrial operations	Emerging recycling systems

The next section explores industrial advances and commercial tech in rare earth recycling, emphasizing current initiatives and emerging infrastructures.

Industrial Developments and Commercial Technologies

Although laboratory studies on rare earth recycling have grown rapidly, industrial use is limited. Moving from experiments to commercial processes needs consistent feedstock, stable quality, and cost-effective designs. Few companies have developed systems specifically for NdFeB magnet recycling.

Recent commercial initiatives focus on direct magnet recycling, hydrogen processing, or combined mechanical and metallurgical recovery. Understanding their maturity is crucial for assessing their future role in rare-earth supply chains (Binnemans & Jones, 2022; Kaya, 2024).

Industrial Recycling Facilities

Few industrial facilities process rare earth magnets from electronic waste, mainly focusing on NdFeB magnets from hard drives, motors, and industrial equipment.

Hitachi pioneered automation to extract magnets from end-of-life hard drives, using robots to isolate actuators and recover magnets before shredding. This boosts rare earth recovery by avoiding magnet dilution in scrap streams (Binnemans & Jones, 2022).

HyProMag advances hydrogen processing of magnet scrap using decrepitation technology to produce recycled magnet powders for manufacturing. Demonstrations show recycled materials can be integrated into new magnet production (Kaya, 2024).

In the U.S., Urban Mining Co. has developed recycling technologies to recover and remanufacture magnet powder, focusing on magnet-to-magnet recycling to reduce chemical processing and preserve magnetic phase structure.

Transitioning from lab-scale to industrial recycling requires integrated supply chains to convert end-of-life magnets into high-quality materials for new magnets. Recent advances show that closed-loop systems can connect electronic waste to magnet manufacturing via mechanical, chemical, and metallurgical processes. These systems recover rare earths efficiently, minimize environmental impact, and reduce reliance on mining. Figure 11 shows a simplified recycling chain for magnets from electronic waste.

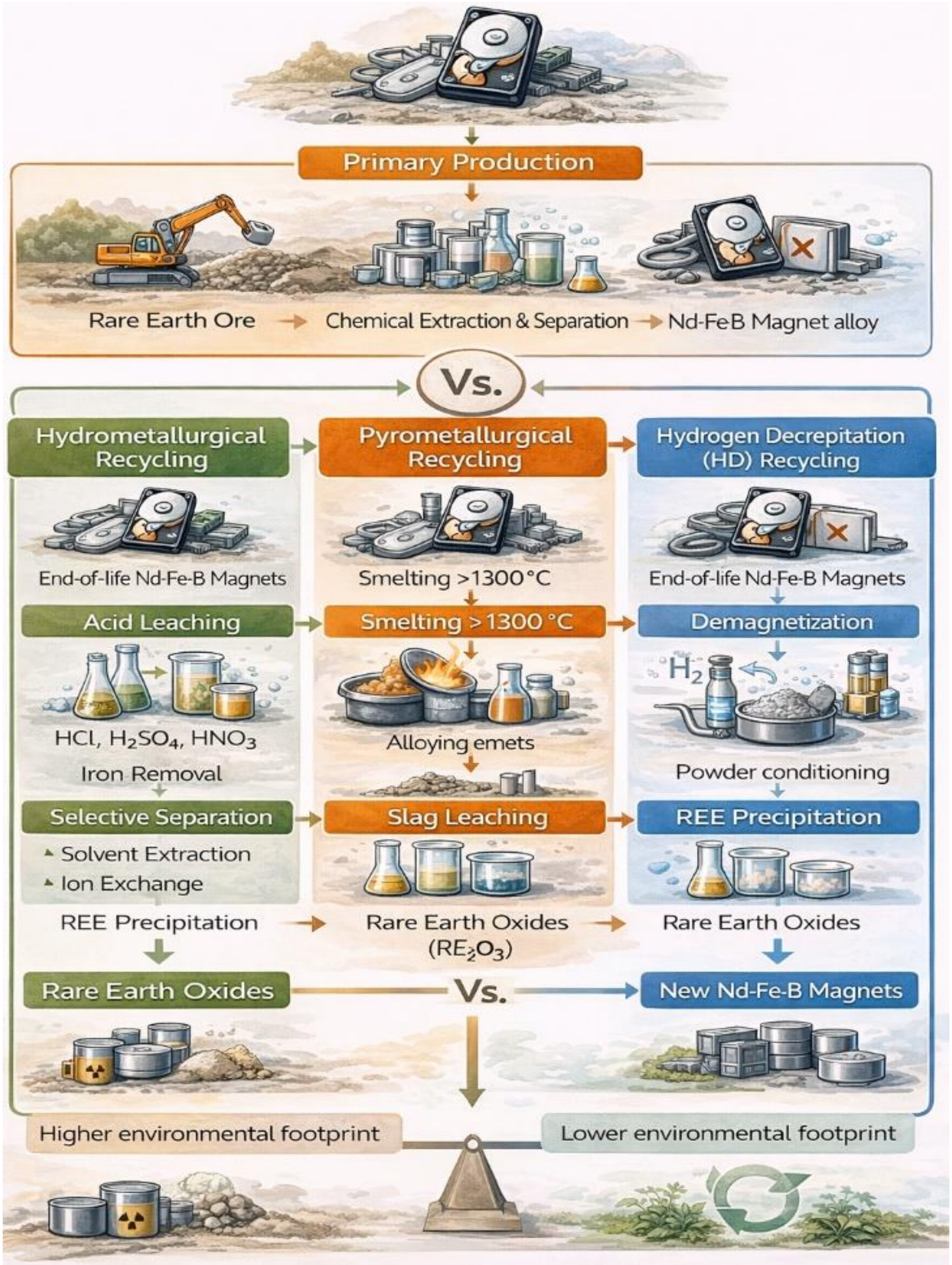

Figure 11. An industrial rare earth magnet recycling chain from electronic waste to magnet manufacturing. The scheme illustrates the stages of magnet extraction, hydrogen processing, powder conditioning, and remanufacturing used in emerging industrial systems. Adapted from Binnemans and Jones (2022) and Kaya (2024).

Figure 11 shows a simplified recycling chain linking electronic waste with magnet manufacturing. Effective magnet separation is crucial, because downstream processes require pure magnet feedstocks.

Commercial Technologies

Commercial rare earth recycling technologies are currently divided into three main categories:

- **Direct recycling technologies**, which preserve magnet material and regenerate magnets through powder metallurgy routes.
- **Hydrometallurgical technologies**, which dissolve magnets and recover individual rare earth elements through chemical separation.
- **Hybrid technologies**, which combine mechanical, thermal, and chemical processing steps.

Direct recycling methods attract industry for their ability to reduce energy and chemical use compared to traditional metallurgy. Hydrogen decarbonization technologies are particularly important in this field (Ullah et al., 2026).

These technologies require well-controlled feedstocks. Mixed e-waste streams contain coatings, adhesives, and metals, complicating recycling. Many processes need extensive pre-treatment before magnet processing.

Technology Readiness Levels (TRL)

Technology readiness levels (TRLs) assess the maturity of rare-earth recycling technology. Lab studies are typically TRL 2–4, showing basic concepts in controlled tests. Pilot systems, TRL 5–6, test in real-world settings. Several hydrogen-based magnet recycling methods are in this range (Akcil et al., 2021).

Full industrial deployment at TRL 7–9 implies commercial-scale implementation with stable production, but few rare-earth recycling technologies have achieved this due to technical and economic challenges (Binnemans et al., 2020; Ramprasad et al., 2022).

Table 6 shows various rarity levels of recycling technologies. While some processes are promising, large-scale use is limited.

Table 6. Technology readiness levels for major rare earth recycling routes. Adapted from Akcil et al. (2021), Binnemans et al. (2020), and Ramprasad et al. (2022).

Technology	Typical TRL	Main characteristics
Hydrometallurgical recycling	5–7	Flexible but chemically intensive
Pyrometallurgical recycling	4–6	Robust but energy intensive
Magnet-to-magnet recycling	6–8	Preserves magnet structure
Hydrogen decrepitation routes	6–8	Industrial pilot systems are emerging

Industrial implementation relies on technology, feedstock, regulations, and supply chains. Without reliable magnet collection and standardized recycling, even mature processes may struggle to scale.

The section reviews the challenges and gaps in rare-earth recycling, focusing on technological barriers and future research opportunities.

Challenges and Research Gaps

Despite progress in rare earth recycling from NdFeB magnets, many challenges remain. While lab processes show high recovery efficiencies, few are stable at an industrial scale. Moving from lab to large-scale recycling needs improvements in feedstock prep, separation selectivity, scalability, and product quality.

A review highlights challenges such as automated magnet extraction, recovering heavy rare-earth elements like dysprosium, controlling iron contamination, scaling up recycling, and developing eco-friendly processing.

Automated Separation and Dismantling

Efficient extraction of NdFeB magnets from electronics is a key challenge in rare-earth recycling. Many lab studies use manual dismantling for pure magnet extraction, but this process is labor-intensive and hard to scale.

Automated dismantling technologies, such as robotic systems and mechanical lines, have been proposed to improve throughput and reduce labor. However, the diversity of electronic device designs makes it challenging to create universal dismantling systems (Burkhardt et al., 2024).

Material flow analyses also show that inefficient magnet extraction can significantly reduce rare earth recovery rates. If magnets are not separated before shredding, rare-earth elements are diluted in mixed scrap streams, making recovery more difficult and less economical (Walzberg et al., 2022).

Recovery of Dysprosium and Selective Separation

Another key challenge is the selective recovery of heavy rare-earth elements, such as dysprosium. Dysprosium is often present in smaller quantities than neodymium and praseodymium, but it plays an important role in improving the thermal stability of NdFeB magnets.

Hydrometallurgical systems frequently recover rare earth elements as mixed concentrates rather than as separated elements. Achieving selective separation between Nd, Pr, and Dy remains difficult due to their similar chemical properties (Zhu, Cheng, & Li, 2022).

Recent studies have investigated improved solvent extraction systems and advanced separation strategies to enhance selectivity between light and heavy rare-earth elements (Rahmati et al., 2025). However, many of these approaches remain at the laboratory scale.

Precipitation-based systems also face limitations because dysprosium may co-precipitate with other rare earth elements under typical process conditions (Zhao, Chen, & Li, 2023).

Iron Contamination and Impurity Control

Iron represents the dominant component of NdFeB magnets and therefore becomes the major impurity during recycling. During hydrometallurgical processing, iron dissolves together with rare earth elements and must be removed through selective precipitation or other separation methods.

Incomplete removal of iron can reduce product purity and complicate downstream processing steps. In addition, iron precipitation often generates large volumes of sludge, which must be managed as a secondary waste stream (Liu, Wang, & Zhang, 2020).

Research has focused on improving iron removal strategies through controlled precipitation and optimized leaching conditions. Nevertheless, co-dissolution of iron remains limitations of hydrometallurgical recycling routes (Emil-Kaya et al., 2023; Zhang, Li, & Wang, 2021).

Industrial Scalability and Reagent Consumption

Many rare earth recycling processes show promising lab results but struggle to scale up. Performance depends on reagent levels, solution chemistry, and reaction control, which are harder to maintain industrially.

In addition, some hydrometallurgical routes require significant quantities of acids, extractants, or precipitation agents. High reagent consumption can increase operational costs and generate secondary waste streams that require treatment (Binnemans et al., 2020).

Economic analyses indicate that industrial deployment requires not only efficient recovery but also a stable supply of magnet scrap and optimized process integration within existing recycling infrastructures (Ramprasad et al., 2022).

Recent studies also highlight the need for integrated recycling strategies that combine mechanical separation, metallurgical processing, and product recovery within a unified process chain (Hamzat et al., 2025).

Green Processing Routes and Bio-Based Technologies

Environmental sustainability has become an important objective in rare earth recycling research. Conventional hydrometallurgical systems rely heavily on mineral acids and organic extractants, which may generate environmental impacts if not properly managed.

To address these concerns, studies have explored alternative bio-based or eco-friendly processing methods, such as biosorption, microbial leaching, and functionalized materials, to selectively capture rare-earth ions (Amato et al., 2021).

Adsorption-based separation systems and hybrid bio-hydrometallurgical processes have also been investigated as potential alternatives to conventional solvent extraction circuits (Magrini et al., 2022; Zhao, Wang, & Zhang, 2021).

Table 7 summarizes the main challenges identified in the current literature. These issues highlight the gap between laboratory-scale research and industrial implementation of rare earth recycling technologies.

Table 7. Key challenges and research gaps in rare earth recycling from NdFeB magnets. Adapted from Binnemans et al. (2020), Ramprasad et al. (2022), and Hamzat et al. (2025).

Challenge	Key issue	Research direction
Magnet extraction	Inefficient dismantling	Automated separation systems
Dy recovery	Low selectivity	Improved solvent extraction
Iron contamination	Co-dissolution in leaching	Optimized precipitation systems
Industrial scale-up	High reagent consumption	Process integration
Environmental sustainability	Chemical waste generation	Bio-based separation routes

Overall, progress in rare earth recycling will depend on integrated solutions that address feedstock preparation, separation selectivity, and process sustainability simultaneously.

The section outlines future prospects for rare-earth recycling from e-waste, focusing on technological and circular supply chain developments.

Future Perspectives

Recovering rare earth elements from hard disk drives will become more important for future critical materials supply chains. Its success depends on technological advances, better collection systems, and integration with e-waste strategies. Current research suggests several promising directions for advancing rare earth recycling in the coming years.

These perspectives include advances in automated dismantling, circular economy frameworks, improved integration with e-waste recycling, and supportive policies. These elements will determine whether rare earth recycling from HDDs transitions from a niche market to a stable industrial sector.

Automation of HDD Dismantling

Automation of HDD dismantling is vital to rare-earth recycling. Manual extraction of NdFeB magnets offers high purity but is labor-intensive and hard to scale. Automated systems can boost capacity and cut costs.

Robotic systems and automated disassembly lines are currently being developed to extract magnets from HDD actuator assemblies. These technologies use mechanical positioning systems and image-based recognition to identify and separate components within electronic devices (Burkhardt et al., 2024).

Material flow analyses demonstrate that improved dismantling technology can increase rare earth recovery by preventing magnet dilution during shredding (Walzberg et al., 2022).

Circular Economy Strategies

Recycling rare earths from HDDs supports the circular economy by emphasizing material recovery and reuse and enhancing resource efficiency throughout product life cycles.

Electronic waste is a key secondary source for critical materials, but circular systems must be carefully designed to avoid unintended effects. Increased recycling might not reduce primary resource extraction if demand rises, known as the rebound effect (Zink & Geyer, 2021).

Circular economy strategies need coordinated efforts in product design, recycling, and material recovery. They must also consider product lifetimes, consumer behavior, and material flow (Zorpas & Loizia, 2021; Cucchiella et al., 2020).

Integration with E-Waste Recycling Systems

Rare-earth recycling from HDDs should integrate with e-waste systems to ensure consistent feedstock and recovery. Currently, e-waste recycling primarily targets bulk metals such as copper and aluminum. Rare-earth magnets are often not recovered because they are dispersed in complex devices or mixed with scrap streams (Akcil et al., 2021).

Enhanced integration of dismantling and rare earth recycling can improve recovery rates. For example, early separation of magnet parts would concentrate rare earths and make processing more efficient (Buchert et al., 2020).

Material flow studies also indicate that enhanced tracking of electronic devices and recycling streams could help identify valuable secondary resources within e-waste systems (Chen, Li, & Xu, 2021; Li, Tan, & Zeng, 2021).

Table 8 presents strategies to enhance rare-earth recycling within existing electronic waste systems.

Table 8. Key strategies for improving the integration of rare earth recycling within electronic waste management systems. Adapted from Akcil et al. (2021), Buchert et al. (2020), and Chen, Li, and Xu (2021).

Strategy	Objective	Expected impact
Magnet extraction before shredding	Prevent dilution of REE materials	Higher recovery rates
Device tracking systems	Identify magnet-containing products	Improved collection
Integrated recycling facilities	Combine dismantling and metallurgical processing	Higher process efficiency
Standardized dismantling protocols	Facilitate automation	Reduced operational costs

Economic Assessment of HDD Rare Earth Recycling

Economic viability is crucial for large-scale rare earth recycling. Although lab and pilot studies show high recovery rates, industrial use depends on investment, operating costs, and feedstock availability.

Several techno-economic assessments show that recycling NdFeB magnets from electronic waste depends on variables like magnet concentration, logistics, process complexity, reagent use, and energy demand (Akcil et al., 2021; Binnemans et al., 2020; Ramprasad et al., 2022).

Compared with primary mining, recycling processes generally operate at smaller scale but can offer advantages in terms of lower environmental impact and reduced dependence on geological resources.

Capital Expenditure (CAPEX)

Capital investment in rare earth recycling depends on process design. Hydrometallurgical plants need shredders, dismantling systems, leaching reactors, solvent extraction, precipitation tanks, and waste treatment. Pyrometallurgical methods may require furnaces, gas treatment, and slag handling.

Published assessments show rare-earth recycling plants generally need less initial investment than primary mining facilities, mainly because they don't require ore beneficiation, large tailings storage, or extensive mining infrastructure (Binnemans et al., 2020).

Dismantling automation systems and solvent extraction circuits can be a major part of the initial investment in recycling plants.

Operating Expenditure (OPEX)

Operating costs are mainly associated with:

- feedstock collection and logistics
- dismantling and pre-processing
- chemical reagents for leaching and separation
- energy consumption
- waste treatment and effluent management

Hydrometallurgical processes often show relatively high reagent consumption. Acid leaching and solvent extraction circuits require careful chemical management to control operating costs and environmental impacts (Ramprasad et al., 2022).

Energy consumption may also become relevant when thermal pretreatment or reduction processes are used prior to hydrometallurgical separation.

Economic Drivers and Market Sensitivity

The profitability of rare-earth recycling depends on the market prices of neodymium, praseodymium, and dysprosium, which can fluctuate widely, affecting project viability.

The concentration of magnets in feedstock affects process economics. HDD recycling streams usually have higher magnet concentrations than mixed electronic waste streams, thereby boosting economic viability (Akcil et al., 2021).

Beyond technological feasibility, the economic viability of rare-earth recycling from NdFeB magnets is crucial for large-scale implementation. The cost depends on stages like waste collection, dismantling, metallurgical processing, and residue management, influenced by automation, technology, and regional logistics. Figure 12 shows a conceptual cost structure for HDD magnet recycling.

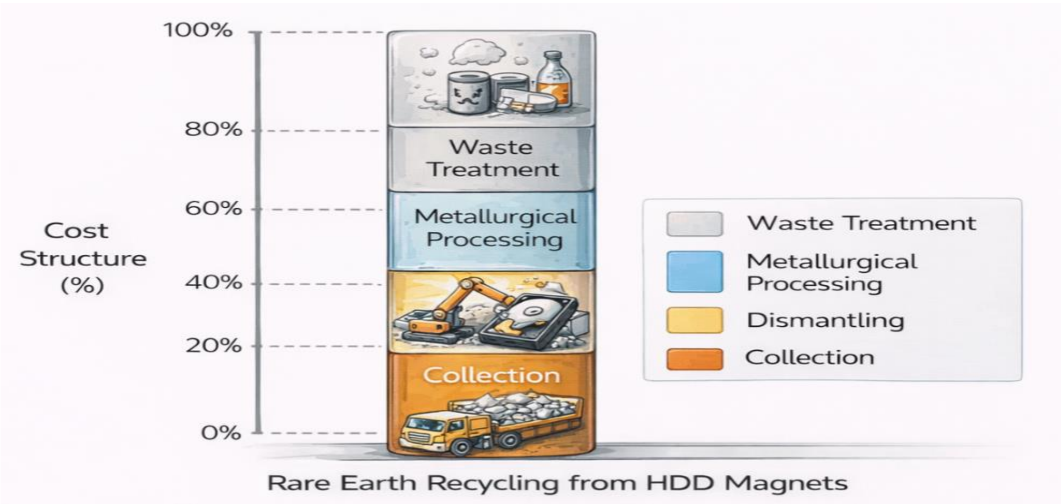

Figure 12. Conceptual cost structure of rare earth recycling from HDD magnets. The figure illustrates typical cost components, including collection, dismantling, metallurgical processing, and waste treatment. Adapted from Binnemans et al. (2020), Akcil et al. (2021), and Ramprasad et al. (2022).

Figure 12 shows that metallurgy usually accounts for the largest part of recycling costs due to energy use, chemicals, and processing infrastructure needed for rare earth separation and purification. Collection and logistics also add substantially, especially when electronic waste is dispersed. Dismantling and magnet extraction costs vary with automation levels. Waste treatment and environmental management are additional costs, necessary for safe residue handling. Knowing the cost distribution helps assess the economic competitiveness of recycling compared to raw mining.

Economic feasibility is crucial for deploying rare earth recycling from hard disk drives. Besides technical recovery efficiency, operational and market factors influence viability, including feedstock composition, waste logistics, reagent and energy use, and market price fluctuations. Table 9 summarizes key parameters impacting the economic performance of HDD recycling systems and their implications.

Table 9. Typical economic parameters influencing the recycling of rare earths from HDD magnets. Adapted from Binnemans et al. (2020), Akcil et al. (2021), and Ramprasad et al. (2022).

Parameter	Economic relevance	Impact on process viability
Magnet concentration in feedstock	Determines REE recovery per ton of scrap	Higher concentrations improve economics
Collection logistics	Influences feedstock availability	Poor logistics increases cost
Reagent consumption	Major operational cost	Efficient separation reduces OPEX
Energy consumption	Depends on process route	Thermal pretreatment increases cost
Rare earth market price	Drives revenue	Price volatility affects profitability

Literature shows rare earth recycling is economically feasible when high-grade magnet scrap is available and efficient dismantling is used.

Uncertainties about feedstock supply, market prices, and process scale hinder widespread industrial deployment.

Policy and Regulatory Frameworks

Policy and regulatory frameworks will significantly impact rare-earth recycling by shaping e-waste management, resource recovery, and circular-economy policies, thereby affecting recycling rates and technology adoption.

Extended producer responsibility (EPR) schemes and recycling targets have already been implemented in several regions to promote responsible. (Zorpas & Loizia, 2021).

Rare earth elements are increasingly classified as critical raw materials, motivating policies to diversify supply chains and support recycling technologies (Golev et al., 2021; Nansai et al., 2021).

This review concludes with a summary of key technological findings, industrial implications, and research priorities for rare earth recycling from HDDs.

Conclusions

Rare earth elements in NdFeB magnets from HDDs are a key secondary resource in the global critical materials supply chain. This review explores the main recovery methods, industrial progress, and research challenges, focusing on mechanical separation, hydrometallurgy, pyrometallurgy, hybrid technologies, and the integration of recycling in e-waste management.

HDDs are a concentrated source of rare-earth magnets compared with other electronic waste. Recycling HDDs favors the recovery of rare earths if magnets are efficiently separated. However, successful recovery relies on effective magnet extraction and high feedstock purity.

Hydrometallurgical routes are the most widely studied for the recovery of rare earth elements from NdFeB magnets. They involve acid leaching, followed by selective precipitation or solvent extraction to separate the rare earths from iron and impurities. Though efficient, challenges include controlling iron dissolution, reducing reagent use, and improving selectivity for heavy rare-earth elements such as dysprosium.

Pyrometallurgical and hybrid recycling routes can simplify separation or reduce chemical use but need more energy and purification stages. The choice of technology depends on feedstock, scale, and economics.

Industrial rare-earth recycling is limited but expanding, with companies developing methods such as hydrogen decrepitation, magnet reuse, and hydrometallurgical recovery. These efforts demonstrate increasing interest in circular supply chains for critical materials.

Economic analyses indicate recycling is competitive with high-grade magnet scrap and efficient dismantling, but performance depends on feedstock logistics, reagents, energy costs, and rare-earth prices.

Environmental assessments highlight recycling's benefits over primary mining, as it requires less land and can well-managed. However, these benefits depend on process design, chemical use, and waste handling.

Despite progress, challenges remain in industrial-scale rare-earth recycling from HDDs, including automating rare-earth-heavy-rare-earth separation, controlling iron contamination, and reducing reagent use and waste.

Future advances will likely come from integrated recycling, automated dismantling, efficient metallurgical processes, and better circular-economy strategies. Policies on critical raw materials and e-waste can support the recycling of rare earths.

Recycling NdFeB magnets from HDDs offers a promising way to boost resource efficiency and cut reliance on primary rare-earth mining. Ongoing research, tech development, and policies are key to establishing these recycling routes as stable industrial supply chains for critical materials.

Declarations

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Conflicts of interest

The author declares no conflict of interest.

Data availability

No datasets were generated or analyzed during this study.

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