metals

Review

Hydrometallurgical Recovery Technology for Rare Earth and Iron Separation from Spent NdFeB Magnets

Mingyan Cheng [1,2,3], Liqing Li [1,*], Yanfei Xiao [1,*] and Helian Liu [1]

[1] Faculty of Materials Metallurgy and Chemistry, Jiangxi University of Science and Technology, Ganzhou 341000, China; 7120230079@mail.jxust.edu.cn (M.C.); 9120130163@jxust.edu.cn (H.L.)
[2] Ganzhou General Inspection and Testing Institute, Ganzhou 341000, China
[3] National Center of Industry Metrology and Testing for Tungsten and Rare Earths, Ganzhou 341000, China
* Correspondence: liliqing@jxust.edu.cn (L.L.); 9120150154@jxust.edu.cn (Y.X.)

Abstract

The recovery of rare earth elements (REEs) from the spent NdFeB magnets has great strategic significance for ensuring the security of critical mineral resources. This process requires scientifically designed separation technologies to ensure high output and purity of the obtained rare earths. Hydrometallurgy has been widely applied to extract REEs from spent permanent magnets. This paper summarizes and reviews hydrometallurgical technologies, mechanisms, and applications for the separation and recovery of REEs and iron (Fe) from the spent permanent magnets. Key methods include: The hydrochloric acid total solution method, where the spent NdFeB is completely dissolved in hydrochloric acid, iron is precipitated and removed, and then REEs are extracted. The hydrochloric acid preferential dissolution method, where spent NdFeB magnets are first fully oxidized by oxidative roasting, converting Fe^{2+} to Fe^{3+}, which hydrolyzes to $Fe(OH)_3$, and is precipitated and removed, allowing for the subsequent extraction of REEs to obtain rare earth oxides. Acid baking and water leaching, where spent NdFeB is calcined with acidification reagents, and the calcined products are dissolved in water to leach out REEs. At the same time, Fe is retained in the leaching residue. Electrolysis in aqueous solution, where Fe is electrolyzed at the anode or deposited at the cathode to separate it from REES. Organic acids leaching, where organic acids dissolve metals through acidolysis and complexation. Bioleaching, which utilizes microorganisms to recover metal through biological oxidation and complexation. Ionic liquid systems, where Fe or REEs are extracted using ionic liquid or leached by deep eutectic solvents. This paper provides an in-depth discussion on the challenges, advantages, and disadvantages of these strategies for recycling spent NdFeB magnets, as well as the leaching and extraction behavior of REEs. It focuses on environmental impact assessment, improving recovery efficiency, and decreasing reagent consumption. The future development direction for recycling spent NdFeB magnets is proposed, and a research idea of proposing a combined process to avoid the drawbacks of a single recycling method is introduced.

Keywords: rare earth elements (REEs); iron (Fe); hydrometallurgical; separation and recycling process; spent NdFeB magnets

check for updates

Academic Editor: Alexandre Chagnes

Received: 11 September 2025
Revised: 27 October 2025
Accepted: 29 October 2025
Published: 7 November 2025

Citation: Cheng, M.; Li, L.; Xiao, Y.; Liu, H. Hydrometallurgical Recovery Technology for Rare Earth and Iron Separation from Spent NdFeB Magnets. *Metals* **2025**, *15*, 1227. https://doi.org/10.3390/met15111227

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

NdFeB magnets, developed in the 1980s as the third-generation permanent magnets, possess very high residual magnetism and coercive force. Due to their excellent magnetic

performance and relatively low price, NdFeB magnets are extensively used in wind power, new energy vehicles, and industrial robotics [1]. The main phase of NdFeB magnets is $Nd_2Fe_{14}B$, containing 60–70% Fe, 20–30% Nd, and 0.3–1% B. To enhance coercivity and Curie temperature, 0.5–7% Pr, 0.2–6% Dy, and other rare earth elements are often used to replace Nd, while 0.1–0.9% Al and 0.4–3% Co, etc., are used to replace Fe [2]. Statistics indicate that global consumption of sintered NdFeB magnets will be approximately 222,000 tons in 2024. In the foreseeable future, consumption is expected to increase at an annual rate of 5.8%, reaching 322,000 tons by 2032. It is estimated that by 2032, NdFeB magnets used in new energy vehicles will account for 32% of the total demand [3].

The lifetime of magnets and the amount of magnet waste generated vary depending on their application in consumer electronics, wind turbines, and electric vehicles. A significant amount of waste is produced after magnets are scrapped. Additionally, approximately one-third of the material becomes spent magnets in the form of sludge or waste during manufacturing [4].

With the rapid development of the NdFeB permanent magnetic materials processing and downstream application industries, secondary rare earth resources—such as grinding mud, material skins, material heads, powder, slag, and scrap products generated during NdFeB magnet processing, as well as those dismantled from retired equipment—are increasing.

Compared to producing rare earth products from raw ores, recycling rare earth secondary resources from NdFeB offers advantages such as a shorter process, lower cost, and less pollution. However, the mainstream production process for recycling NdFeB rare earth secondary resources currently involves a “long hydrometallurgical process”. This process includes demagnetization, crushing, blending, roasting, and classification of the secondary resources to obtain calcined oxide clinker. The clinker then undergoes acid dissolution, purification, impurity removal, extraction, separation, precipitation, and calcination to produce rare earth products like praseodymium-neodymium oxide. This oxide can subsequently be smelted into praseodymium-neodymium metal or alloy, which serves as a raw material for manufacturing NdFeB permanent magnetic materials, thereby achieving rare earth recycling.

Under current national export controls on the recycling and utilization of rare earth secondary resources, the recycling of NdFeB secondary resources can effectively supplement the gap in raw rare earth ore resources and ensure the security of the rare earth strategic resource supply chain.

In general, the total recycling amount of waste NdFeB magnets will increase linearly with output growth and is predicted to exceed tens of thousands of tons in the next 10 to 15 years [5]. These wastes, with relatively low pollution levels, are often recycled and reused at the production site. However, to effectively utilize REEs and other valuable metals, separate treatment of the oxidized scraps/waste is required, making this an area of great practical value and significance.

Researchers have conducted extensive studies on recycling spent NdFeB magnets, proposing technologies such as pyrometallurgy, hydrometallurgy, bio-metallurgy, and direct regeneration [6]. Emerging methods include electrochemical-assisted and mechanical–chemical-assisted recycling. The essence of these methods lies in optimizing recycling efficiency using external driving forces and reducing chemical reagent consumption [7]. Among them: (1). Direct recycling technology (e.g., Hydrogenation-Disproportionation-Desorption-Recombination, hydrogen decrepitation and re-sintering, remelting and recasting) is only suitable for clean and unoxidized magnets. (2). Pyrometallurgy includes methods like Molten Salt Extraction, Selective Chlorination, the Glass Slag Method, Vacuum Induction Melting

(VIM), and Liquid Metal Extraction. While pyrometallurgy is efficient, it often suffers from low recovery rates, high roasting temperatures, and poor consideration for iron recovery.

In contrast, hydrometallurgy offers high recovery rates, high efficiency, and is easier to adapt for industrial continuous production [8]. This paper systematically introduces hydrometallurgical technologies for recovering spent NdFeB magnets, focusing on methods for separating REEs and Fe from the waste, and prospects the future development direction of this field.

2. Direct Leaching by Inorganic Acid

Hydrometallurgy is among the most promising methods because it is suitable for NdFeB magnets of different shapes and compositions. The process involves different leaching approaches: complete leaching and selective leaching.

Acids are typically used as leaching agents in hydrometallurgical recovery. By reasonably adjusting the pH value, rare earth elements and iron can be separated, and single rare earth compounds can be obtained through multi-stage extraction. Finally, rare earths are converted into salts using precipitants.

Leaching methods using inorganic acids, including hydrochloric acid, nitric acid, sulfuric acid, and phosphoric acid, are summarized in Table 1.

The inorganic acid direct leaching method involves completely dissolving REEs and Fe from spent NdFeB using inorganic acid, oxidizing Fe^{2+} to Fe^{3+}, and then removing Fe^{3+} by precipitation as $Fe(OH)_3$ by pH adjustment, before extracting the rare earth elements. A general process flowchart is shown in Figure 1.

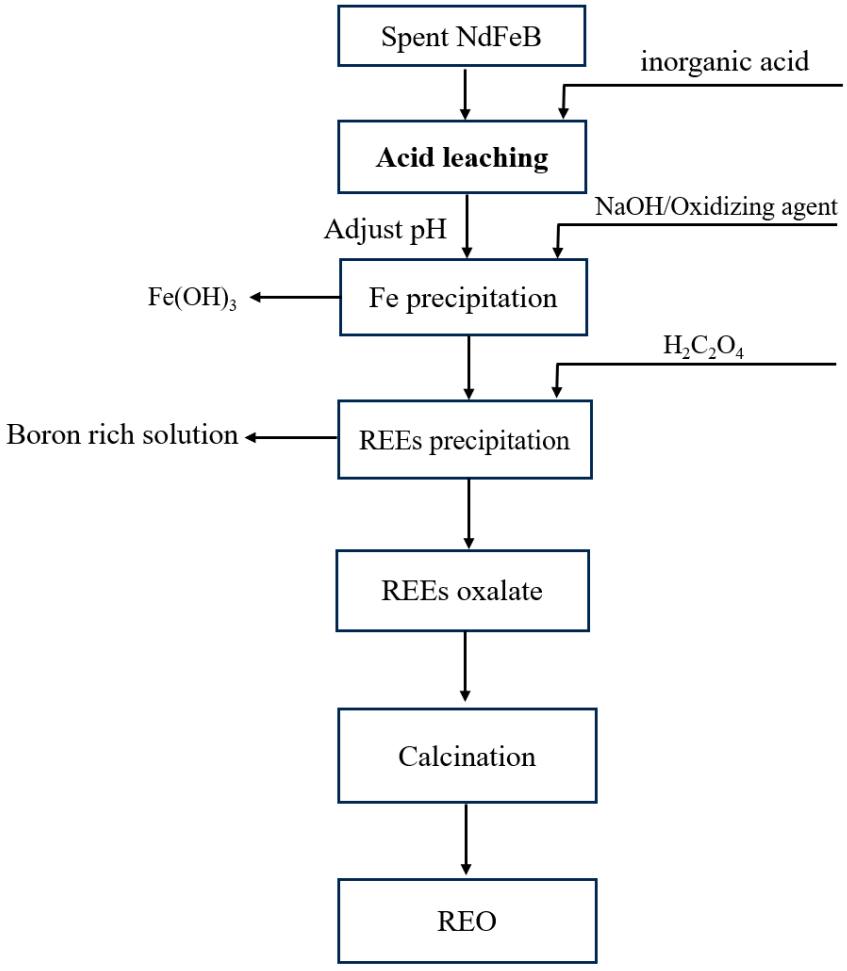


Figure 1. General flowchart for leaching and separating REEs and Fe from NdFeB magnets using inorganic acid direct leaching.

Table 1. Recovery and separation of REEs and Fe from spent NdFeB magnet by inorganic acid direct leaching.

Methods	Reagents	Raw Materials	Conditions/Parameters	Product/Remarks/Conclusion	Pros and Cons	References
Direct leaching	Hydrochloric acid	Flake NdFeB magnets	6 M HCl/50 g/L tartaric acid, 40 °C	Extraction yields: Fe > 67.99%, REEs > 99.27%; Purity: RE oxide products > 95.83%; Recovery: RE oxide products > 90.18%	High efficiency, low cost, but high acid consumption, large-scale industrial production, low selectivity, complicated process	[9]
Direct leaching	Nitric acid	NdFeB magnetic sludge	1 M HNO_3, 0.3 M H_2O_2, 5 min, 80 °C	>98% Nd, 80% Dy, 99% B,99% Fe dissolved; pH = 3, Fe removed as $Fe(OH)_3$	Oxidize Fe^{2+} to Fe^{3+}, sulfuric acid double salt precipitation, rare earths, and separation from Fe, but cause environmental pollution	[10]
Direct leaching	Sulfuric acid	NdFeB scrap	2 M H_2SO_4, 80 °C, 1–2 h, two-step solvent extraction	Yield > 95%; Purities: mixed Pr/Nd oxide, Dy oxide > 99%	High recovery rate, but environmental pollution	[11]
Direct leaching	Phosphoric acid	NdFeB slurry	4 M H_3PO_4, 80 °C, L/S = 30/1, 1.5 h	Recovery: Fe 98.76%, REEs 1.09%; Purity: mixed RE oxide 99.49%, $FeC_2O_4 \cdot 2H_2O$ 97.17%	Low efficiency, high cost, rare earth phosphate precipitation, high selectivity, low volatility, environmentally friendly	[12]

Tian YL et al. [9] used hydrochloric acid to efficiently recover rare earths from NdFeB magnets. Under optimal leaching conditions, the recovery rate of rare earths in the leachate was 99.3%, and the iron recovery rate was 67.9%. Rabatho JP et al. [10] developed a nitric acid leaching process to effectively extract REEs from NdFeB sludge. At a leaching temperature of 80 °C and pH = 3, Fe was removed as $Fe(OH)_3$, achieving recovery rates of 98% for Nd and 81% for Dy.

Gruber V et al. [11] used sulfuric acid leaching and solvent extraction to recover REEs from magnet scrap, achieving a yield of over 95% and a purity of individual components exceeding 99%. Conversely, He L et al. [12] utilized phosphoric acid to leach and separate REEs and Fe from waste NdFeB magnets. In this case, rare earth phosphates precipitated in the leaching residue, while ferrous phosphate remained in the leaching solution. Iron was subsequently precipitated using oxalic acid.

Therefore, the hydrochloric acid total solution method is a typical approach within inorganic acid direct leaching. It is suitable for subsequent extraction processes. However, since complete leaching lacks selectivity for iron, the purity of precipitated products is usually not high. Thus, finding methods to decrease acid consumption and increase product purity is key to optimizing the hydrometallurgical process.

3. Selective Leaching

To avoid a separate Fe removal process, "selective leaching" processes have been developed to selectively leach REEs from the spent magnet, leaving Fe in the residue.

3.1. Oxidation Roasting-Hydrochloric Acid Preferential Dissolution Method

This method involves fully oxidizing spent NdFeB through oxidation roasting. The purpose of roasting is to oxidize iron and rare earth metals into Fe_2O_3 and RE_2O_3, respectively, reducing iron leaching during the subsequent acid dissolution step. According to the potential-pH diagrams of the Fe-H_2O and Nd-H_2O systems, selective leaching can theoretically exploit the fact that at pH 1.0 to 7.0, Nd and Fe mainly exist as Nd^{3+} and Fe_2O_3, thereby achieving selective dissolution of Nd_2O_3 while leaving Fe in the residue as Fe_2O_3. The pH value of the solution is then adjusted to allow REOs to react preferentially with hydrochloric acid, converting them to RE^{3+}. Finally, rare earth oxides are obtained through precipitation and calcination. Methods using oxidation roasting and inorganic acid leaching are summarized in Table 2, and the process flowsheet is shown in Figure 2. The overall process can be summarized by reactions (1)–(5).

$$4RE + 3O_2 \rightarrow 2RE_2O_3 \quad (1)$$

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3 \quad (2)$$

$$RE_2O_3 + 6HCl \rightarrow 2RECl_3 + 3H_2O \quad (3)$$

$$2RECl_3 + 3H_2C_2O_4 \rightarrow RE_2(C_2O_4)_3 \downarrow + 6HCl \quad (4)$$

$$2RE_2(C_2O_4)_3 + 3O_2 \rightarrow 2RE_2O_3 + 12CO_2 \uparrow \quad (5)$$

Table 2. Recovery and separation of REEs and Fe from Spent NdFeB magnets by oxidation roasting and inorganic acid leaching.

Reagents	Experimental Conditions	Conclusion	Reference
HCl leaching	Roasting: 850 °C, 6 h Leaching: HCl = 0.5 M, L/S = 100 g/L, 95 °C, 500 rpm, 5 h Leaching kinetics: the mixed controlled kinetic model, Ea = 30.1 kJ/mol, 348–368 K Precipitation: pH = 2, 1 M $H_2C_2O_4$ solution	Mixed rare earth oxides purity: >99%	[13]
HCl, H_2SO_4, HNO_3 leaching	Roasting: 800 °C, 120 min Roasting: 800 °C, 2 h Leaching: Unpretreated WPMs, 5 M HCl, 65 °C, 24 h, S/L = 2%, 800 rpm, 0.250 mm	The most influential parameter for the leaching experiment: the acid type 78% Nd, 83% Pr, and 76% Dy *p*-values: 0.007, 0.01, and 0.071	[14]
HCl pressure leaching	Roasting: 800 °C, 2 h Leaching: HCl = 0.6 M, 2 g/L $NaNO_3$ oxidant, L/S = 10 mL/g, 180 °C, 2 h Precipitation: n(oxalic acid)/n(REEs) = 1 Extraction: 30% (EHD) and 70% sulfonated kerosene (volume ratio) Na_2S precipitation: CoS	REEs and B recovery rates: 99% and 97%, <0.1% of Fe dissolved; The extracted REEs have >99% and 99.95% purity; 99.5% of B was recovered	[15]
HCl leaching	Roasting: 400 °C, 2 h Co-Leaching: HCl 6 mol/L, 2 h, L/S = 5, 90 °C Precipitation REEs: $H_2C_2O_4$ 1 mol/L, 30 min, 60 °C Complexation: $H_2C_2O_4$ 2 mol/L, 30 min, 60 °C Reduction and Precipitation: Iron power 1 mol/L, 30 min, 30 °C—$FeC_2O_4 \cdot H_2O$ Wastewater: Evaporation and crystallization	98.28% REEs recovered ($RE_2(C_2O_4)_3 \cdot 10H_2O$), 94.65% Fe recovered ($FeC_2O_4 \cdot H_2O$)	[16]
HCl leaching	Roasting: 400–800 °C Leaching: 0.2 M HCl, 90 °C, 3 h	Oxidation efficiency of NdFeB oil sludge: >99.2%	[17]

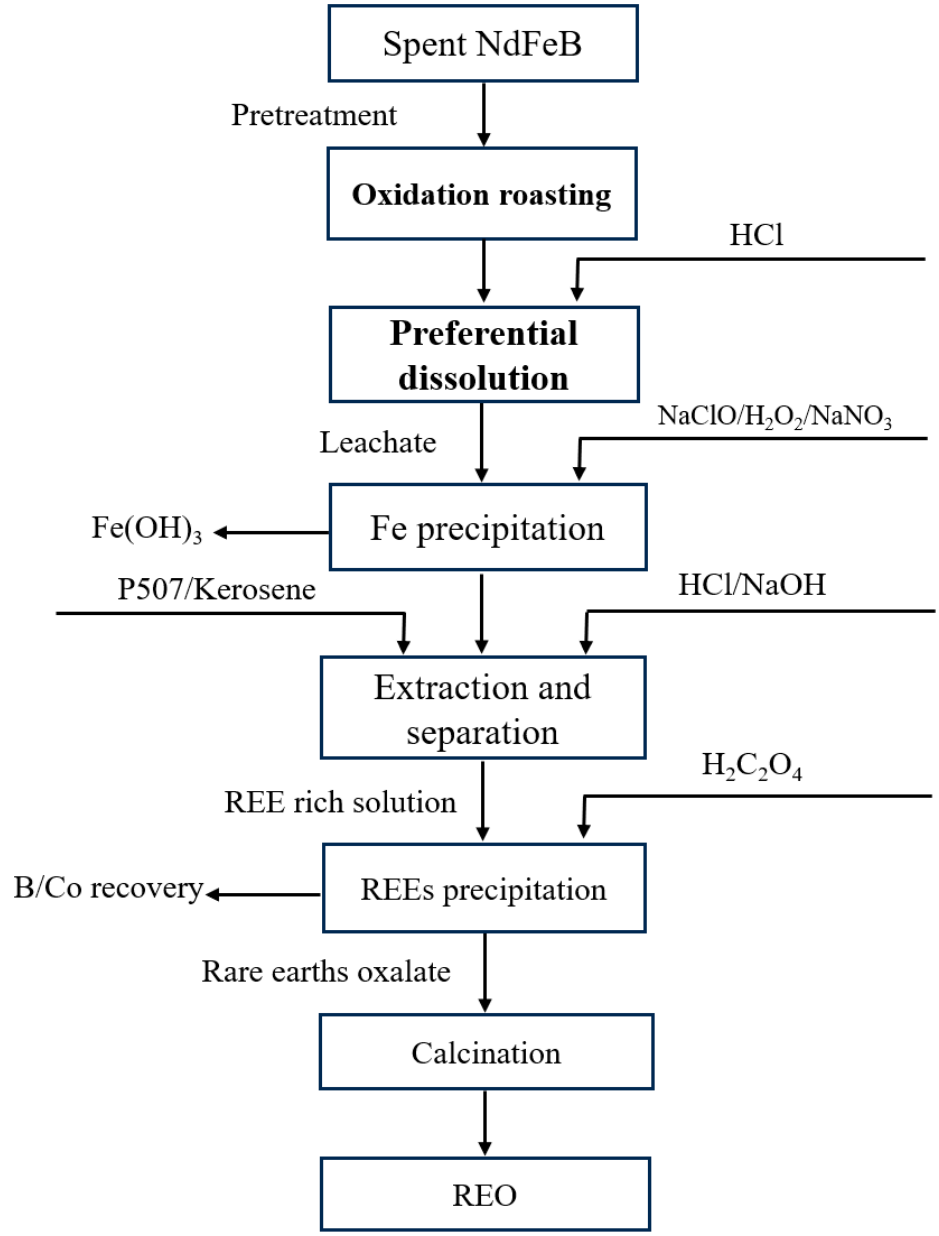


Figure 2. General process flow for recovering and separating REEs and Fe from spent permanent magnets using the hydrochloric acid preferential dissolving method.

Kumari A et al. [13] calcined spent permanent magnet, transforming REs and Fe into their respective oxides. Under optimal conditions, REEs were selectively recovered, while Fe_2O_3 remained in the residue.

Niam AC et al. [14] pretreated calcined permanent magnet powder. Using the Taguchi method, 5 M HCl was determined to be the optimal leaching agent under conditions of 65 °C, 24 h, 2% S/L, 800 rpm, and 0.250 mm powder particles.

Liu FP et al. [15] used hydrochloric acid pressure leaching on calcined NdFeB powder with $NaNO_3$ as an oxidant. Recovery rates were 99% for rare earths, 97% for B, and 0.1% for Fe. Cobalt was also recovered using a Na_2S precipitation method. Similarly, Liu ZS et al. [16] roasted NdFeB sludge for 2 h. Under conditions of 6 M HCl, L/S = 5, 90 °C for 2 h, REEs were precipitated with $H_2C_2O_4$. After reduction with iron powder, oxalic acid precipitated iron, achieving recovery rates of 98.28% for REEs and 94.65% for Fe.

Zhang ZH et al. [17] studied the mechanism of the hydrochloric acid preferential dissolution method, finding that the oxidation efficiency of NdFeB oil sludge increased to 99.2% with rising temperature.

Among oxidation roasting and inorganic acid leaching methods, the hydrochloric acid preferential dissolution method is the primary technique for large-scale production from NdFeB sludge in China. It is similar to the existing hydrometallurgical cascade extraction process for rare earth ores. The disadvantages of this method include high roasting temperature and energy consumption. However, iron is effectively precipitated and removed, and rare earths can be selectively leached.

3.2. Acid Baking and Water Leaching

Acid baking and water leaching involve calcining spent NdFeB with acidification reagents, followed by dissolving the calcined products in water to leach out rare earth elements, while Fe is retained in the leaching residue. This includes sulfation, chlorination, and nitration roasting, followed by water leaching. The reagents used are shown in Table 3, the methods are summarized in Table 4, and the general process flow is shown in Figure 3.

Table 3. Reagents of the acid baking and water leaching process.

Methods	Sulfation Roasting and Water Leaching	Chlorination Roasting and Water Leaching	Nitration Roasting and Water Leaching
Reagents	H_2SO_4, $Fe_2(SO_4)_3$, $(NH_4)_2SO_4$ $ZnSO_4 \cdot H_2O$, $FeSO_4 \cdot 7H_2O$	NH_4Cl, $CaCl_2 \cdot 2H_2O$, $FeCl_3 \cdot H_2O$	Fe $(NO_3)_3 \cdot 9H_2O$

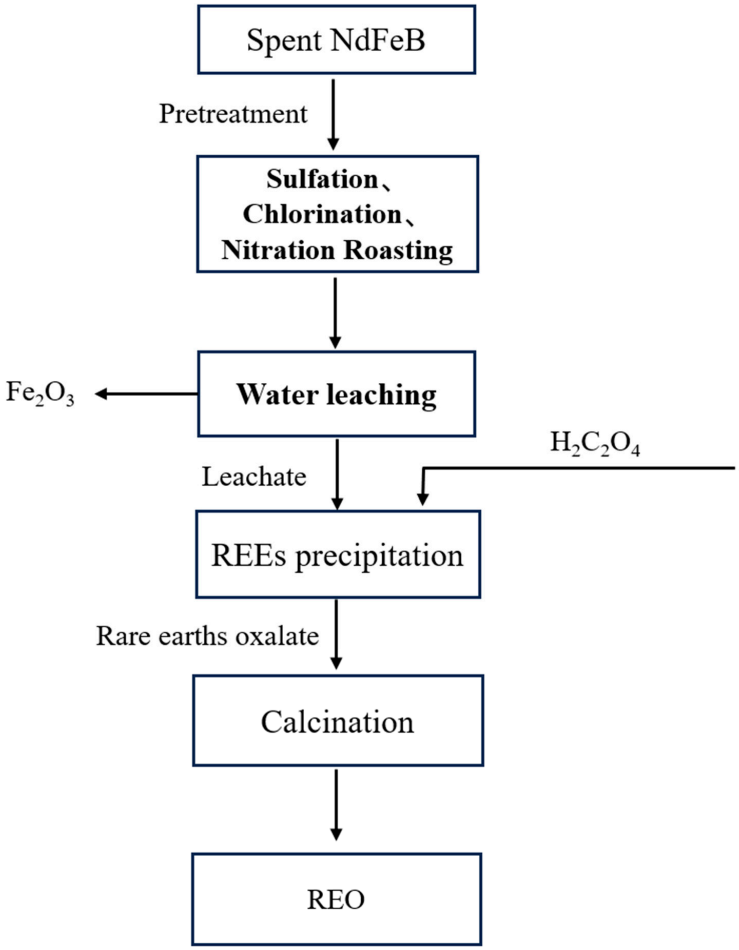


Figure 3. General process flow for recovering and separating REEs and Fe using acid baking and water leaching method.

Table 4. Recovery and separation of REEs and Fe from Spent NdFeB magnet by acid baking and water leaching.

Treatment Method	Reagents	Experimental Conditions	Conclusion	Reference
Sulfation roasting and water leaching	H_2SO_4	<40 μm particle size Acid: 60 g/L, 12–16 M at 25 °C Drying: 24 h at 110 °C Roasting: 750 °C for 1 h Water Leaching: 20 g/L, 25 °C for 1 h	The extraction rate of REMs is 95–100 wt%, and that of Fe is ~0 wt%	[18]
	$Fe_2(SO_4)_3$	Grinding: Mechanochemical grinding, ball-to-powder ratio: 5/1 (g/g), 800 rpm, 2 min 400 rpm, 10–60 min Calcination: 900 °C, 5 h Leaching: L/S: 40–10 mL/g, 1–24 h at 25 °C	The rare earth leaching rate exceeds 95%, and cobalt is completely recovered	[19]
	$(NH_4)_2SO_4$	First roasting: 1 h, 400 °C Molar ratio: (Fe + RE)/($(NH_4)_2SO_4$):1/0.6–1/3 Second roasting: 2 h, 750 °C Molar ratio: (Fe + RE)/($(NH_4)_2SO_4$):1/2 Water Leaching: L/S: 20/1, 0.5 h, 30 °C	RE extraction yields up to 96%. Fe, Al, Cu, and Co extraction yields are 0.008%, 0.27%, 1.64%, and 3.48%, respectively	[20]
Chlorination roasting and water leaching	NH_4Cl	Temperature: 250–400 °C Stoichiometric ratio of NdFeB/NH_4Cl: 1:1–1:5 Time: 0.5–3 h Water leaching: 95 °C, S/L: 100 g/L, 500 rpm, 1 h.	99.2% REOs, 96.4% Fe_2O_3 were obtained	[21]
	$CaCl_2 \cdot 2H_2O$	600 °C, dosage ($CaCl_2 \cdot 2H_2O$: NdFeB = 2:1), 90 min; Water leaching: 90 °C, 1 h, S/L = 10; 0.5 M HCl leaching, S/L: 1/10 g/mL, 90 °C, 3 h; Oxalic acid precipitation: 60 °C, 20 min, pH = 2; Calcination: 850 °C, 2 h.	The maximum dissolution of Nd ~ 89%, Dy ~ 88%, rare earth oxides 96% purity	[22]
	$FeCl_3 \cdot 6H_2O$	Temperature: 350–600 °C, 0.5–3 h, n (chlorinating agent)/n(scrap): 0.5–2.5:1 Water leaching: L/S = 10 mL/g/1, 1 h at 90 °C	REEs and Co were extracted 96.51%, 64.29%, respectively, 92 wt% iron oxide was achieved	[23]
	$FeCl_3 \cdot 6H_2O$	Grinding: 0–1.5 h, 0–400 rpm, m (ball)/m(powder): 15/1 Roasting temperature: 200–600 °C, time: 10–90 min, molar ratios of N/F: 1:0–2.5 Leaching: temperature of 90 °C for 1 h, L/S = 25 g/mL	high leaching efficiencies of 98.94% for REEs, 99.99% for Co, and 93.36% for B, 96.73 wt% for iron oxide	[24]
Nitration roasting and water leaching	$Fe(NO_3)_3 \cdot 9H_2O$	Nitration: NFB powders were converted into a mixture of nitrate metals at 25 °C for 1 h. Calcination: 200 °C, 1 h Water leaching: S/L ratio = 60 g/L, 1 h Resting duration: 110 °C, 6–24 h (unnecessary); Particle size: 200 μm–500 μm, 1000 μm (ball milling avoided)	>95% for Nd, Dy, Pr, and Gd, and <1% Fe achieved	[25]

3.2.1. Sulfation Roasting and Water Leaching

Sulfation roasting involves reacting spent NdFeB magnets with sulfuric acid or sulfates to convert valuable metals into corresponding sulfates, which are then recovered through water leaching and separation steps. Leaching efficiency with sulfuric acid is high, but it causes severe equipment corrosion. Ammonium sulfate roasting occurs at lower temperatures, but the recovery process is lengthy. Ferric sulfate fully recovers iron from NdFeB, but REE loss is relatively significant during iron removal. The overall process can be summarized by reactions (6)–(10).

$$xM + yH_2SO_4(aq) \rightarrow M_x(SO_4)_{y(aq)} + yH_2 \uparrow \quad (6)$$

$$xM + 2yH_2SO_4(aq) \rightarrow M_x(SO_4)_{y(aq)} + 2yH_2O \uparrow + ySO_2 \uparrow \quad (7)$$

$$R_2(SO_4)_3 \rightarrow R_2O_2(SO_4) + 2SO_3 \uparrow \quad (8)$$

$$R_2O_2(SO_4) \rightarrow R_2O_3 + SO_3 \uparrow \quad (9)$$

$$2FeSO_4 \rightarrow Fe_2O_3 + SO_2 \uparrow + SO_3 \uparrow \quad (10)$$

(M: metal; R: REM)

Önal M.A.R. et al. [18] studied the selective separation and recovery of rare earths using sulfation roasting and water leaching. Within a temperature range of 650 to 850 °C, magnet powder was completely converted to sulfate by calcination with H_2SO_4 for 15 to 120 min. The calcination products were then treated with selective water leaching to recover rare earths.

Loy S. V. and Önal M.A. R. [19] recovered valuable metals from NdFeB magnets through mechanochemically assisted ferric sulfate leaching. REEs and Co were leached from the roasting products via water leaching, achieving high leaching rates for REEs (>95%) and complete recovery of cobalt. Fe^{2+} was oxidized to Fe^{3+} using appropriate oxidants (e.g., bubbling air), thus regenerating the reagent.

Liu FP et al. [20] found that rare earths could be selectively recovered by a two-stage ammonium sulfate calcination and water leaching process. Adopting a two-stage roasting process significantly reduced the dosage of $(NH_4)_2SO_4$ and enhanced the separation efficiency of rare earths.

3.2.2. Chlorination Roasting and Water Leaching

Chlorination roasting involves reacting spent NdFeB magnets with hydrochloric acid or chlorides to convert valuable metal components into corresponding chlorides. Rare earth chlorides are easily soluble in water and are recovered through water leaching and separation steps. Spent NdFeB magnets can be chlorinated and calcined with NH_4Cl at relatively low temperatures. $CaCl_2 \cdot 2H_2O$ is a solid chlorination reagent with the advantages of being environmentally friendly, free of toxic gases, and economically efficient. Through a mechanochemical reaction with $FeCl_3 \cdot 6H_2O$ during low-temperature calcination, unchlorinated rare earth and cobalt are thoroughly chlorinated. Complete separation of rare earths, cobalt, boron, and iron is achieved through water leaching, further reducing acid consumption. The overall process can be summarized by reactions (11)–(15).

$$NH_4Cl \rightarrow NH_3 + HCl \quad (11)$$

$$Fe + 3NH_4Cl + 0.75O_2 \rightarrow FeCl_3 + 3NH_3 + 1.5H_2O \quad (12)$$

$$Nd + 3NH_4Cl + 0.75O_2 \rightarrow NdCl_3 + 3NH_3 + 1.5H_2O \quad (13)$$

$$Fe + 0.75O_2 \rightarrow 0.5Fe_2O_3 \quad (14)$$

$$FeCl_3 + 0.75O_2 \rightarrow 0.5Fe_2O_3 + 1.5Cl_2 \quad (15)$$

Kumari A et al. [21] developed an NH_4Cl chlorination calcining process to extract REEs. Using NH_4Cl as the chlorination agent at a reduced calcination temperature of 300 °C, 99.2% REO was obtained, with a by-product leaching residue containing 96.4% Fe_2O_3.

Gahlot R. and Dhawan N. [22] used $CaCl_2 \cdot 2H_2O$ for chlorination roasting, followed by water leaching and acid leaching. Maximum dissolution was approximately 89% for Nd and 88% for Dy. The removal rate of Ca by water leaching after calcination was approximately 87%, and the rare earth oxalate precipitation rate was 99%, resulting in an REE extraction rate of approximately 89%.

Wu J et al. [23] studied the co-chlorination and water leaching of magnet scrap using $FeCl_3 \cdot 6H_2O$ to recover REEs. Under appropriate leaching conditions, 96.51% of REEs and 64.29% of Co were simultaneously leached into the leachate, yielding 92% iron oxide.

Wu J and Wang D et al. [24] adopted a mechanochemical strategy, mixing spent NdFeB magnet powder with $FeCl_3 \cdot 6H_2O$, followed by grinding, calcination, and water leaching, achieving complete separation of rare earth, cobalt, boron, and iron.

3.2.3. Nitration Roasting and Water Leaching

Nitration roasting involves reacting spent NdFeB magnets with nitric acid or nitrate to convert valuable metal components into corresponding nitrates, which are then recovered through water leaching and separation steps. Nitration calcination of spent NdFeB magnet powder with $Fe(NO_3)_3 \cdot 9H_2O$ decreases the roasting temperature and is suitable for all types of permanent magnets. This method offers high reactivity, and the relatively high solubility of rare earth nitrates facilitates downstream separation. The overall process can be summarized by reactions (16)–(21). (M: REE, Fe)

$$Fe(NO_3)_3 \cdot 9H_2O \rightarrow Fe(OH)(NO_3)_2 \cdot 2H_2O + HNO_3 \uparrow + 6H_2O \uparrow \quad (16)$$

$$Fe(OH)(NO_3)_2 \cdot 2H_2O \rightarrow Fe(OH)_2NO_3 + HNO_3 \uparrow + H_2O \uparrow \quad (17)$$

$$Fe(OH)_2NO_3 \rightarrow FeOOH + HNO_3 \uparrow \quad (18)$$

$$2FeOOH \rightarrow Fe_2O_3 + H_2O \uparrow \quad (19)$$

$$2M + 6HNO_3 \rightarrow 2M(NO_3)_3 + 3H_2 \uparrow \quad (20)$$

$$M + 4HNO_3 \rightarrow M(NO_3)_3 + NO \uparrow + 2H_2O \uparrow \quad (21)$$

Önal M.A.R. et al. [25] found that magnet powder was completely converted into a metal nitrate mixture at room temperature within 1 h. Through calcination with $Fe(NO_3)_3 \cdot 9H_2O$ at 200 °C and water leaching treatment, REE extraction exceeded 95%.

The acid roasting and water leaching process uses acidification reagents instead of direct inorganic acid, reducing equipment corrosion and enabling selective leaching of rare earths. The chosen acidifiers are mostly Fe sulfates, chlorides, or nitrates, fully utilizing the 60–70% Fe content in NdFeB.

4. Electrolysis in Aqueous Solution

NdFeB magnetic chips have high electrical conductivity and can be directly used as anodes, avoiding high-energy-consuming processes like crushing, grinding, and calcination. Advantages of electrolytes in aqueous solution include high solubility of metal salts, low volatility, and low cost. Recovering spent permanent magnets by electrolysis at room temperature can reduce the consumption of acids, bases, and energy.

4.1. Direct Anodic Dissolution

As active anodes, the magnets are directly dissolved to generate RE^{3+} and Fe^{2+}. (Equations (22) and (23)). Fe^{2+} is oxidized at the inert anode and hydrolyzed in situ to ferric hydroxide, separating it from the rare earths. The process flowsheet is shown in Figure 4.

Venkatesan P et al. [26] electrochemically oxidized and leached NdFeB magnets directly in an NH_4Cl solution using a double anode system. One anode was a large piece of NdFeB magnet scrap, while the other was an inert anode that converted Fe^{2+} to Fe^{3+} in situ via electrochemical oxidation. Rare earths were then selectively leached from the mixed hydroxide with a low HCl/REE ratio (nHCl/nREE $\leq$ 3.5).

Zhang ZH et al. [27] studied a double anode electrochemical system to selectively leach REEs in a $ZnCl_2$ electrolyte solution. The NdFeB magnet acted as an active anode, generating RE^{3+} and Fe^{2+}. Fe^{2+} was oxidized and hydrolyzed to ferric hydroxide, separating it from REEs. Subsequently, Na_2SO_4 was added to form $RE_2(SO_4)_3$ precipitate, enabling the recycling of the $ZnCl_2$ electrolyte. A small amount of Zn was dissolved in NaOH solution to obtain $Nd(OH)_3$. Both $Fe(OH)_3$ and $Nd(OH)_3$ were calcined to obtain their respective oxides.

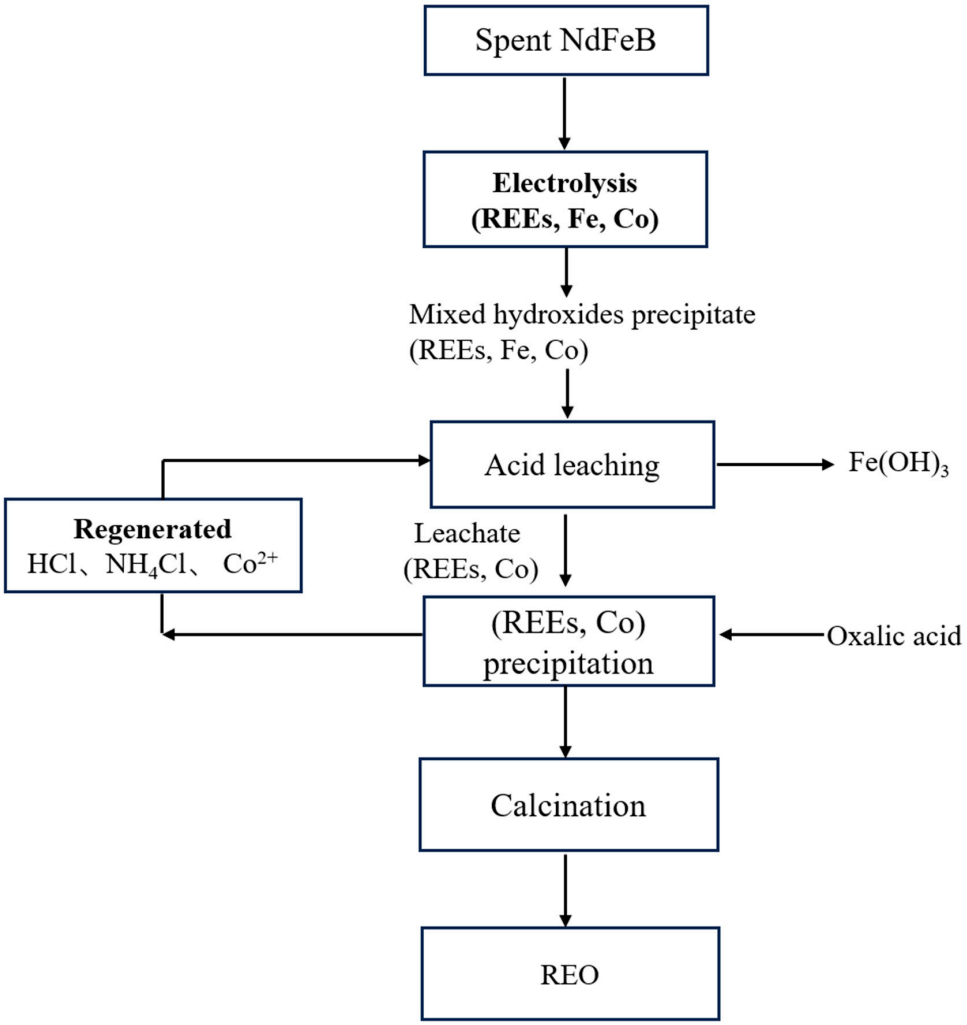


Figure 4. General process flow for REEs recovery through electrolysis in aqueous solution.

Xu X et al. [28] developed a method to selectively dissolve magnet scrap in an organic N, N-dimethylformamide (DMF) $FeCl_2$ electrolyte at room temperature. By adjusting the anode current density to less than 5 mA/cm^2, the selective dissolution order of the

magnet's internal phases was: first metallic Nd, then intergranular $NdFe_4B_4$, and finally the matrix phase $Nd_2Fe_{14}B$.

$$Nd_2Fe_{14}B - 37e^- \rightarrow 2Nd^{3+} + 14Fe^{2+} + B^{3+} \quad (22)$$

$$Fe^{2+} - e^- \rightarrow Fe^{3+} \quad (23)$$

4.2. Direct Depositing on the Cathode

As an alternative to anodic oxidation of Fe^{2+} to promote hydrolysis, direct cathodic deposition of metallic iron can be employed. (Equations (24) and (25)).

Xu X et al. [29] developed an environmentally friendly and simpler electrochemical method for recovering NdFeB permanent magnets. This method achieves selective rare earth recovery and simultaneous green chemical deposition of Fe metal, with full electrolyte reuse, creating a closed-loop process.

Yang Y et al. [30] directly recovered rare earths using a one-step precipitation in HF solution, while Fe was dissolved through electrodeposition. Nanoscale FeF_2(s) and Fe(s) were cathodically deposited at pH 2.3 and pH 2.89, respectively. The process of reducing Fe^{3+} to Fe was investigated using cyclic voltammetry, chronopotentiometry, and open-circuit chronopotentiometry, and the hydrofluoric acid was reused.

Xiao FS et al. [31] developed a combined electrochemical-hydrometallurgical process for recovering spent NdFeB. Electrolysis was carried out at 60 °C, Fe^{2+} was deposited as Fe at the cathode, and Nd was recovered through crystallization to obtain $Nd_2(SO_4)_3 \cdot nH_2O$ mixed crystals with an iron content of 0.1 wt%.

Venkatesa P et al. [32] completely leached an NdFeB magnet in hydrochloric acid. Fe^{2+} in the leachate was then selectively oxidized to Fe^{3+} by in situ electrochemical oxidation. Ammonium hydroxide was added to remove iron as $Fe(OH)_3$. Subsequent oxalic acid precipitation recovered REEs, finally yielding a cobalt-rich solution. Electrowinning on this solution proved the feasibility of recycling pure cobalt metal.

Makarova I et al. [33] investigated the electrochemical leaching of Fe and REEs from permanent magnets in sulfuric acid and oxalic acid, using a 3D-printed titanium mesh as the anode to leach metals from the magnet surface. Oxalic acid was used to precipitate rare earths, separating the REE-oxalate precipitate at a lower battery voltage.

Makarova I et al. [34] recovered REEs via electrochemical leaching in sulfuric and oxalic acids. A dense REE oxalate layer and iron solid residue were retained for further recovery. Rare earth cathodic deposition was attributed to the electrostatic attraction of rare earth oxalate particles.

The aqueous solution electrolysis method effectively addresses the issues of high energy consumption and unsustainability in existing NdFeB recycling technologies.

Additionally, REMs in NdFeB magnets can react spontaneously with water. However, REE recovery in aqueous solutions is often limited by mass transfer. Challenges remain, such as slow reaction rates, the need for precise control of anode and cathode reactions, and scaling up the process. Designing a reasonable recovery process and appropriately utilizing the H^+ generated at the in-situ anode, OH^- generated at the cathode, and oxidants generated during electrolysis may improve leaching efficiency and reduce the use of strong acids and bases. Methods using electrolysis in aqueous solution are summarized in Table 5.

$$Fe^{2+} + 2e^- \rightarrow Fe \quad (24)$$

$$2Nd_2Fe_{14}B + 18H^+ \rightarrow 4Nd^{3+} + 28Fe + 2B^{3+} + 9H_2 \uparrow \quad (25)$$

Table 5. Recovery and separation of REEs and Fe from spent NdFeB magnets by electrolysis in aqueous solution.

Methods	Electrolyte/Reagents	Experimental Conditions	Process Steps	Conclusion	References
inorganic acid	HCl/NH_4Cl	Three-electrode system: Anode: NdFeB magnet and cylindrical Ti/Pt Cathode: Nickel wire RE: Ag/AgCl CE: a glassy carbon	1. Leaching of spent magnets 2. Fe^{2+} electrochemical oxidation 3. $H_2C_2O_4$ precipitates REEs 4. Neutralization of base (1) RE oxalate precipitation (2) Cobalt electrodeposition	>97% of REEs precipitated, and the REOs' purity of 99.2% obtained; two routes: (a) Fe →$FeCl_3$; (b) Fe →Fe$(OH)_3$; Co: electro-winning →Pure Cobalt	[26]
chloride salt solution	$ZnCl_2$	Double anode system: Three-electrode system: WE: NdFeB magnets and inert anode (Pt electrodes); RE: Ag/AgCl electrodes; CE: Pt electrodes	1. Potentiodynamic polarization; kinetic potential polarization tests 2. Linear sweep voltammetry 3. Electrochemical dissolution	Nd_2O_3 and Fe_2O_3 are obtained	[27]
chloride salt solution	nonaqueous dimethylformamide (DMF)/$FeCl_2$	Three-electrode system: WE: NdFeB magnet and Pt wire (Anode) Cathode: Cu QRE (quasi-reference electrode): Another Pt wire CE: A Pt plate	1. Electrochemical etching of the NdFeB magnet and cathodic deposition of pure Fe metal 2. $Nd_2Fe_{14}B$ grains, REE^{3+}, Fe^{2+} and REE-based particles separation 3. Hydrometallurgy Electrolysis REE metals/alloys obtained 4. REE metals/alloys with obtained $Nd_2Fe_{14}B$ grains to make new NdFeB magnets	$Nd_2Fe_{14}B$ particles, REE electrolyte, REE-based particles, and pure Fe metal are obtained	[28]
inorganic acid	H_2SO_4	Three-electrode system: WE: a spent NdFeB magnet and a Pt wire (Anode) Cathode: Cu foil RE: Ag/AgCl CE: A Pt plate	1. Linear sweep voltammetry (LSV) test at room temperature; 2. Electrochemical leaching of the NdFeB magnets and Fe metal deposition; 3. Selective precipitations of the REEs with Na_2SO_4	Fe–Co, deposited on the cathode; REEs, precipitated in the electrolyte	[29]
inorganic acid	HF	Three-electrode system: CE/WE: Pt foil (99.95% purity) RE: Hg/Hg_2SO_4	1. Recycling of REEs 2. The influence of pH on the electrodeposition of Fe 3. At pH = 2.89, the electrochemical behaviors of iron	(1) Cathode deposition of Nano-sized FeF_2(s) and Fe(s) at pH 2.3 and pH 2.89; (2) The relationship between the diffusion coefficient and temperature was obtained: (3) Diffusion-activation-energy: -15.01 kJ mol^{-1}; (4) Fe-Pt Gibbs energy: $\Delta G = -487.53 + 0.936$ T.	[30]
sulfate solution	$Nd_2(SO_4)_3$ FeSO4	Three-electrode system: Anode: NdFeB waste Cathode: Titanium sheet RE: Hg/Hg_2SO_4 electrode CE: Ti/Pt sheet	1. Electrochemical-analysis tests: polarization curves and Cyclic voltammetry (CV) 2. Electrochemical dissolution of NdFeB waste 3. Crystallization with elevated temperature of the electrolyte	Fe^{2+} was recovered by electrodeposition; RE^{3+} recovered as $Nd_2(SO_4)_3 \cdot nH_2O$ by elevated-temperature crystallization	[31]
chloride salt solution	NH_4Cl	Three-electrode system: Anode: magnet and Ti/Pt electrode Cathode: Cu RE: Ag/AgCl CE: Cu	1. Electrochemical dissolution of spent NdFeB magnet Scrap and 2. Fe^{2+} oxidized→$H_2C_2O_4$ precipitation.	More than 97% of REEs and REOs of purity (99.2%) obtained; Fe, REEs, and Co were selectively recycled	[32]
inorganic acid	H_2SO_4 $H_2C_2O_4$	Three-electrode system: Anode: NdFeB magnet and 3D printed Ti Cathode: Cu RE: Ag/AgCl CE: Pt	1. Potentiodynamic polarization scans 2. Chemical leaching and Electro-leaching 3. Leaching mechanism	$RE(C_2O_4)_3 \cdot nH_2O$ is recycled in the cathodic deposits; Nd-rich phase dissolved preferentially	[33]
inorganic acid	H_2SO_4 $H_2C_2O_4$	Three-electrode system: WE: NdFeB magnet(anode) copper plate(cathode) RE: Ag/AgCl CE: Pt wire	1. Electrochemical leaching of NdFeB magnet in galvanostatic mode using a power supply 2. Electrochemical measurements: 3. Polarization test and Cathodic polarization curves	93% dense layer of REE oxalates on the cathode, and iron remains in solution	[34]

5. Organic Acids Leaching

5.1. Organic Acids Leaching of Spent NdFeB

The mechanism of organic acid leaching involves dissolving metals through acidolysis and complexation. In acidolysis, H^+ dissolves the metal into the solution. In complexation, organic acids form stable complexes or chelates with metal ions.

Hydrometallurgical recovery using organic acids has a lower environmental impact than inorganic acids. Therefore, the effects of various organic acids have been studied. The process flowsheet is shown in Figure 5.

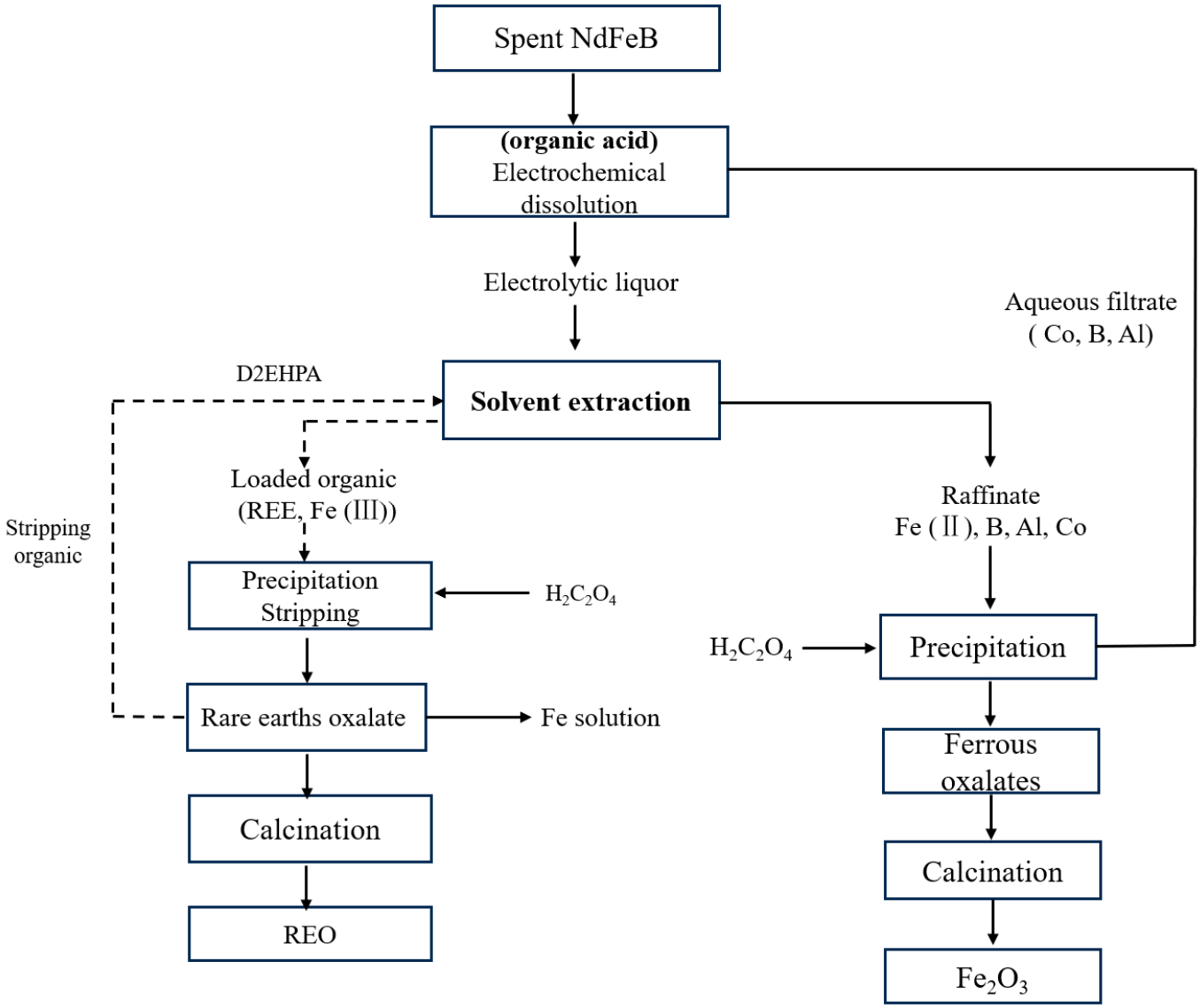


Figure 5. General process flow for recovery and separation of REEs and Fe from spent magnets using organic acids leaching.

Behera S. S. and Parhi PK. [35] developed a CH_3COOH leaching process for RE from NdFeB scraps. Research showed that when NdFeB magnets are treated with acetic acid, Nd can be successfully leached with a rate over 99%, although iron was co-leached. Menad NE et al. [36] confirmed that acetic acid can effectively leach Nd, Dy, and Fe, but selectively does not leach the nickel from the protective layer on the magnet surface, allowing nickel recovery in the solid phase after filtration.

Belfqueh S et al. [37] studied the leaching of REEs from NdFeB magnets using different organic acids such as acetic acid, formic acid, citric acid, and tartaric acid. Acetic acid yielded the highest recovery.

Liu Q S et al. [38] developed a new method using oxalic acid to leach NdFeB magnets. Rare earth oxalate remained in the slag, while $Fe(C_2O_4)_3^{3-}$ remained in the leachate. The leachate was treated by reducing the iron oxalate solution with iron powder to form ferrous oxalate.

Gergoric M et al. [39] used glycolic, maleic, and ascorbic acids to leach out REEs. The leaching rate for glycolic and maleic acids (95%) was higher than for ascorbic acid (50%). Various extractants (TBP, D2EHPA, Cyanex 272, 923, TODGA) and diluents (1-octanol, cyclohexanone, hexane, pentane, dodecane) were studied in the extraction procedure, showing good potential for leaching REEs from NdFeB.

Reisdorfer G et al. [40] studied the leaching of unroasted and roasted magnets using maleic acid or citric acid. The leaching efficiencies of Nd and Fe from unroasted magnets were both higher than those from roasted magnets.

Kumari A et al. [41] investigated the electrochemical leaching of spent NdFeB magnets in citric acid, recovering REEs and valuable metals to obtain mixed oxides of Nd, Pr, Dy, and iron oxide.

These studies show that organic acids are very effective in leaching REEs. If sourced cheaply and conveniently, such as from waste streams, the total cost and environmental impact of the process can be decreased. Organic acid leaching methods are summarized in Table 6.

Table 6. Recovery and separation of REEs and Fe from Spent NdFeB magnet by Organic acid leaching.

Treatment Method	Reagents	Experimental Conditions	Conclusion	References
Organic acid leaching	acetic acid	Leaching: 800 rpm, S/L: 1% (W/V), 80 °C, 0.4 M, particle size: 106–150 µm	>99% Nd were reached, Co-leaching of Fe	[35]
	acetic acid	Leaching: all metals except nickel are dissolved within 7 h	>90% Nd, Dy, Fe were reached, 0% Ni	[36]
	acetic acid, formic acid, citric acid, tartaric acid	Leaching: (acetic acid, formic acid, citric acid, and tartaric acid), 1.6–10 M, S/L: 0.5–10%, 60 °C	>90% for Nd, Dy, and Pr were leached in acetic acid	[37]
	oxalic acid	Leaching: 90 °C, 6 h, oxalic acid: 2 M, L/S: 60 mL/g, ferric oxalate solution reduced using Fe powder	93.89% Fe was leached, $RE(C_2O_4)_3 \cdot n\ H_2O$ precipitation rate: 93.17%, $FeC_2O_4 \cdot 2H_2O$ is obtained.	[38]
Oxidation roasting and organic acid leaching	glycolic, maleic, ascorbic acids	Roasting: 1.5 h at 400 °C Sieved: <355 µm particle size Leaching: S/L ratio = 1/50 g/mL, 25 ± 1 °C, 0.6–1 M, S/L ratio = 1/30–1/80 g/mL, 1 M, 25 ± 1–70 ± 1 °C, 400–1000 rpm. time: 100, 200, 300, 400 min, 24 h Liquid–Liquid Extraction: TBP, D2EHPA, TODGA, Cyanex272, Cyanex923	>95% REEs were obtained, 1 M, S/L ratio = 1/80.	[39]
	malic and citric acids leaching	Roasting: 900 °C, 480 min Leaching: 30–90 °C, 0.2–1.2 mol/L, S/L ratio: 1:10–1:50, 10–900 min	Nd from unroasted NdFeB powder reached 99%, but it is not selective. The optimal values are determined.	[40]
Organic acid leaching	citric acid	1. Electrochemically dissolved NdFeB magnets; 2. Using D2EHPA extract REEs; 3. Oxalic acid precipitation REEs	$(Nd, Pr, Dy)_2O_3$ 99.9% purity, Iron oxide (98.6% pure) obtained	[41]

5.2. The Structure-Activity Relationship of Organic Acids

The structural formulas of organic acids are shown in Figure 6, and their formula and pK_a values are summarized in Table 7.

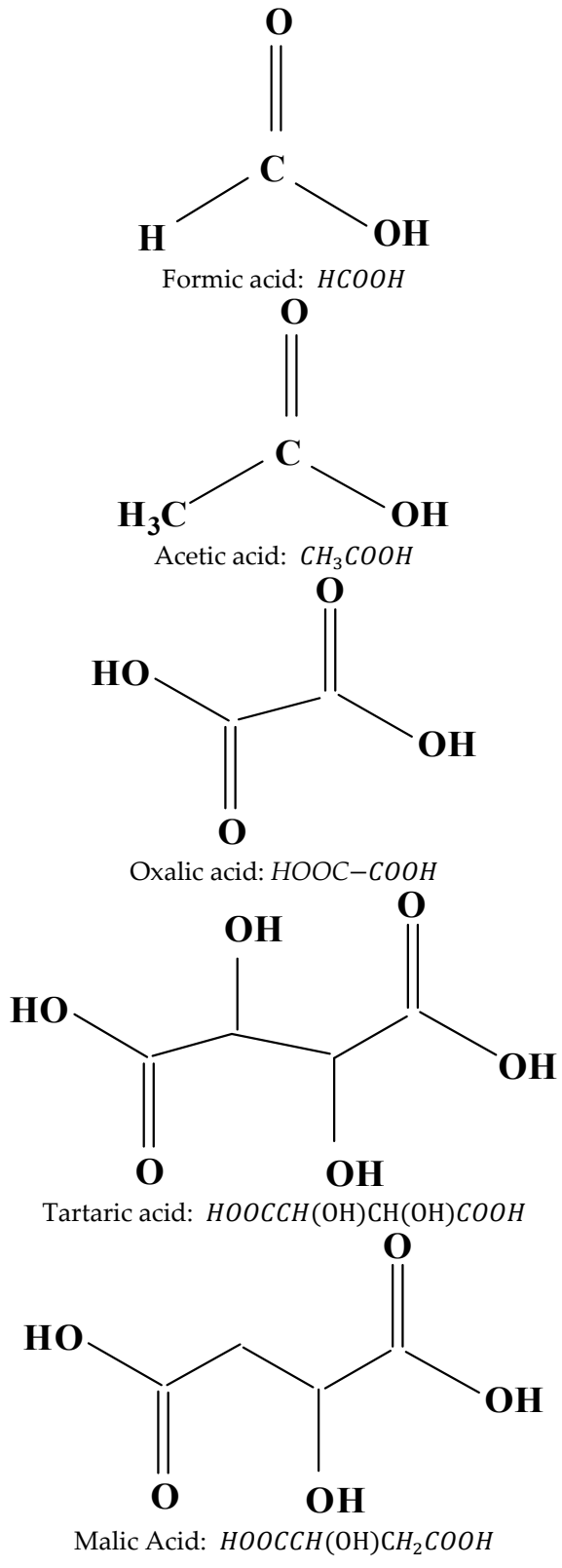
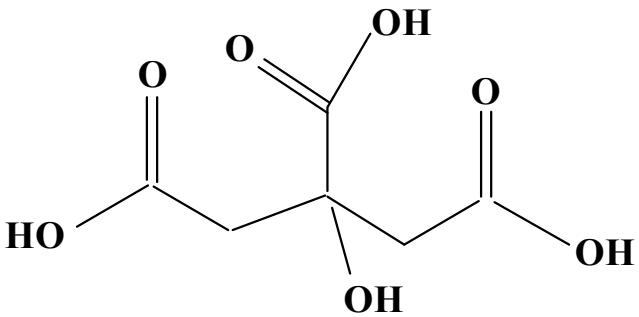
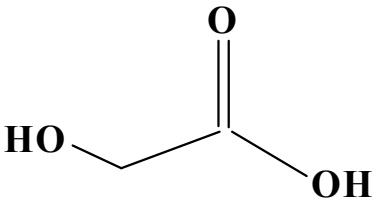


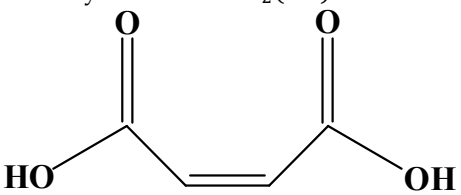
Figure 6. *Cont.*



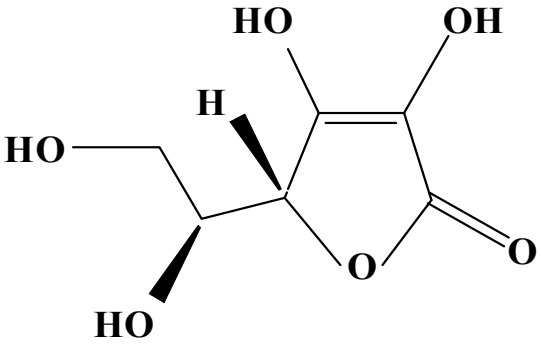
Citric Acid: $HOOCCH_2$COOH(OH)CH_2COOH



Glycolic acid: CH_2(OH)$COOH$



Maleic acid: $HOOCHC = CHCOOH$



Ascorbic acid: $C_6H_8O_6$

Figure 6. Structural formulas of organic acids.

The selection of organic acid leaching agents depends on the number of carboxyl groups, hydroxyl groups, and carbon-carbon double bonds in their molecular structure, which is reflected in their pK_a values. At pH values where acid ions and anions are at equal concentrations, a lower pK_a indicates a stronger acid. Their metal-dissolving ability will also differ, but most organic acids are non-toxic and environmentally friendly. For example, ascorbic acid is only corrosive at low pH values. They are often low-cost, easy to use, and composed only of C, H, and O atoms, emitting only CO_2 and water upon combustion. Most are thermally stable and can form strong chelates, playing a key role in dissolving metals through acid hydrolysis and complexation. The strength of the H-O bond in carboxylic acids affects the complexation rate, and acids with more hydroxyl groups generally react more quickly [42].

Organic acids are highly efficient and environmentally friendly leaching agents for recycling spent NdFeB, causing neither secondary pollution nor significant equipment corrosion. They pose relatively low potential risks to operators and can selectively leach metals. Moreover, they are biodegradable and avoid most environmental or cost problems

associated with inorganic acids. However, reaction times can be long; hence, improving leaching kinetics is an important consideration.

Table 7. The formula and pK_a of organic acids.

Organic Acids	Molecular Formula	pK_a
Formic acid	HCOOH	3.74
Acetic acid	CH_3COOH	4.74
Oxalic acid	$H_2C_2O_4$	pK_{a1} = 1.12 pK_{a2} = 4.19
Tartaric acid	CH(OH)COOH | CH(OH)COOH	pK_{a1} = 3.04 pK_{a2} = 4.37
Malic Acid	CH(OH)COOH | CH_2COOH	pK_{a1} = 3.44 pK_{a2} = 4.12
Citric Acid	CH_2COOH | C(OH)COOH | CH_2COOH	pK_{a1} = 3.13 pK_{a2} = 4.76 pK_{a3} = 6.40
Glycolic acid	$CH_2(OH)COOH$	3.8
Maleic acid	CHCOOH ‖ CHCOOH	pK_{a1} = 1.9 pK_{a2} = 6.1
Ascorbic acid	$C_6H_8O_6$	pK_{a1} = 4.2 pK_{a2} = 11.6

6. Bioleaching

The mechanism of bioleaching involves utilizing microorganisms to convert insoluble metal compounds into water-soluble forms, recovering metals through biological oxidation, complexation, and the activation of metal ions.

Auerbach R et al. [43] developed bioleaching for permanent magnets using different bacteria such as *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, and *Leptospirillum ferrooxidans*. The highest rare earth leaching efficiency (86% Dy, 91% Nd, 100% Pr) was achieved with *Acidithiobacillus* and *Leptospirillum ferrooxidans*.

Bioleaching is a sustainable, environmentally friendly, and potentially economically effective technology. Microorganisms dissolve metals from spent NdFeB magnets through acid hydrolysis and redox processes [44]. However, challenges such as long culture times, slow process kinetics, low solid–liquid ratios, and metal toxicity remain. Bioleaching primarily depends on metabolite generation, microbial tolerance to toxic metals, low-cost media, and optimization of operational parameters [45].

7. Ionic Liquid Systems

Traditionally, ionic liquids (ILs) are defined as organic salts composed entirely of organic cations and organic or inorganic anions, with a melting point below 100 °C. Deep Eutectic Solvents (DESs) are often grouped with ILs due to their similar properties, and together they are collectively referred to as ionic liquid systems.

These systems possess outstanding ion extraction and transport capabilities, as well as stable electrochemical windows, giving them broad application prospects in fields such as REE extraction, metal leaching, and the electrochemical recovery of metals.

7.1. Ionic Liquid Extraction

The distinct compositions of DESs and ILs lead to different primary applications in the separation and recycling of NdFeB magnets. Typically, ILs are used as extractants in liquid–liquid separation processes, while DESs are more commonly employed as direct leaching agents. The recovery and separation of REEs and Fe using ILs and DESs are summarized in Table 8, with a general process flowsheet provided in Figure 7.

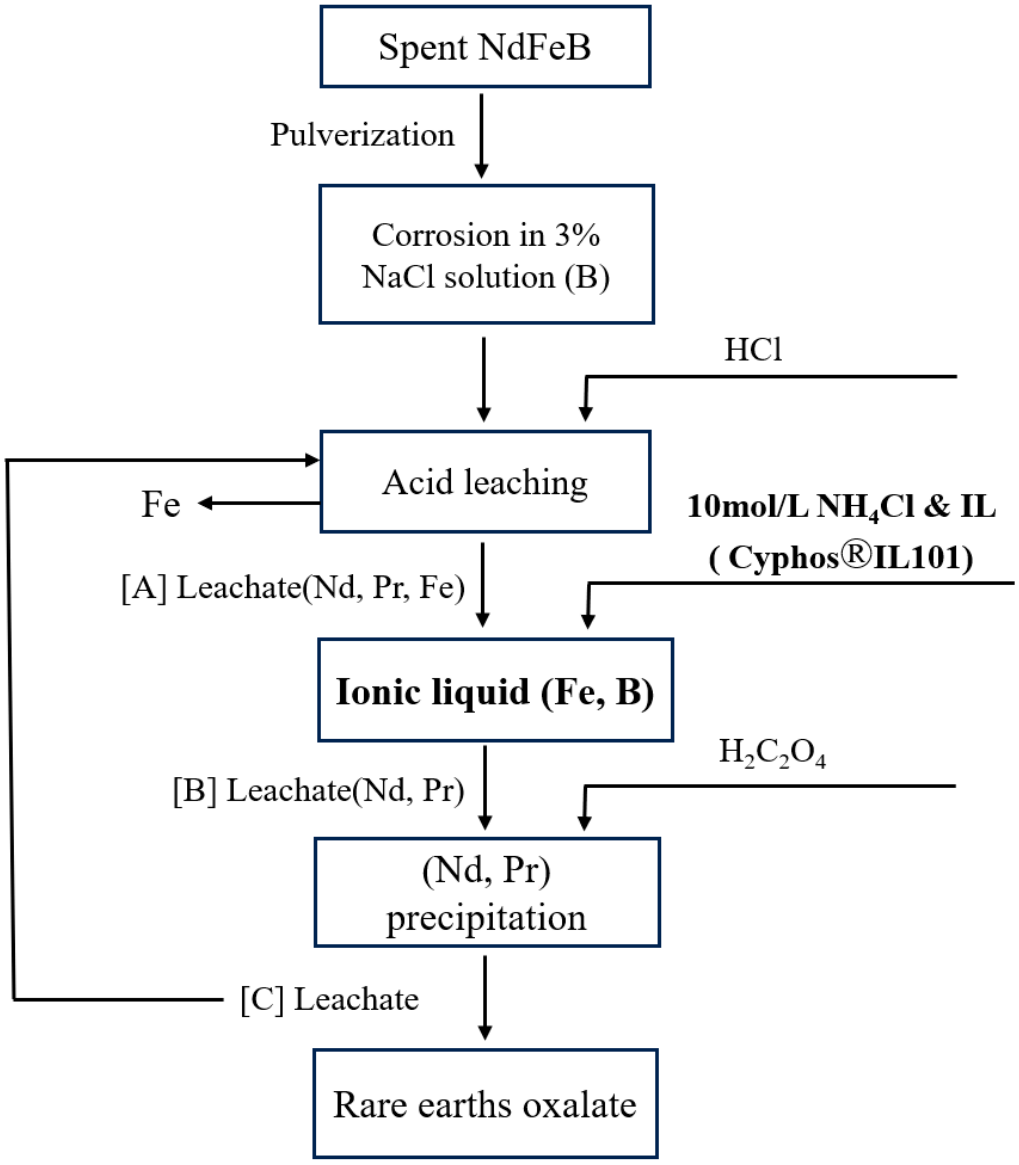


Figure 7. General process flow for the recovery of REEs from the spent NdFeB magnet by ionic liquid extraction.

Table 8. Recovery and separation of REEs and Fe by ILs/DESs.

Methods	Reagents	Experimental Conditions	Conclusion	References
ILs Ionic Liquid leaching	Trihexyl(tetradecyl)phosphonium chloride (Cyphos®IL101)	(1) Corrosion in 3% NaCl solution, 1 week (2) Acid leaching: 0.2 M or 0.5 M HCl, 1–2 h (3) IL (Fe, B): ILCyphos®IL101 (HCl/IL:4/1 V/V), 10 mol/L NH_4Cl (4) Oxalic acid: (Nd, Pr)	NaCl solution is used to separate approximately 30% of B, and acid leaching yields approximately 60% of Fe; Recovery: Nd 99%, Pr 97%	[46]
ILs Ionic Liquid leaching	trichloride ionic liquid	(1) Cl_2 IL-Cl Synthesis of IL-Cl_3 (2) NdFeB Leaching-Solid residue (3) NaCl solution Stripping REE-REE (4) NH_3 solution Stripping Fe and Co-Co and Fe $(OH)_3$ precipitate	(1) Dissolve NdFeB magnets: 50 mg powder in 1 mL the mixture of (V/V):1/1, 50 °C, 300 rpm, 1 day (2) Rare earth and transition metals were removed with 3 M NaCl and >2 M NH_3	[47]
ILs Ionic Liquid	[A336] [BTA], [A336] [OTA]	1 Synthesized [A336] [BTA] [A336] [OTA]; 2 Extraction of Nd; 3 Separation of REEs; 4 Stripping and recycling;	Extraction efficiency: >99.1%, [A336] [OTA] Extraction efficiency: Still 95.6% after seven cycles	[48]
ILs Electrochemical Leaching	TMPAC-EG IL	(1) electrolyte preparation: TMPAC-EG type ionic liquid; (2) Electrochemical measurements: (3) electrodeposition Potential (−2.30 to −2.90 V vs. Fc^+/Fc) at (313–353 K), 3 h, cathode: carbon paper; anode: graphite sheet	(1) Nd^{3+} diffusion coefficient: 10^{-12} m^2 s^{-1}. Nd^{3+} diffusion activation energy: 22.8 kJ mol^{-1} (2) Neodymium metal obtained with a caterpillar, nodular, layered rock, or porous structure	[49]
Oxidation roasting and DESs leaching	GUC-GA/LAC/MA/EG/GLY, AGU-GA/LAC, DAG-GA/LAC,	Metal dissolution: S/L ratio = 1:50, 50 °C water bath, 24 h, 12,000 rpm; NdFeB powders/(DES/GUC-LAC): 1/2, S/L ratio = 1/10, 40 °C, 6 h; Precipitation: solid oxalic acid: Nd-loaded DESs S/L ratio = 1:100; Calcination: 900 °C, 3 h, obtained Nd_2O_3 product	The separation factor > 1300, Nd_2O_3 product with 99% purity	[50]
Oxidation roasting and Deep Eutectic Solvent leaching	TEAC-L, TEAC-LAC, TEAC-GA, TEAC-MA	Metal oxide leaching: S/L ratio (The metal oxide: DES): 4/100, 60 °Coil bath, 24 h. 10,000 rpm three times; NdFeB leaching: S/L ratio (NdFeB: DES): 8/100, 90 °C oil bath, 9 h, centrifuged at 10,000 rpm three times Precipitation: m(Solid oxalic acid): m(Nd-dissolved DES) = 1:100, 50 °C, 9 h; Rare earth oxalate precipitation was obtained; Calcination: 900 °C, 3 h, obtained Nd_2O_3 product	The leaching rate of Nd was 97.63%, Fe < 0.435%, the separation coefficient was > 9000, and the purity of Nd_2O_3 in the obtained product was 99.649%.	[51]

Kitagawa J et al. [46] developed a method for extracting REEs from NdFeB magnets. Their process begins with a corrosion pretreatment in a 3% NaCl solution, followed by the extraction of iron from an HCl solution using the ionic liquid trihexyl(tetradecyl)phosphonium chloride ([$P_{666,14}$][Cl]) (Cyphos® IL101). Finally, REEs are precipitated from the solution using oxalic acid.

Li XH et al. [47] developed a solvent metallurgical process to recover REEs and Co from spent permanent magnets. This process utilizes trihexyltetradecylphosphonium trichloride ([$P_{666,14}$][Cl_3]) or a mixture of [$P_{666,14}$][Cl_3] and the corresponding chloride ionic liquid [$P_{666,14}$]Cl.

Xue WF et al. [48] synthesized two low-viscosity, carboxylic acid-based ionic liquids, [A336][BTA] and [A336][OTA], for the extraction of Nd^{3+} from spent permanent magnets. These ILs achieved an extraction efficiency exceeding 99%, which remained above 95% even after seven cycles of reuse.

Li JR et al. [49] investigated the electrodeposition of Nd in a novel analogous ionic liquid (AIL) based on phenyltrimethylammonium chloride and ethylene glycol (TMPAC-EG). Spectral analysis indicated that Nd^{3+} interacts with Cl^- and ethylene glycol to form a complex, [$Nd(EG)_6$-yCl_y]$^{3-y}$, allowing $NdCl_3$ to dissolve in the TMPAC-EG IL. This method successfully produced metallic Nd with various morphologies, including caterpillar-shaped, nodular, layered rock, and porous structures.

7.2. Deep Eutectic Solvents (DESs) Leaching

Commonly, the selective leaching mechanism of the spent NdFeB by DESs is due to the dissolution reaction of polyols, organic acids, and quaternary ammonium salts, polyols and acids, and urea in DESs. DESs may be due to the formation of more stable complexes between RE^{3+} and HBD, consequently enhancing the dissolution of Nd_2O_3.

Liu CY et al. [50] designed a method to recover NdFeB permanent magnets using deep eutectic solvents (DESs). The guanidine hydrochloride−lactic acid (GUC-LAC) complex DES achieved the highest separation factor (>1300) by simply dissolving the mixture of Nd_2O_3 and Fe_2O_3. The dissolved mass concentration of Nd could reach 67 g/L. The viscosity of this type of DES was 36 cP at 50 °C. After three cycles, the solubility and chemical stability of GUC-LAC DES remain unchanged.

Cheng SP et al. [51] designed a novel Deep Eutectic Solvent (DES) synthesized from tetraethylammonium chloride (TEAC) and levulinic acid (LA) and achieved selective leaching of REEs. The solubility of Nd_2O_3 in TEAC-LA exceeds 75.6 g/L. Its viscosity at the working temperature was 12.8 cP. After three cycles, TEAC-LA still maintains its leaching capacity and thermal stability.

Ionic liquid systems are environmentally friendly, highly purified, biodegradable, and recyclable. However, the preparation cost of ionic liquids is usually higher than that of ordinary leaching agents. In actual large-scale production and application, the preparation and synthesis cost, the impact of high viscosity on leaching efficiency, the performance after circulation, the methods of recovery and impurity removal, and the biodegradability and reduction in environmental impact should be comprehensively considered. It is becoming a green solvent, which is applied to the efficient recovery and comprehensive utilization of the permanent magnets.

Therefore, a comparison of recycling methods for the spent permanent magnets is summarized in Table 9. and the processing for recovering rare earth elements by hydrometallurgy technology are shown in Figure 8.

Table 9. Comparison of recycling methods for the spent NdFeB magnets.

Methods	Suitable for Types of Spent NdFeB	Mechanisms	Advantages	Limitations
Hydrochloric acid total solution method	all types of spent NdFeB magnets	Magnets directly react with concentrated hydrochloric acid, and H_2O_2 oxidizes Fe^{2+} to Fe^{3+}. REEs extracted and separated	High efficiency, low cost	REEs and Fe are completely dissolved, with high reagent consumption
Hydrochloric acid preferential dissolution method	high content of rare earths for NdFeB magnet	Spent NdFeB fully oxidized, Fe^{3+} hydrolyzed to $Fe(OH)_3$, REEs extracted, precipitated	Similar to the existing hydrometallurgical cascade extraction process for rare earth ores	Require roasting pretreatment
Acid baking and water leaching	NdFeB magnets containing multiple metals	Spent NdFeB is calcined with acidification reagents, and the calcined products are dissolved in water to leach out rare earth elements	Recycle other valuable metals	Complex process, high reagent consumption
Electrolysis in aqueous solution	highly conductive and block-shaped magnet scraps	Fe is electrolyzed at the anode or deposited at the cathode to separate from the rare earths	The high-energy consumption process is avoided	Precise control of anode and cathode reactions, low efficiency
Organic acids leaching	spent NdFeB with higher iron content and fewer impurities	Organic acids dissolve the metal through acidolysis and complexation	Good alternative to strong mineral acids, low pollution, and biodegradable	Long reaction time; leaching kinetics need to be improved
Bioleaching	powder or fine particle, with high iron content, especially those of low grade, complex composition, or pre-oxidation treatment	Microorganisms activate metal ions through biological oxidation and complexation to recover metals	Low pollution, low energy consumption	complex process, long time, low leaching kinetics
Ionic Liquid Systems	containing rare earth elements and cobalt, especially spent NdFeB after natural oxidation pretreatment	Fe or REEs Extracted by ionic liquid or leached by deep eutectic solvents	Biodegradability, low melting point, high chemical stability, designable properties	High viscosity, high synthesis cost

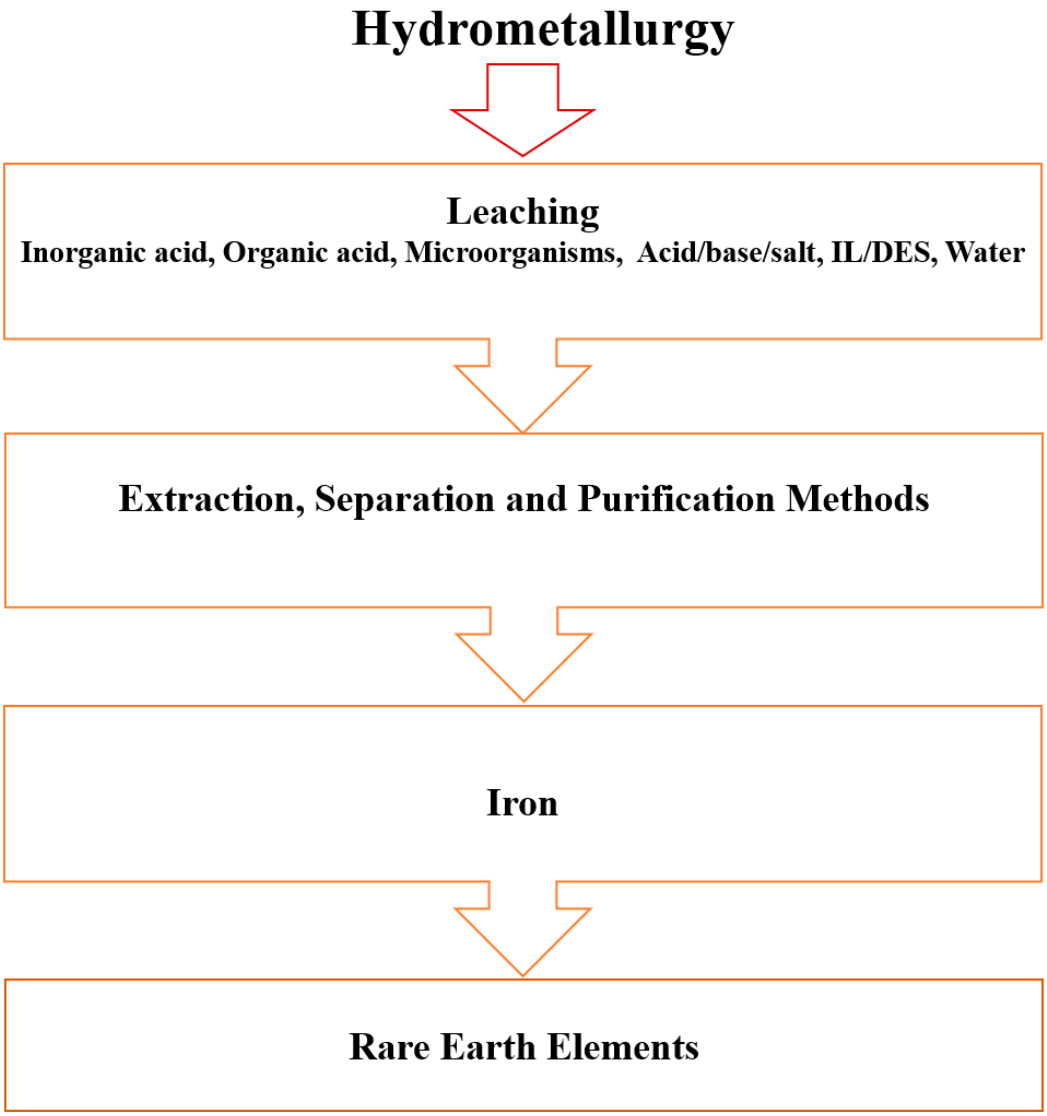


Figure 8. The processing of recovering rare earth elements and iron by hydrometallurgy technology.

8. Conclusions

Spent NdFeB magnets represent a significant secondary resource with high recycling value. For waste materials characterized by a high degree of oxidation, severe contamination, and complex composition, hydrometallurgical processing is the most suitable recycling route. The effectiveness of this approach depends on the careful selection of leaching agents and methods for extraction, separation, and purification.

Extensive research by scholars worldwide on the hydrometallurgical recovery of spent NdFeB magnets has yielded positive results. However, several challenges remain unresolved. To advance the development of short-process, sustainable, and green recycling technologies, future research should focus on the following areas:

(1) Adoption of Combined Processes: The selection of an optimal recycling process is influenced by factors such as raw material type, chemical composition, cost, and environmental impact. A single recycling method is often insufficient; therefore, combined processes that integrate the strengths of different techniques while mitigating their individual shortcomings present a more effective solution.

(2) Focus on Iron Recovery and Selective Leaching: The primary objectives of recycling are energy conservation, reduced consumption, and environmentally friendly technology.

Given that iron constitutes 60–70% of the magnet's weight, its recovery must be strengthened and integrated into the process. Consequently, selective leaching, which enables the separation of rare earth elements (REEs) from iron at the source, represents a crucial long-term research direction. As an alternative, the holistic recovery of iron via electrodeposition or roasting should also be comprehensively considered alongside REE recovery.

(3) Mechanistic Studies on Pretreatment: The difficulty in controlling oxidation and roasting conditions, coupled with the slow kinetics of subsequent REE leaching, significantly limits the deep separation of REEs from Fe. Research into the mechanisms of natural and low-temperature oxidation can optimize these pretreatment steps, enabling them to be completed under low-energy and short-duration conditions. This will enhance industrial efficiency and the comprehensive utilization of other valuable elements like Boron and Cobalt.

In summary, spent NdFeB permanent magnets are a vital urban mineral resource. The recovery of key valuable metals from this waste stream is essential for achieving sustainable resource development and constitutes a critical component of the rare earth strategic supply chain, thereby supporting green manufacturing and a circular economy.

Ultimately, a holistic approach that considers cost, energy consumption, and benefit is required. The shortcomings and advantages of various methods must be evaluated to integrate iron utilization from the pretreatment and reagent selection stages, while optimizing REE recovery during leaching. The final goal is to achieve the high-value and efficient recycling of all components within spent NdFeB magnets.

Author Contributions: M.C.: Writing—review and editing, Writing—original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. L.L.: Visualization, Supervision, Conceptualization. Y.X.: Writing—review and editing, Visualization, Supervision, Funding acquisition, Conceptualization. H.L.: Writing—review and editing, Methodology, Data curation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Natural Science Foundation of Jiangxi Province (20244BAB28056), the Administration for Market Regulation Program of Jiangxi Province (GSJK202409), the Bureau of Science and Technology Program of Ganzhou City (GZ2024ZSF883), and the Natural Science Foundation of Jiangxi Province (20224ACB203010).

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Kumari, A.; Sahu, S.K. A comprehensive review on recycling of critical raw materials from spent neodymium iron boron (NdFeB) magnet. *Sep. Purif. Technol.* **2023**, *317*, 123527. [CrossRef]
2. Brião, G.V.; Silva, M.G.; Vieira, M.G. Adsorption potential for the concentration and recovery of rare earth metals from NdFeB magnet scrap in the hydrometallurgical route: A review in a circular economy approach. *J. Clean. Prod.* **2022**, *380*, 135112. [CrossRef]
3. Yadav, J.; Sarker, S.K.; Bruckard, W.; Jegatheesan, V.; Haque, N.; Singh, N.; Pramanik, B.K. Greening the supply chain: Sustainable approaches for rare earth element recovery from neodymium iron boron magnet waste. *J. Environ. Chem. Eng.* **2024**, *12*, 113169. [CrossRef]
4. Ju, J.; Feng, Y.; Li, H.; Xu, C.; Xue, Z.; Wang, B. Extraction of valuable metals from minerals and industrial solid wastes via the ammonium sulfate roasting process: A systematic review. *J. Chem. Eng.* **2023**, *457*, 141197. [CrossRef]
5. Kaya, M. An overview of NdFeB magnets recycling technologies. *Curr. Opin. Green Sustain. Chem.* **2024**, *46*, 100884. [CrossRef]
6. Cong, L.; Yu, L.; Zhou, Q.; Lu, Q.; Yue, M. Short-process recycling of Nd-Fe-B sintered magnet sludge wastes: Challenges and approaches. *J. Rare Earths* **2023**, *41*, 1467–1477. [CrossRef]

7. Jyothi, R.K.; Thenepalli, T.; Ahn, J.W.; Parhi, P.K.; Chung, K.W.; Lee, J.Y. Review of rare earth elements recovery from secondary resources for clean energy technologies: Grand opportunities to create wealth from waste. *J. Clean. Prod.* **2020**, *267*, 122048. [CrossRef]
8. Xu, X.; Jia, X.; Zhao, K.; Xu, P.; Jing, P.; Liu, B.; Zhang, J. Recent progress in electrochemical recycling of waste NdFeB magnets. *Chem. Commun.* **2025**, *61*, 2257–2268. [CrossRef]
9. Tian, Y.; Liu, Z.; Zhang, G. Recovering REEs from NdFeB wastes with high purity and efficiency by leaching and selective precipitation process with modified agents. *J. Rare Earths* **2019**, *37*, 205–210. [CrossRef]
10. Rabatho, J.P.; Tongamp, W.; Takasaki, Y.; Haga, K.; Shibayama, A. Recovery of Nd and Dy from rare earth magnetic waste sludge by hydrometallurgical process. *J. Mater. Cycles Waste Manag.* **2013**, *15*, 171–178. [CrossRef]
11. Gruber, V.; Carsky, M. New technology for lanthanide recovery from spent Nd-Fe-B magnets. *S. Afr. J. Chem. Eng.* **2020**, *33*, 35–38. [CrossRef]
12. He, L.; Xu, Q.; Li, W.; Dong, Q.; Sun, W. One-step separation and recovery of rare earth and iron from NdFeB slurry via phosphoric acid leaching. *J. Rare Earths* **2022**, *40*, 338–344. [CrossRef]
13. Kumari, A.; Sinha, M.K.; Pramanik, S.; Sahu, S.K. Recovery of rare earths from spent NdFeB magnets of wind turbine: Leaching and kinetic aspects. *Waste Manag.* **2018**, *75*, 486–498. [CrossRef] [PubMed]
14. Niam, A.C.; Fen, W.; Wei, C.; Jie, Y. Recovery of rare earth elements from waste permanent magnet (WPMs) via selective leaching using the Taguchi method. *J. Taiwan Inst. Chem. Eng.* **2019**, *97*, 137–145. [CrossRef]
15. Liu, F.; Porvali, A.; Wang, J.; Wang, H.; Peng, C.; Wilson, B.P.; Lundström, M. Recovery and separation of rare earths and boron from spent Nd-Fe-B magnets. *Miner. Eng.* **2020**, *145*, 106097. [CrossRef]
16. Liu, Z.; Zhou, H.; Li, W.; Luo, X.; Wang, J.; Liu, F. Separation and coextraction of REEs and Fe from NdFeB sludge by co-leaching and stepwise precipitation. *Sep. Purif. Technol.* **2022**, *282*, 119795. [CrossRef]
17. Zhang, Z.; Wang, D.; Liu, C.; Zhi, W.; Xiao, W.; Qian, G.; Li, G. New insight into oxidative roasting and leaching for NdFeB waste. *J. Environ. Chem. Eng.* **2022**, *10*, 108946. [CrossRef]
18. Önal, M.A.R.; Borra, C.R.; Guo, M.; Blanpain, B.; Gerven, T.V. Recycling of NdFeB magnets using sulfation, selective roasting, and water leaching. *J. Sustain. Metall.* **2015**, *1*, 199–215. [CrossRef]
19. Loy, S.V.; Önal, M.A.R.; Binnemans, K.; Gerven, T.V. Recovery of valuable metals from NdFeB magnets by mechanochemically assisted ferric sulfate leaching. *Hydrometallurgy* **2020**, *191*, 105154.
20. Liu, F.; Chen, F.; Wang, L.; Ma, S.; Wan, X.; Wang, J. Selective separation of rare earths from spent Nd-Fe-B magnets using two-stage ammonium sulfate roasting followed by water leaching. *Hydrometallurgy* **2021**, *203*, 105626. [CrossRef]
21. Kumari, A.; Raj, R.; Randhawa, N.S.; Sahu, S.K. Energy efficient process for recovery of rare earths from spent NdFeB magnet by chlorination roasting and water leaching. *Hydrometallurgy* **2021**, *201*, 105581. [CrossRef]
22. Gahlot, R.; Dhawan, N. Chloridizing roasting studies of spent NdFeB magnets for recovery of rare earth values. *Process Saf. Environ. Prot.* **2024**, *191*, 1534–1547. [CrossRef]
23. Wu, J.; Wang, D.; Ye, C.; Wang, Z.; Hu, X. Selective extraction and separation of REEs from NdFeB magnets scrap using co-chlorination and water leaching. *Sep. Purif. Technol.* **2023**, *306*, 122452. [CrossRef]
24. Wu, J.; Wang, D.; Zhang, Z.; Ye, C.; Wang, Z.; Hu, X. Mechanical activation induced treatment for the synergistic recovery of valuable elements from spent NdFeB magnets. *Waste Manag.* **2024**, *178*, 76–84. [CrossRef]
25. Önal, M.A.R.; Aktan, E.; Borra, C.R.; Blanpain, B.; Gerven, T.V.; Guo, M. Recycling of NdFeB magnets using nitration, calcination and water leaching for REE recovery. *Hydrometallurgy* **2017**, *167*, 115–123. [CrossRef]
26. Venkatesan, P.; Sun, Z.; Sietsma, J.; Yang, Y. An environmentally friendly electro-oxidative approach to recover valuable elements from NdFeB magnet waste. *Sep. Purif. Technol.* **2018**, *191*, 384–391. [CrossRef]
27. Zhang, Z.; Wang, Z.; Wang, D.; Min, R.; Xiao, W.; Yong, L.; Li, G. An acid-free process for selective REE recovery from spent NdFeB magnets by room-temperature electrolysis. *Green Chem.* **2023**, *25*, 10653–10663.
28. Xu, X.; Sturm, S.; Samardzija, Z.; Vidmar, J.; Scancar, J.; Zuzek, R.K. Direct Recycling of Nd-Fe-B Magnets Based on the Recovery of $Nd_2Fe_{14}B$ Grains by Acid-free Electrochemical Etching. *ChemSusChem* **2019**, *12*, 4754–4758. [CrossRef] [PubMed]
29. Xu, X.; Sturm, S.; Samardzija, Z.; Scancar, J.; Markovic, K.; Zuzek, R.K. A facile method for the simultaneous recovery of rare-earth elements and transition metals from Nd-Fe-B magnets. *Green Chem.* **2020**, *22*, 1105–1112. [CrossRef]
30. Yang, Y.; Lan, C.; Wang, Y.; Zhao, Z.; Li, B. Recycling of ultrafine NdFeB waste by the selective precipitation of rare earth and the electrodeposition of iron in hydrofluoric acid. *Sep. Purif. Technol.* **2020**, *230*, 15870. [CrossRef]
31. Xiao, F.; Hu, W.; Zhang, Z.; Bo, L.; Zhu, H. Recovery of neodymium and iron from NdFeB waste by combined electrochemical-hydrometallurgical process. *Sep. Purif. Technol.* **2025**, *353*, 128301. [CrossRef]
32. Venkatesan, P.; Vander, T.; Binnemans, K.; Sun, Z.; Sietsma, J.; Yang, Y. Selective Extraction of Rare-Earth Elements from NdFeB Magnets by a Room-Temperature Electrolysis Pretreatment Step. *ACS Sustain. Chem. Eng.* **2018**, *6*, 9375–9382. [CrossRef]
33. Makarova, I.; Soboleva, E.; Osipenko, M.; Kurilo, I.; Laatikainen, M.; Repo, E. Electrochemical leaching of rare-earth elements from spent NdFeB magnets. *Hydrometallurgy* **2020**, *192*, 105264. [CrossRef]

34. Makarova, I.; Ryl, J.; Sun, Z.; Kurilo, I.; Górnicka, K.; Laatikainen, M.; Repo, E. One-step recovery of REE oxalates in electro-leaching of spent NdFeB magnets. *Sep. Purif. Technol.* **2020**, *251*, 117362. [CrossRef]
35. Behera, S.S.; Parhi, P.K. Leaching kinetics study of neodymium from the scrap magnet using acetic acid. *Sep. Purif. Technol.* **2016**, *160*, 59–66. [CrossRef]
36. Menad, N.E.; Seron, A.; Maât, N.; Breton, J.M.L.; Virginie, N. Process Recovery of Nd-Fe-B Permanent Magnets from Hard Disc Drives. *J. Geogr. Nat. Disasters* **2017**, *S6*, 008. [CrossRef]
37. Belfqueh, S.; Seron, A.; Chapron, S.; Arrachart, G.; Menad, N. Evaluating organic acids as alternative leaching reagents for rare earth elements recovery from NdFeB magnets. *J. Rare Earths* **2023**, *41*, 621–631. [CrossRef]
38. Liu, Q.; Tu, T.; Guo, H.; Cheng, H.; Wang, X. High-efficiency simultaneous extraction of rare earth elements and iron from NdFeB waste by oxalic acid leaching. *J. Rare Earths* **2021**, *39*, 323–330. [CrossRef]
39. Gergoric, M.; Barrier, A.; Retegan, T. Recovery of rare-earth elements from neodymium magnet waste using glycolic, maleic, and ascorbic acids followed by solvent extraction. *J. Sustain. Metall.* **2019**, *5*, 85–96. [CrossRef]
40. Reisdorfer, G.; Bertuol, D.A.; Tanabe, E.H. Recovery of neodymium from the magnets of hard disk drives using organic acids. *Miner. Eng.* **2019**, *143*, 105938. [CrossRef]
41. Kumari, A.; Dipali; Randhawa, N.S.; Sahu, S.K. Electrochemical treatment of spent NdFeB magnet in organic acid for recovery of rare earths and other metal values. *J. Clean. Prod.* **2021**, *309*, 127393. [CrossRef]
42. Golmohammadzadeh, R.; Faraji, F.; Rashchi, F. Recovery of lithium and cobalt from spent lithium ion batteries (LIBs) using organic acids as leaching reagents: A review. *Resour. Conserv. Recycl.* **2018**, *136*, 418–435. [CrossRef]
43. Auerbach, R.; Bokelmann, K.; Stauber, R.; Gutfleisch, O.; Schnell, S.; Ratering, S. Critical raw materials-Advanced recycling technologies and processes: Recycling of rare earth metals out of end-of-life magnets by bioleaching with various bacteria as an example of an intelligent recycling strategy. *Miner. Eng.* **2019**, *134*, 104–117. [CrossRef]
44. Joshi, K.; Magdouli, S.; Kaur, B.S. Bioleaching for the recovery of rare earth elements from industrial waste: A sustainable approach. *Resour. Conserv. Recycl.* **2025**, *215*, 108129. [CrossRef]
45. Roy, J.J.; Cao, B.; Madhavi, S. A review on the recycling of spent lithium-ion batteries (LIBs) by the bioleaching approach. *Chemosphere* **2021**, *282*, 130944. [CrossRef]
46. Kitagawa, J.; Uemura, R. Rare Earth Extraction from NdFeB Magnet Using a Closed-Loop Acid Process. *Sci. Rep.* **2017**, *7*, 8039. [CrossRef] [PubMed]
47. 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]
48. Xue, W.; Liu, R.; Liu, X.; Wang, Y.; Lv, P.; Yang, Y. Selective extraction of Nd (III) by novel carboxylic acid based ionic liquids without diluent from waste NdFeB magnets. *J. Mol. Liq.* **2022**, *364*, 119919. [CrossRef]
49. Li, J.; Xu, C.; Xiang, G.; Chen, W.; Gu, D.; Zhang, Q.; Hua, Y.; Li, Y. TMPAC-EG deep eutectic solvent for sustainable recovery of Nd by electrodeposition. *Electrochim. Acta* **2024**, *501*, 144817. [CrossRef]
50. Liu, C.; Yan, Q.; Zhang, X.; Lei, L.; Xiao, C. Efficient Recovery of End-of-Life NdFeB Permanent Magnets by Selective Leaching with Deep Eutectic Solvents. *Environ. Sci. Technol.* **2020**, *54*, 10370–10379. [CrossRef]
51. Cheng, S.; Zhang, Z.; Wang, D.; Zheng, W.; Qi, T.; Wang, Z.; Xiao, W.; Lin, Y.; Li, G. Selective leaching and recovery of rare earth from NdFeB waste through a superior selective and stable deep eutectic solvent. *Sep. Purif. Technol.* **2025**, *353*, 128498.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.