


# Hydrogen decrepitation of post-consumer NdFeB magnets: a sustainable pre-processing route for rare earth recycling


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## Abstract

The growing generation of waste electrical and electronic equipment (WEEE) has driven the search for sustainable strategies to recover critical and strategic minerals, such as NdFeB magnets, widely used in hard disk drives (HDDs). These magnets contain elements with increasing demand and limited supply, making the development of efficient recycling processes essential. In this context, hydrogen decrepitation stands out by enabling selective fragmentation of the magnets and recovery of their constituents. This study addressed the disassembly of post-consumer HDDs to extract NdFeB magnets and their processing through the decrepitation hydrogen method. The samples were characterized using XRF, ICP-OES, and XRD techniques, revealing variations in major elements such as Fe and Nd, along with traces of Si, Al, Zr, and Co, influenced by the type of magnet. SEM analysis confirmed the presence of intergranular cracks typical of the hydrogen decrepitation mechanism. It was observed that the untreated sample had a milling efficiency of 25.33%, while the hydrogen-treated sample reached 73.33%, indicating a significant improvement in particle embrittlement. The results demonstrate that hydrogen decrepitation is a beneficiation alternative aimed at the direct recycling of NdFeB magnets, promoting circularity and reducing the need for extraction of virgin raw materials.

**Keywords:** Waste electrical and electronic equipment; Urban mining; NdFeB magnets; Hydrogen decrepitation.

## 1 Introduction

The growing demand for electrical and electronic equipment (EEE), driven by rapid technological advances and the programmed obsolescence of devices, has led to a significant increase in solid waste generation and in the consumption of raw materials required to sustain this demand. In response to these challenges, increasing attention has been directed toward the development of recycling methodologies for waste electrical and electronic equipment (WEEE), aiming to reduce the extraction of non-renewable natural resources and to mitigate the improper disposal of electronic waste [1,2]. Within this context, the demands for technologies associated with the energy transition and digitalization have intensified the importance of so-called critical and strategic minerals, among which rare earth elements used in the manufacture of NdFeB permanent magnets stand out. In the Brazilian context, this discussion has gained relevance with the proposal of Bill No.

2780/2024, which establishes the National Policy on Critical and Strategic Minerals, aiming to strengthen supply security, stimulate technological development, and promote value addition along mineral production chains [3]. This policy recognizes not only the role of primary mining but also the need to incorporate alternative routes, such as recycling and the recovery of residues containing critical minerals, in line with principles of the circular economy, reduced external dependence, and environmental sustainability. In this framework, international standards such as the ISO 59000 series, particularly ISO 59014, provide guidance for the characterization, classification, and traceability of secondary materials, supporting transparency and technical consistency in the use of recycled flows [4,5]. Consequently, the recovery of NdFeB magnets from electronic waste, such as hard disk drives (HDDs), emerges as a promising strategy to complement the supply of these strategic materials and

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contribute to the consolidation of a more resilient production chain in Brazil [6].

WEEE encompasses a wide range of devices discarded by their users with no intention of reuse. These wastes correspond to post-consumer items of domestic or commercial origin that contain circuits or electrical components powered by energy or batteries [1].

The most recent data on WEEE generation was presented in *The Global E-Waste Monitor 2024* report. According to the report, global WEEE generation reached 62 billion kg in 2022, corresponding to an average of 7.8 kg per capita. However, only 13.8 billion kg (approximately 22%) of the generated WEEE were properly collected and recycled [1].

WEEE stands out for its complexity and diversity, being composed of a wide variety of materials and components, including miniaturized parts and different types of products [4]. The composition of this waste varies according to the equipment and its application requirements and may contain up to 69 distinct elements, including common metals, precious metals, and the so-called Rare Earth Elements (REEs), many of which are technically recoverable [1,6], such as neodymium (Nd), praseodymium (Pr), and gallium (Ga). REEs are among the raw materials with the highest risk of supply shortage, not only due to geological availability but also due to geopolitical instability in the producing countries, the low recycling potential, and the difficulty in substituting these elements [7,8].

WEEE deposits are often referred to as urban mines, as they contain valuable materials such as precious metals and REEs [1]. These wastes represent a significant source of resources that can be recovered for the manufacture of new products, contributing to the reduction of primary raw material extraction and acting as a secondary source of various materials [7,9]. The recycling of metals derived from WEEE offers a sustainable alternative, allowing the recovery of valuable materials without the need to extract large quantities of ore.

In 2020, the European Union (EU) published a list identifying 30 critical minerals that are essential for short-term supply, specifically those required for the development of clean technologies, such as Nd [10], due to its wide application in advanced technologies, particularly in high-performance magnets used in electric motors, wind turbines, and electronic devices. Its growing demand, combined with the geographical concentration of production (dominated by China) and supply limitations, reinforces the need for efficient recycling and recovery strategies.

NdFeB magnets contain high concentrations of rare earth elements (REEs), which account for more than 90% of the material's cost according to estimates based on standard composition and current market prices, making them highly vulnerable to supply disruptions [9]. Furthermore, Kaya [11] reported that there are currently no alternative materials capable of replacing NdFeB magnets in modern technologies while maintaining equivalent performance and cost.

In this context, recycling strategies for NdFeB magnets have gained increasing attention due to both

economic and environmental concerns. Recent studies have demonstrated that direct recycling routes present significant environmental advantages when compared to primary rare earth production. Life Cycle Assessment (LCA) studies report substantial reductions in greenhouse gas emissions, energy consumption, water consumption, and toxicity impacts associated with the recovery of rare earth elements from end-of-life magnets [11]. These environmental benefits are mainly related to the reduction of processing stages and the avoidance of high-energy and chemically intensive operations commonly employed in conventional extraction routes.

The recycling of NdFeB magnets is particularly relevant considering that approximately 22% of global REE production is used in magnet manufacturing [12]. Among the recycling methodologies currently investigated, hydrogen decrepitation has emerged as a promising route for the recovery and beneficiation of NdFeB magnets. The process promotes hydrogen absorption by the material, inducing embrittlement and facilitating fragmentation, which enables more efficient comminution and subsequent reuse of the recovered material in direct recycling approaches such as "magnet-to-magnet" recycling. Therefore, the development of efficient recycling routes for NdFeB magnets from WEEE is essential for promoting sustainability, reducing dependence on primary rare earth extraction, and strengthening circular economy strategies.

Among the current recycling routes, the hydrogen decrepitation (HD) process stands out as an effective method for the beneficiation of NdFeB magnets for subsequent direct recycling [13]. This process consists of exposing magnets to a hydrogen gas ( $H_2$ ) atmosphere, which causes volumetric expansion and leads to material fragmentation. The resulting powder can be directly reintroduced into new magnet production, reducing milling costs by up to 70% and improving energy efficiency [13,14].

The hydrogen-based route is considered a sustainable alternative compared to the traditional magnet production process. Furthermore, it enables the preservation of up to 90% of the original magnetic properties of the material [13,15]. Therefore, hydrogen decrepitation presents itself as a promising alternative, offering an efficient, economical, and low environmental impact route for the recovery of REEs and the production of new magnets from NdFeB waste.

Given the increasing demand for REEs in the production of various devices, especially NdFeB magnets, it is crucial to develop new technologies to obtain these materials through WEEE recycling, optimizing recovery processes to maximize economic benefits without compromising environmental sustainability [16]. This is particularly relevant for NdFeB magnets, whose rising demand in clean technologies contrasts with high disposal rates.

Research suggests that hydrogen can be an efficient beneficiation agent for the recycling of NdFeB magnets found in WEEE, as it promotes material embrittlement and facilitates subsequent processing with fewer steps [14]. These recycled magnets can be produced through powder

metallurgy routes, starting from the hydrogen decrepitation process [9].

The magnet-to-magnet (direct recycling) approach, also referred to as a short-loop recycling route, which employs hydrogen processing, stands out as an environmentally suitable alternative. This method has lower environmental impacts and greater energy efficiency compared to hydrometallurgical and pyrometallurgical processes traditionally used for post-consumer NdFeB magnet recycling [14].

Beneficiation of NdFeB magnets via hydrogen decrepitation represents a strategic alternative to conventional pyrometallurgical and hydrometallurgical REE recovery routes. Unlike these processes, which require high temperatures or extensive use of acids and solvents, hydrogen decrepitation occurs at moderate temperatures, offering greater selectivity, lower hazardous waste generation, and better preservation of valuable constituents [14,17,18].

Recycling NdFeB magnets via the HD process is justified by several factors: conservation of critical raw materials, reduced import dependence, and lower energy consumption, leading to a reduction in CO<sub>2</sub> emissions [13]. Hydrogen also plays a crucial role in the production of sintered NdFeB magnets, as it is adsorbed onto the magnet fragments, increasing their reactivity and facilitating sintering. This hydrogen can later be released during vacuum sintering and potentially recovered for reuse, depending on the decrepitation setup [13,19].

Considering that WEEE is among the fastest-growing waste streams globally and that permanent magnets are present in numerous devices, the reuse of discarded magnets fits into a circular economy model, transforming waste into industrial feedstock. Thus, hydrogen decrepitation not only contributes to reducing primary resource extraction but also extends the life cycle of critical materials already in the production chain.

A review of the literature on REE recovery studies indicates that magnet recycling from WEEE has received the most attention, due to the projected high growth in NdFeB magnet demand and the presence of highly critical REEs in their composition. Among the methodologies developed so far, the hydrogen decrepitation route has proven effective for REE recovery, allowing their reuse in the production of recycled sintered magnets. Therefore, this paper focuses on

the beneficiation of magnets recovered from post-consumer HDDs, applying manual disassembly methodologies for the WEEE received and subsequent treatment of NdFeB magnets using HD process. The objective is to promote sustainability and circular economy principles through the efficient recovery of critical and strategic materials.

## 2 Materials and methods

The sampling procedure was carried out according to the stages presented in Figure 1, including separation of the NdFeB magnets, demagnetization, removal of the protective coating, manual fracture of the magnets, hydrogen decrepitation, and grinding.

### 2.1 Sampling of NdFeB magnets

The sampling stage was divided into manual separation of the magnets, demagnetization, removal of the protective coating, and fracture. The HDDs were disassembled following the methodology developed and validated by Wei [20].

Subsequently, the magnets were demagnetized using a muffle furnace heating method, applying a temperature of 350 °C for 45 minutes. Under this condition, the magnets lose their magnetic properties. After demagnetization, the protective coating of the WEEE magnet samples was manually removed, and the magnets were then fragmented by twisting, allowing them to break into smaller pieces. Removing the protective coating and fragmenting the magnets into smaller sizes serves to create an exposed surface, improving the efficiency of the hydrogen decrepitation process [13,15].

### 2.2 Characterization tests of NdFeB magnets

Due to the diversity of the obtained NdFeB magnets, it was necessary to evaluate their composition, which is an important step to establish a targeted recycling strategy. The initial characterization included microstructural and compositional analyses, both qualitative and semi-quantitative, at different stages of the process.

For the characterization assays, it was necessary to reduce the particle size of the magnet samples in order to ensure

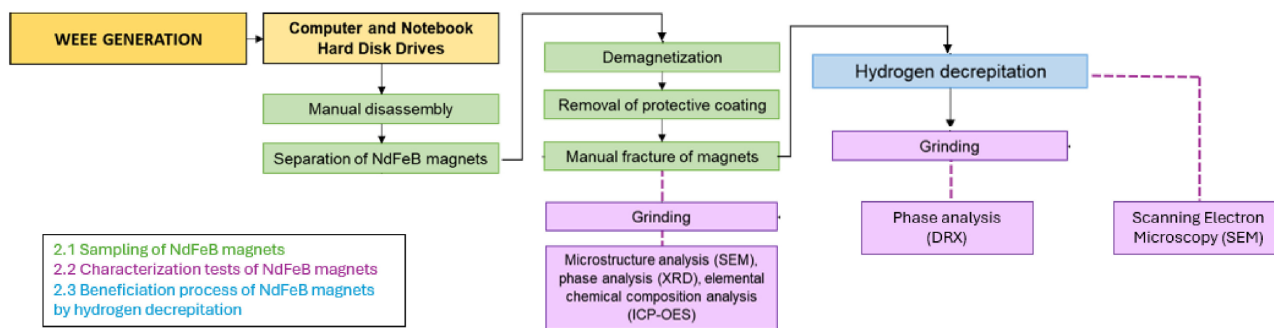


Figure 1. Steps for HDD magnet processing.

analytical suitability for both X-ray diffraction (XRD), and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analyses. Accordingly, the samples were mechanically comminuted prior to characterization and chemical digestion using an eccentric-type ball mill. Milling was performed in a Retsch ball mill operating in eccentric mode (PM model), employing alumina grinding media. A ball-to-sample mass ratio of 10:1 was applied, using alumina spheres as grinding bodies. The grinding media consisted of alumina spheres with diameters of 1 cm (2.5 g) and 2 cm (18.5 g). The milling process was conducted for 45 minutes, in accordance with the procedure described by Wei [20]. After milling, the material was sieved, and the fraction passing through a 325-mesh Tyler sieve (corresponding to 45  $\mu\text{m}$ ) was collected for subsequent XRD characterization and ICP-OES analysis.

Quantitative characterization of the magnet composition was performed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), using a Thermo Fisher Scientific iCAP 7200 Duo instrument. The method consisted of digesting 250 mg of sample using 5 mL of aqua regia, prepared from a mixture of nitric and hydrochloric acids in a volumetric ratio of 1:3 ( $\text{HNO}_3:\text{HCl}$ , v/v). The digestion was carried out in a closed-vessel microwave digestion system for 30 minutes at 230  $^\circ\text{C}$ , using a Milestone ETHOS UP microwave oven.

X-ray Diffraction (XRD) analysis was conducted to investigate the crystal structure and phase composition of the NdFeB powder fractions before and after hydrogen decrepitation. Measurements were performed using an Empyrean diffractometer (Panalytical) in reflection–transmission configuration with a sample spinner, over a  $2\theta$  range of 10–90 $^\circ$ , a step size of 0.01 $^\circ$ , and a counting time of 1030 s per step, using  $\text{CuK}\alpha$  radiation (40 kV, 40 mA). Bragg–Brentano geometry was employed, and the diffracted beam was detected with a PIXcel 3D Medipix3 area detector. Phase identification was carried out using QualX software, referencing the PDF database from the International Centre for Diffraction Data (ICDD).

To monitor how the processes may influence modifications on the magnet surfaces exposed to hydrogen, the structure and morphology of the materials were analyzed using Scanning Electron Microscopy (SEM).

SEM analyses were performed using a JEOL scanning electron microscope, model JSM-6010LA. The SEM analysis employed two different detectors: Secondary Electron (SE) and Backscattered Electron (BSD).

Images obtained with the BSD detector provided information on both surface topography and elemental composition. The micrographs were used to show the evolution of the microstructure during the initial and intermediate stages of processing comparatively.

### 2.3 Beneficiation process of NdFeB magnets by hydrogen decrepitation

The process was carried out in a muffle furnace equipped with an attached stainless-steel tube, specifically designed and adapted to allow hydrogen injection, vacuum

control, and operation under positive pressure. Due to the pilot-scale nature of the experiment and because the equipment was still under development, a single hydrogen decrepitation experiment was conducted for validation purposes. In this validation test, approximately 30 g of magnet samples were processed in a single run. The experiment was intended to assess the operational feasibility and suitability of the adapted system, serving as a preliminary step prior to further optimization and validation at larger production scales.

The reactor was evacuated to  $10^{-1}$  mbar for 30 minutes to remove adsorbed gases from the sample. It was then pressurized with high-purity hydrogen (1–2 bar) at room temperature. Pressure control was performed using an analog manometer, with adjustments until the samples were saturated, after approximately 2 hours. The system was then evacuated again, heated to 500  $^\circ\text{C}$  for 2 hours to desorb the hydrogen, and allowed to cool naturally for approximately 3 hours and 30 minutes. The diagram of this process is shown in Figure 2. The magnets tend to absorb hydrogen at room temperature, with a slight subsequent temperature increase due to the exothermic nature of the reaction. However, in the present study, this temperature increase was not detected due to the reactor's design characteristics [13,15].

## 3 Results and discussion

Through the disassembly of HDDs, it was possible to identify that NdFeB magnets exist in various shapes and geometries, varying according to brand and model. Figure 3 illustrates an HDD with its segregated components, highlighting the NdFeB magnets selected for use in the development of this study.

For the development of this study, no separation by magnet model was performed; all magnets were mixed, reflecting the reality in which these materials are often discarded [1].

Approximately 250 g of NdFeB magnets, including their protective coating, were used in total. Removing the magnet's coating layer is recommended to ensure direct contact with  $\text{H}_2$ , thereby guaranteeing the efficiency of the decrepitation process [13]. Figure 4 shows WEEE magnets that have been demagnetized and stripped of their protective coating.

### 3.1 Characterization tests

The initial quantitative composition of the uncoated samples was determined using ICP-OES analysis. For comparison, Table 1 compiles data from other studies on NdFeB magnets recovered from post-consumer HDDs.

The results of this study are consistent with the literature, highlighting Fe as the predominant element, with variations between 60% and 78%, as reported by Stalter [2], München and Veit [22]. Nd was also consistently detected,

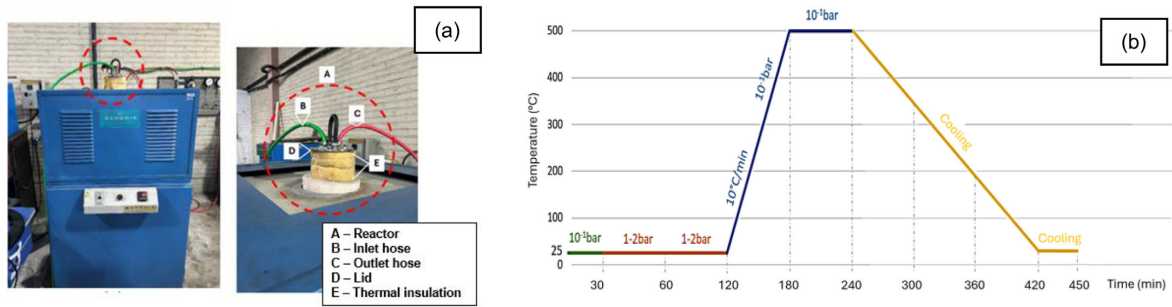


Figure 2. (a) Reactor for hydrogen decrepitation process (b) Steps to carry out the hydrogen decrepitation process.

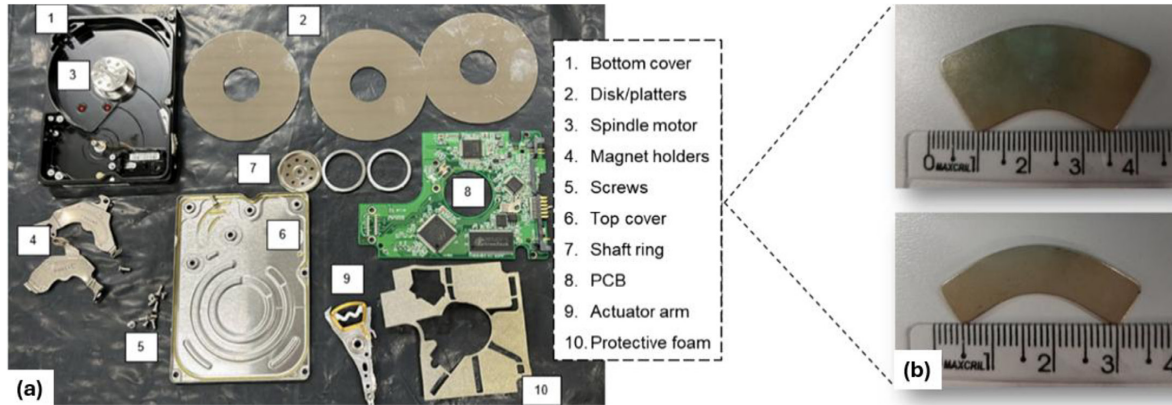


Figure 3. Hard disk drive (HDD) and NdFeB magnets used in this study: (a) HDD after component segregation; (b) NdFeB magnets.

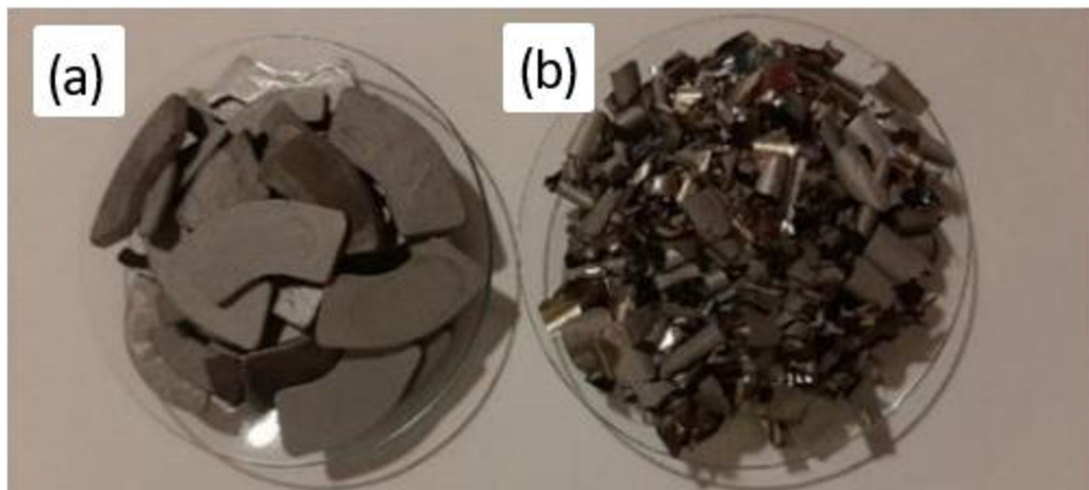


Figure 4. WEEE magnets without protective coating (a) and the coating after removal (b).

Table 1. Composition of NdFeB magnets from WEEE reported by different authors, in mass percent (w%), based on ICP-OES analysis

Authors	Elements found								
	Fe	Nd	Pr	B	Co	Ni	Al	Dy	Others
This research	65.29	23.81	3.16	0.86	0.96	0.17	-	-	5.75
Stalter (2022) [2]	60.01	22.12	3.71	0.87	0.95	2.44	0.48	1.04	8.40
Li et al. (2019) [21]	67.13	23.02	6.63	0.98	0.87	-	0.24	-	1.13
München and Veit (2017) [22]	64.56	25.30	3.83	0.97	2.42	-	-	2.66	0.26
Zakotnik and Tudor (2015) [23]	78.64	10.50	3.04	5.92	-	-	0.52	0.12	1.26

with levels similar to those found by Zakotnik, Tudor [23], and Li et al. [21]. Elements such as Pr and B were within the ranges reported by Li et al. [21] and Stalter [2], with Pr used as a partial substitute for Nd [9]. Variations in elements such as Co, Ni, Al, Si, and Zr were attributed both to the original magnet formulation and to potential contamination during milling, as suggested by München [24]. The presence of Ni reinforces its use as an anti-corrosion agent, as noted by Zakotnik and Tudor [23].

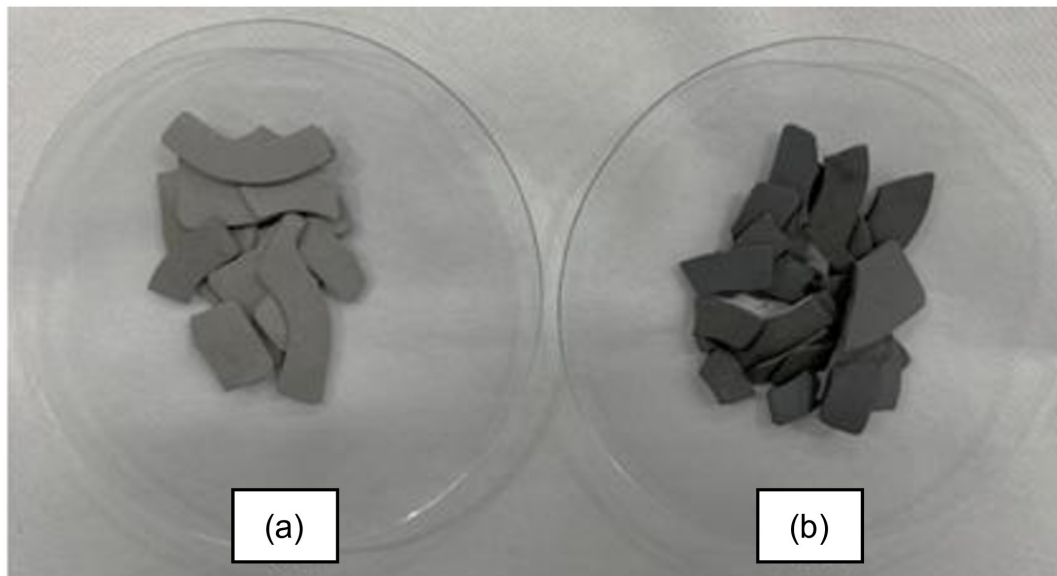
The variations in magnet composition reflect adaptations to specific application requirements, costs, and manufacturing strategies. Magnet composition may vary according to year, manufacturer, and equipment origin, such as HDDs of different brands and models, in addition to the analytical techniques used (XRF and ICP-OES) [24]. Nevertheless, a trend toward similar composition among NdFeB magnets

extracted from HDDs is observed, corroborating this study's results with literature data.

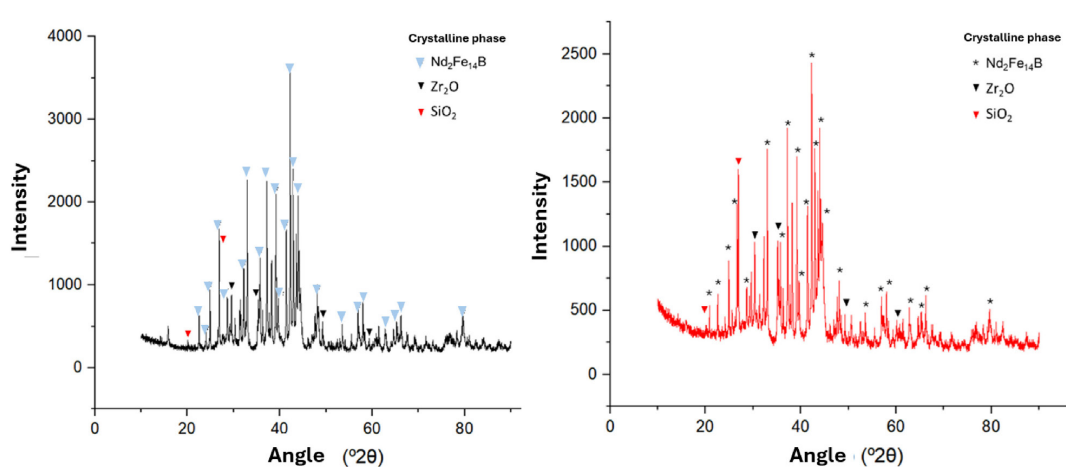
Figure 5 presents the samples before and after the hydrogen decrepitation process. It is possible to observe changes in the coloration of the samples after treatment, indicating that the material was influenced by the hydrogen decrepitation process.

Qualitative XRD analysis was performed to investigate possible structural changes in the samples after the hydrogen decrepitation process. Figure 6 shows the superposition of diffractograms of the samples.

XRD analysis revealed the main phase  $\text{Nd}_2\text{Fe}_{14}\text{B}$ , as well as secondary phases such as  $\text{ZrO}_2$  and  $\text{SiO}_2$ , associated both with the magnet coating and potential contamination from wear of the jars and ceramic milling balls [25]. München and Veit [22], Ma et al. and Kaya et al. [11] also identified



**Figure 5.** NdFeB magnet samples before (a) and after (b) the hydrogen decrepitation process, highlighting the visual changes in coloration observed after treatment.



**Figure 6.** Diffractograms of “WEEE magnet” samples (black) and “magnet after  $\text{H}_2$  decrepitation” (red).

the tetragonal  $\text{Nd}_2\text{Fe}_{14}\text{B}$  phase as predominant in magnets removed from HDDs, reporting secondary diffraction peaks related to impurities.

The diffractograms confirm the preservation of the magnet crystalline structure even after the decrepitation process, indicating that hydrogen removal was effective, as evidenced by the absence of characteristic neodymium hydride peaks [19], and confirming that the target  $\text{Nd}_2\text{Fe}_{14}\text{B}$  phase is still present. The identified phases included neodymium iron boron ( $\text{Nd}_2\text{Fe}_{14}\text{B}$ ; ICDD 01-088-2285), silicon oxide (ICDD 01-078-1252), and zirconium oxide (ICDD 03-065-0461).

Hydrogen decrepitation occurs through the absorption of hydrogen gas in the main  $\text{Nd}_2\text{Fe}_{14}\text{B}$  phase, causing expansion of the crystal lattice. This phenomenon generates internal stresses that fragment the material. Additionally, hydrogen induces temporary decomposition of the main phase into secondary phases, causing expansion that weakens cohesion between grains, resulting in spontaneous fragmentation of the magnet [13]. Figure 7 shows SEM images with SE detector of the samples before (a) and after  $\text{H}_2$  decrepitation (b = 2,500x; c = 5,000x).

Cracks and fractures are observed due to volumetric expansion caused by hydrogen absorption, initially in the Nd-rich phase and later in the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  matrix. The formation of Nd-hydride at grain boundaries produces differential expansion between phases, resulting in intergranular fractures and decrepitation of the material into smaller particles, with visible cracks and microfissures [15]. Milling tests of the samples before and after hydrogen decrepitation demonstrated a reduction in the time required to reach the target particle size for subsequent magnet recycling, increasing process efficiency (Table 2).

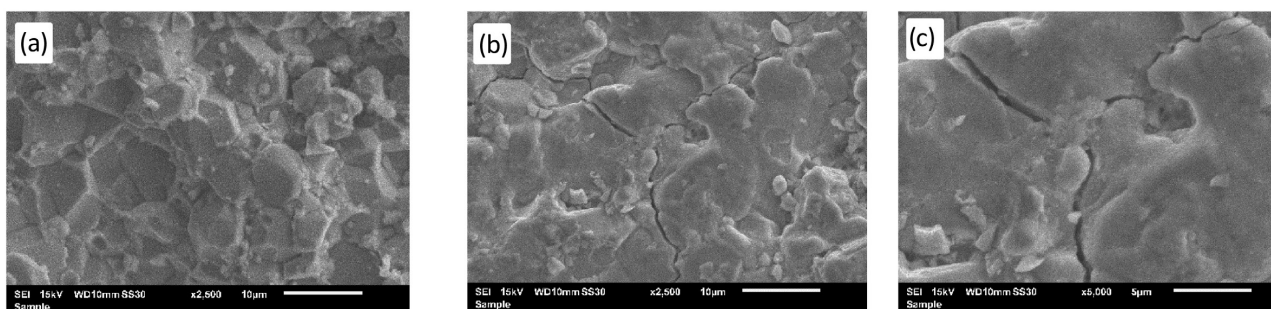
Conventional NdFeB processing relies on mechanical grinding, typically requiring 8–12 h of milling to achieve particle sizes of 5–10  $\mu\text{m}$ , due to the high mechanical strength of the bulk material. When hydrogen decrepitation

is applied prior to milling, hydrogen-induced embrittlement accelerates comminution, reducing the required grinding time to 2–4 h for comparable or finer particle sizes, which corresponds to an approximate 70% reduction in milling time [15,26]. In the present study, the process parameters were not optimized to meet magnet-grade granulometric specifications; after HD and 45 min of grinding, an average particle size of approximately 45  $\mu\text{m}$  was obtained. As the objective of this work was to validate the hydrogen decrepitation process rather than to produce magnet-grade powder, no further milling was conducted to reach standard particle size requirements.

In this context, the reported improvement does not refer to a maximum process efficiency in terms of final particle size, but rather to a reduction in comminution time associated with the application of hydrogen decrepitation prior to grinding, as reported in the literature.

Within the scope of the present pilot-scale study, the objective was limited to validating the effectiveness of hydrogen decrepitation in promoting material embrittlement, rather than achieving standard particle size specifications for magnet manufacturing. Under the selected experimental conditions and given the development structures available for the project, a maximum particle size reduction to approximately 45  $\mu\text{m}$  was reached after 45 min of grinding. This particle size therefore represents the endpoint defined by the project scope and experimental infrastructure, and not an optimized or limiting value of the process.

Prior hydrogen decrepitation increased the fraction of material effectively ground within a fixed milling time, facilitating the milling process of WEEE NdFeB magnets under the validated milling parameters [20]. Under identical experimental conditions, the decrepitated sample reached a ground fraction of 73.3%, whereas the non-decrepitated sample reached 25.3%, and literature data for untreated material report 37.1% [20]. In terms of throughput, the



**Figure 7.** Surface morphology of the sample showing fractured regions. In (a) the sample before the decrepitation process, at 2500x magnification, and in (b) and (c) after the decrepitation process at 2500x and 5000x magnifications, where it is possible to observe the fissures caused by the process.

**Table 2.** Milling yield of magnets before and after hydrogen decrepitation

Sample	Initial Quantity	Final Quantity	Efficiency	Yield (kg/h)
WEEE Magnet	15g	3.8g	25.33%	0.0051
Magnet after HD		11g	73.33%	0.0147

grinding rate increased from  $0.0051 \text{ kg}\cdot\text{h}^{-1}$  for the untreated sample to  $0.0147 \text{ kg}\cdot\text{h}^{-1}$  for the decrepitated material. These results indicate an increase in grinding yield and mass throughput within a given time. For reference, literature data reported by Wei [20] for grinding without hydrogen decrepitation indicate a ground fraction of 37.1% under similar conditions. These results show that, within the same grinding time, a larger fraction of the material is ground after decrepitation. In other words, hydrogen decrepitation effectively reduces the grinding effort required, achieving a 48 to 48.2 percentage point increase in the ground fraction compared to non-decrepitated samples, which corresponds to an approximately 2.9 times higher comminution yield. This is due to the structural changes induced by hydrogen decrepitation: microcracks and lattice expansion weaken the material, facilitating breakage and increasing grinding efficiency compared to non-decrepitated magnets.

#### 4 Conclusion

The objective of this study was to evaluate the beneficiation of NdFeB magnets recovered from post-consumer HDDs through hydrogen decrepitation, aiming to support the recovery of critical rare earth elements and contribute to circular economy strategies.

The adopted methodology included manual disassembly of WEEE, characterization of the recovered magnets, and application of the hydrogen decrepitation process as a pre-treatment step for material fragmentation and beneficiation.

The results demonstrated that hydrogen decrepitation effectively promoted the weakening and fragmentation of the NdFeB magnets, increasing the milling efficiency from 25.33% to 73.33% compared to untreated samples. SEM analyses revealed the formation of fissures induced by hydrogen absorption, while XRD results confirmed the preservation of the main crystalline phases after treatment. These findings indicate that hydrogen decrepitation is a viable route for the beneficiation of NdFeB magnets aiming at their direct recycling, contributing to the recovery of strategic materials with potential environmental and energy benefits aligned with sustainability and circular economy principles.

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