Study of the Mechanical Recycling Process of Electric Motors for the Recovery and Valorization of NdFeB Magnet Content

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Abstract

The demand for NdFeB permanent magnets, known as the strongest permanent magnets on the market, is projected to rise significantly. These magnets, made from rare earth elements (REEs) such as neodymium (Nd), praseodymium (Pr), and dysprosium (Dy), are essential for various high-tech applications, including electric motors for e-mobility, wind turbines, electronics, and air conditioners. However, their production is heavily reliant on REEs—classified as critical raw materials in the EU due to limited geographic availability and supply risks. Over 60% of global REE production occurs in China, which also controls 91% of REEs refinement and 94% of the permanent magnet market. Given Europe's lack of internal REEs production and refining capabilities, this dependency on Chinese imports poses a supply risk.

To address this problem, Europe must establish alternative REE sources, either by exploiting local mines or implementing recycling. Projections indicate that by 2050, recycling could potentially meet up to 75% of Europe's REE demand. However, current recycling efforts are limited, with less than 1% of REEs being recovered. This study aims to investigate a recycling method capable of recovering REEs, particularly from NdFeB magnets embedded within electric motors from e-mobility. The focus centers on a mechanical pretreatment approach that combines shredding with physical separation techniques, such as magnetic separation. The primary objective is to isolate a NdFeB-enriched fraction—a material stream containing a substantially higher concentration of NdFeB magnets than the original motor composition.

An industrial-scale trial was conducted on electric motors that were initially thermally demagnetized. This demagnetization step is crucial to mitigate issues related to magnet agglomeration during subsequent mechanical processing. The demagnetized motors were then shredded and processed via magnetic separation within an industrial facility. The separated fractions were subjected to laboratory pretreatment, involving sample homogenization, sieving, and magnetic attraction, to concentrate the NdFeB content. The samples were analyzed through MP-AES to quantify the REE content, including Nd, Pr, Ce, Dy, and Gd. This data provided insights into the enrichment of NdFeB magnets in the treated fraction.

A material flow analysis (MFA) was conducted to assess the distribution of magnets throughout the process. The MFA revealed that 71.3% of magnets entering the treatment facility were retained in the ferrous fraction, while 28.3% were found in the non-ferrous fraction. The ferromagnetic properties of the NdFeB magnets facilitated their attraction to the magnetic separator, enhancing the concentration of magnets in the ferrous fraction. A significant increase was observed in the magnet concentration in the non-ferrous fraction after additional magnetic separation, with the concentration rising from 9.47% in the initial non-ferrous fraction to 50.8% in the final attracted fraction.

The findings of the study provided key information for the future design of an optimized mechanical pretreatment process that could achieve both a higher concentration of NdFeB magnets and an improved process yield.

1. Introduction

The recycling of REEs, in particular end-of-life products containing NdFeB magnets, offers a sustainable and strategic alternative to primary REE production. Recycling could emerge as one of Europe's main internal REE sources, reducing dependency on imports and diversifying a market dominated by Asia, particularly China. Diversifying the REE market is crucial to mitigate risks from external factors, such as supply disruptions from major suppliers, which can significantly affect REE prices, known for their volatility. By establishing robust recycling capabilities in Europe, exposure to such risks can be minimized, stabilizing market prices and offering greater predictability for industries reliant on these critical materials (European Commission 2024) (Rizos et al., 2022) (Gregoir & van Acker, 2022).

REE recycling also supports the circular economy by reducing the environmental impact of REEs mining and processing while promoting the sustainable use of resources (Sprecher et al., 2014). The European Union is actively exploring alternatives to mining, such as reuse, substitution, and recycling, which could potentially meet over 75% of the EU's REE demand by 2050 (Gregoir & van Acker, 2022). However, despite this ambition, only 1% of REEs are currently recycled (Jowitt et al., 2018), and no commercial process exists to recycle NdFeB magnets from end-of-life products.

Most Waste Electrical and Electronic Equipment (WEEE) is shredded and subjected to mechanical separation for valuable materials like iron, copper, aluminum, and precious metals. However, NdFeB magnets end up in the ferrous fraction due to their magnetic properties, at concentrations too low for economic REE recovery. Bandara et al. conducted a study on the REE content within the ferrous fraction separated at WEEE recycling plants, revealing that ferrous fractions contain between 130 and 290 ppm of neodymium—significantly lower than the 1000-1500 ppm typically found in mining by-products. Without a dedicated recycling process targeting NdFeB magnets, REE recovery from WEEE is not feasible.

A potential solution for recovering NdFeB magnets from end-of-life products is to separate them before the waste is shredded. This requires overcoming several challenges: the magnets are often integrated into the product, fixed with adhesives, and surrounded by screws or other fasteners. Additionally, demagnetization is necessary, which involves heating the magnets above their Curie temperature to allow extraction. Two main approaches are available for recovering NdFeB magnets: automated or semi-automated extraction, and HPMS technology.

Automated or semi-automated extraction involves designing disassembly machinery tailored to specific product categories to recover magnets. For instance, Hitachi has developed machines capable of efficiently extracting NdFeB magnets from products like Hard Disk Drives (HDDs). These machines use a rotating drum mechanism that applies vibrations and impacts to loosen screws securing the HDD casing, allowing the separation of Voice Coil Motors (VCMs), which contain magnets, from the casing. Once dismantled, the VCMs undergo demagnetization in an electric furnace. Afterward, another machine separates the magnets from their external support, typically bound by adhesive. Hitachi and Mitsubishi Materials have also developed similar technology for the automated disassembly of air conditioner compressors containing NdFeB magnets (Baba et al., 2010).

Simon et al. proposed a semi-automatic system using modified 3D printer components to automate the HDD disassembly process for magnet recovery. This system integrates tools such as drills and microcontrollers to optimize disassembly. A microcontroller, along with barcode scanners and other electronics, semi-automates the identification and removal of screws from the HDD, reducing the time and labor required for magnet recovery, making the process faster and more cost-efficient.

Another extraction method is the Hydrogen Processing of Magnet Scraps (HPMS) (Walton et al., 2015) (Jönsson et al., 2020), developed by the University of Birmingham. This technique involves exposing end-of-life HDDs to hydrogen flow at atmospheric pressure and room temperature. Sintered magnets react with the hydrogen, forming $NdH_{2.7}$ at grain boundaries, causing a 5% volumetric expansion. Due to the fragile nature of magnets, this results in their breakage into friable, hydrogenated powder. This powder's coercivity becomes so low that it is no longer magnetically attracted to the ferrous components in the waste. The NdFeB powder is then separated from the waste using a specifically designed centrifuge reactor.

Materials recovered through these technologies, such as intact magnets or powdered magnets, can be directly used as raw material for producing new magnets through direct recycling processes. Alternatively, they can undergo indirect recycling, where REEs are extracted in pure form. In the direct or "short-loop" recycling method, the recovered NdFeB alloy is processed through hydrogen decrepitation, milling, sintering, and pressing to produce new magnets (Zakotnik et al., 2009). Compared to indirect or "long-loop" recycling, this approach has a smaller environmental footprint, as fewer steps are required, and resource and energy consumption are lower, leading to reduced production costs (Sprecher et al., 2014) (Yang et al, 2016).

However, challenges remain, such as the need to adapt production techniques when using recycled material due to the impurities it contains. For example, NdFeB magnets from end-of-life products typically have 2000–5000 ppm of oxygen, much higher than the 300–400 ppm in virgin NdFeB alloy. This oxygen is trapped in the grain boundary phase, which does not melt during sintering due to the high melting point of oxides (>2000°C), resulting in lower density and altered magnetic properties compared to virgin magnets (Meakin et al., 2016). Zakotnik et al. proposed a solution by adding 2% NdH2.7 to hydrogenated NdFeB powder, achieving comparable density to magnets made from virgin material. Nonetheless, challenges like standardizing recycled magnets and achieving comparable magnetic properties to virgin magnets remain.

An alternative to direct recycling methods is indirect recycling, which involves extracting pure REEs from end-of-life magnets. This process yields a product with the sample properties to mined raw materials but requires more processing steps, energy, and chemical reagents. The two main indirect recycling methods are the pyrometallurgical route (Vander et al, 2014) and the hydrometallurgical route (Lyman et al.,1993).

In the pyrometallurgical route, after mechanical grinding, the magnets undergo high-temperature oxidative roasting (above 800°C). This transforms the NdFeB alloy into oxides, enabling selective leaching of REEs using strong acids like HCl, leaving iron as a solid residue. This selectivity is possible because iron oxide is more resistant to acidic leaching than REOs. After solvent extraction removes transition metals like cobalt and copper from the leachate, REEs are precipitated using oxalic acid. The final product is REO, obtained after calcining the oxalates.

In contrast, the hydrometallurgical route dissolves the ground magnets in sulfuric acid, followed by REEs precipitation using basic compounds (e.g., ammonium, sodium, or potassium hydroxides) to adjust the pH to 1,5. The resulting double sulfate salts of neodymium are then converted into fluorides through treatment with hydrofluoric acid, preparing them for metallization.

A greener alternative to traditional recycling processes is the replacement of strong inorganic acids (e.g., HCl, HNO_3, and H_2SO_4) with weaker organic acids. Organic compounds explored include acetic, formic, citric, and tartaric acids (Belfqueh et al., 2023) (Romano et al., 2023) (Niskanen et al., 2022).

As discussed earlier, semi-automated, fully automated disassembly or HPMS technology are key methods for NdFeB magnet recycling. However, these methods face significant challenges due to the complex integration of magnets into products, which are not designed for easy disassembly. Developing suitable disassembly technologies is difficult, and HPMS is challenging to implement because the hydrogen access to the magnets is limited.

The focus of this work is to explore an alternative, mechanical treatment-based approach for separating NdFeB magnets from end-of-life products. Specifically, the study examines mechanical separation techniques such as milling, magnetic separation, and eddy currents to create a NdFeB-rich fraction suitable for indirect recycling to recover REEs. Unlike previous methods that rely on automated extraction, this mechanical approach seeks to recover the magnets themselves from the treated material. An initial step of thermal demagnetization is required because standard industrial treatments fail to effectively recover REEs, which end up diluted in the ferrous fraction in concentrations too low for recovery as noted by Bandara et al..

In this study, 160 kg of motors containing NdFeB magnets, sourced from electric scooters, underwent thermal demagnetization. The motors were then processed in an industrial facility using a traditional motor recycling process that includes milling and magnetic separation. This allowed for observation of the physical behavior of the NdFeB magnets during processing and the mass flow distribution of the magnets within the system. The data collected will be useful in designing an optimized recycling process specifically aimed at efficiently separating and recovering the NdFeB magnet fraction.

2. Materials and method

2.1 Characterization and industrial processing of electric motors

The motors used in this study were sourced from different electric scooters of the same model, ultimately resulting in experimental replicates for the knowledge of experimental variability, and are brushless direct current (BLDC) motors with NdFeB permanent magnet rotors.

One of the motors was weighed and manually disassembled using standard workshop tools such as a hammer, crowbar, circular grinder, wrenches, Allen keys, an electric drill, and various-sized pullers, chisels, and a vise. After disassembly, each component was weighted and categorized by material type using Niton™ XL5 Plus Handheld XRF Analyzer—magnets, aluminum, copper, iron, plastic parts, and wiring. This characterization was carried out both for the entire motor and for each of its individual components.

Figure 1: Electric motor before (left) and after (right) disassembly.

Before being sent to the industrial treatment plant, 46 motors were disassembled (Figure 1). Portions of the rotors were filed down to fit into a muffle furnace for thermal demagnetization at 310°C for 25 minutes. The purpose of this operation was to reach the Curie temperature of the magnets, which would then facilitate their separation from the ferromagnetic fraction during processing. After demagnetization, the motors were reassembled (excluding the cables, which were cut during disassembly) and weighed again.

The demagnetized motors were processed at a ferrous waste treatment facility using a hammer mill for milling, followed by magnetic separation. This process produced two distinct material fractions: a ferromagnetic fraction attracted by the industrial magnet and a non-ferromagnetic fraction that was not. Both fractions were weighed in the lab. Figure 2 provides a diagram of this initial sequence of operations applied to the motors.

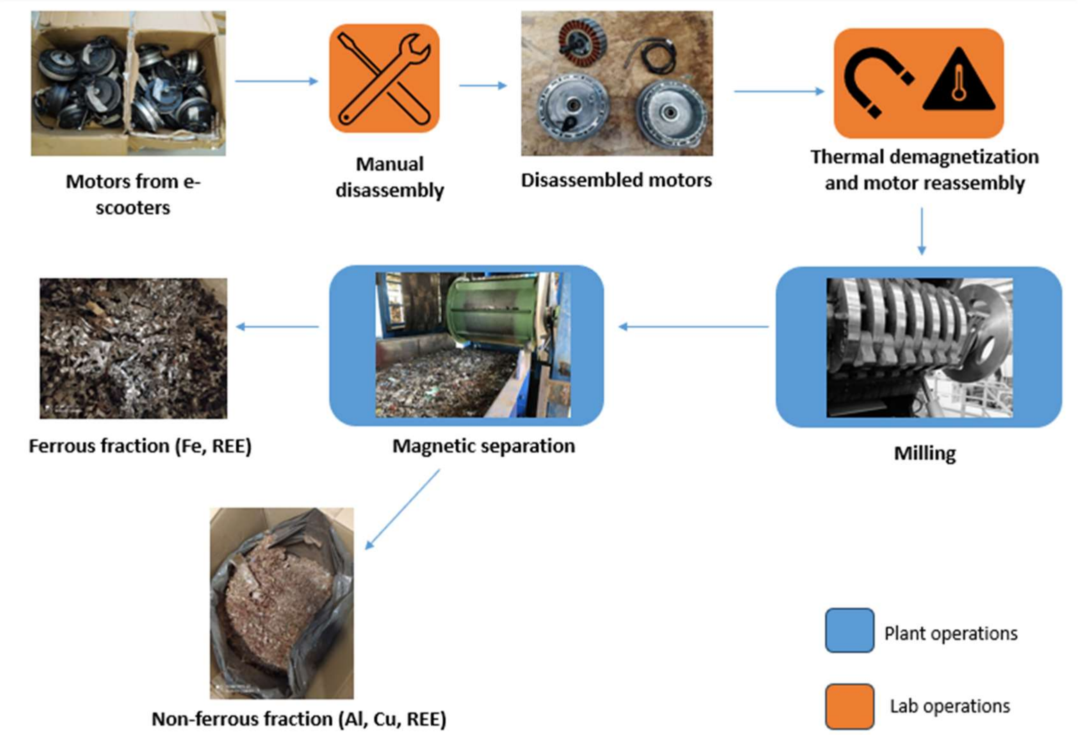

Figure 2: Diagram of the operations performed on electric motors up to the industrial test, showing the two output products from the plant: the non-ferrous fraction and the ferrous fraction.

After the industrial processing, a detailed characterization of the non-ferrous fraction was conducted to enable a comprehensive MFA study of the permanent magnets throughout the recycling process. This analysis aimed to trace and quantify the distribution and behavior of NdFeB magnets within the material streams, providing critical insights into their separation efficiency and recovery potential during each processing stage. This step is essential for optimizing the recycling strategy and understanding the flow of REEs through the system.

2.2 Non-ferrous fraction pretreatment

Larger aluminum pieces were manually removed from the non-ferrous fraction to prevent complications during subsequent characterization and laboratory treatment processes. The remaining mass was then screened at 0.1 mm to eliminate the finer, dust-like particles. In the next step, a representative sample weighing 12.6 kg was extracted from the total 37.3 kg of the non-ferrous fraction and sieved at 4 mm, separating the material into oversize (>4 mm) and undersize (<4 mm) fractions.

Magnets were applied manually to both fractions to segregate the ferromagnetic material from the non-ferromagnetic one, specifically targeting the fraction containing NdFeB magnets, which exhibit ferromagnetic properties. This procedure aimed to obtain a fraction enriched of NdFeB magnet, thereby facilitating the subsequent digestion and analysis needed for the MFA study of the magnets.

Moreover, following the MP-AES analyses, the effectiveness of this enrichment process was assessed to determine its feasibility for integration into a recycling process for NdFeB magnets. Lastly, the ferromagnetic fraction was further sieved manually at 1 mm, resulting in three distinct fractions with varying particle sizes. Figure 3 illustrates all the steps undertaken on the non-ferrous fraction.

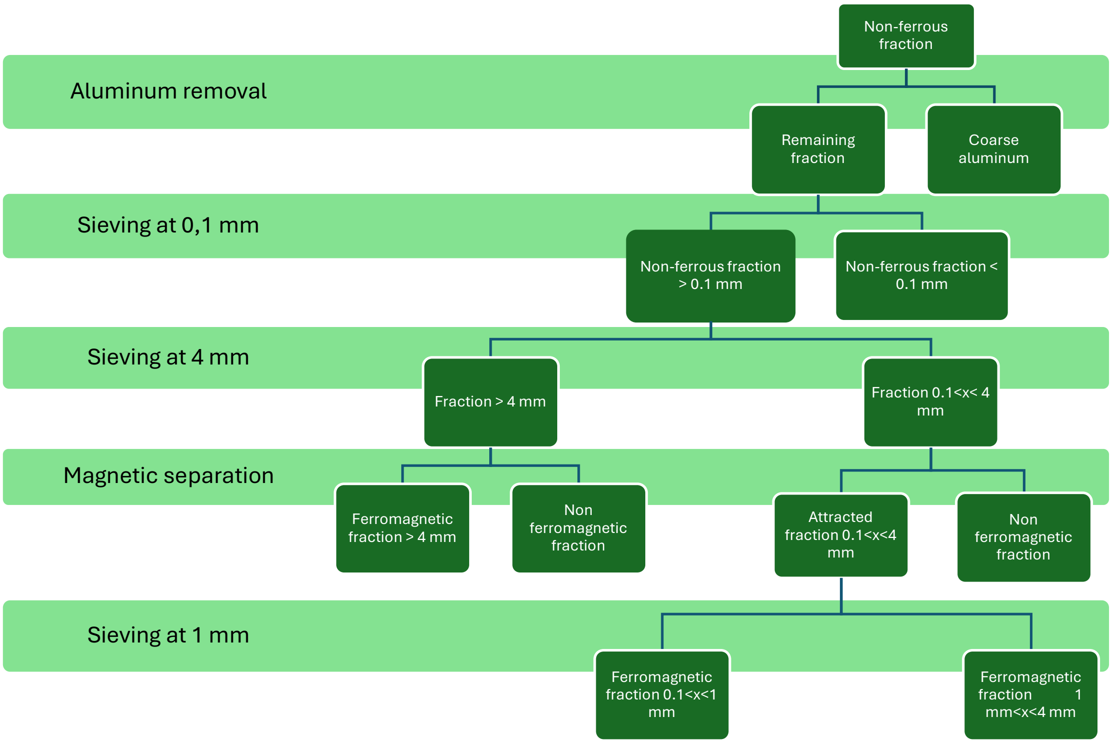

Figure 3: Flowchart of the laboratory operations performed after obtaining the ferrous and non-ferrous fractions following treatment at the processing facility

The obtained fractions were digested using acid solutions and characterized using the Agilent MP-AES 4210 model, as detailed in the section "Digestion and Characterization of Samples via MP-AES," to determine the content of REEs within the different fractions to conduct an MFA study of the magnets in the process Additionally, the fractions were analyzed using a Total Organic Carbon Analyzer to assess the organic fraction present. The fraction with particle sizes greater than 4 mm was not analyzed due to its excessive heterogeneity, as samples for the TOC analysis must not exceed a specific weight limit

2.3 Digestion and MP-AES characterization

NdFeB magnets from electric motors

Six magnets were randomly extracted from different electric motors, and 0,25 g aliquots were taken from each magnet using steel shears. Each aliquot was placed into a 50 mL flask along with 2 mL of 65% HNO_3. This procedure was conducted under a fume hood to manage the formation of nitrogen dioxide. Once the brown nitrogen dioxide fumes had dissipated, 8 mL of 37% HCl was added to each flask. The volume in each flask was then brought to 50 mL with Milli-Q water. The digested samples were diluted at ratios of 1:10 and 1:100 with a 2% HNO_3 solution for MP-AES analysis. The elements analyzed included Fe, Nd, Pr, Dy, Ce, Gd, Cu, Co, and Al, which are the primary constituents of NdFeB magnets.

Ferromagnetic fraction with particle size between 0.1 mm and 1 mm

Three samples of approximately 1 g each were taken from the ferromagnetic fraction with particle size between 0.1 mm and 1 mm and calcined in a muffle furnace for 1.5 hours at 600°C. Each sample was then reflux-digested in a flask for 10 hours with 20 mL of aqua regia (4 mL 65% HNO_3 and 16 mL 37% HCl). The resulting solutions were transferred to 100 mL flasks, along with the digestion residue, and the final volume was adjusted. Before MP-AES analysis, the samples were filtered and diluted at ratios of 1:10 and 1:100 using a 2% HNO_3 solution.

Ferromagnetic fraction with particle size between 1 mm and 4 mm

Three samples of approximately 25 g each were taken from the ferromagnetic fraction with particle size between 1 mm and 4 mm and calcined in a muffle furnace for 1.5 hours at 600°C. Each sample underwent reflux digestion in a flask for 10 hours with 100 mL of aqua regia (20 mL 65% HNO_3 and 80 mL 37% HCl). The solutions were then transferred to 250 mL flasks, along with the digestion residue, and the final volume was adjusted. Prior to MP-AES analysis, the samples were filtered and diluted at ratios of 1:10 and 1:100 with a 2% HNO_3 solution.

Ferromagnetic fraction with particle size greater than 4 mm

A sample weighing 180 g, taken from the ferromagnetic fraction with particle size greater than 4 mm, was calcined at 600°C for 1.5 hours. Subsequently, the sample was screened using a steel sieve with a 2 mm sieving size. The oversize fraction was manually separated into homogeneous components, such as iron, copper, and magnets, which were visually identifiable at this size. The undersize fraction was divided into three replicates of approximately 20 g each, which were then reflux-digested in a flask with 80 mL of aqua regia (composed of 16 mL of 65% HNO_3 and 64 mL of 37% HCl) and brought to volume in 250 mL and

500 mL flasks. This methodology was adopted to reduce the amount of sample requiring digestion. Before MP-AES analysis, the samples were filtered and diluted at ratios of 1:10 and 1:100 using a 2% HNO_3 solution. The elements analyzed included Fe, Nd, Pr, Dy, Ce, Gd, Cu, Co, and Al.

Non-ferrous fraction with particle size less than 0.1 mm

For the characterization of the fraction smaller than 0.1 mm, three aliquots of approximately 250 mg were digested in a microwave (Advanced Microwave Digestion System ETHOS EASY) with 10 mL of aqua regia (composed of 2 mL of 65% HNO_3 and 8 mL of 37% HCl) at a temperature of 190°C for 25 minutes. After cooling, the solutions were diluted in 50 mL flasks using 0,2% HNO_3 and analyzed using MP-AES. The elements analyzed included Nd, Pr, Dy, Gd, and Ce.

Non ferromagnetic fractions with particle size greater than 4 mm and between 1mm and 4mm

The non-ferromagnetic fractions with particle sizes greater than 4 mm and between 1 mm and 4 mm were excluded from analysis. Thorough inspection with magnets confirmed that these fractions contained no remaining ferromagnetic material (e.g., NdFeB magnets), rendering further analysis via digestion and MP-AES unnecessary for the purposes of this research.

2.4 Mass Flow Analysis (MFA) Study

The MFA study of NdFeB magnets within the treatment process was conducted using data obtained from the industrial trial and laboratory characterization. Specifically, the MFA analysis utilized the masses of the different fractions generated during the industrial trial, the results from screening and magnetic separation performed in the laboratory, and the percentage of neodymium (Nd) measured via MP-AES in these fractions.

The total mass of NdFeB magnets in the treated electric motors was calculated by multiplying the average mass of magnets per motor—determined during the material characterization of the motors—by the total number of motors processed at the facility. To estimate the quantity of magnets in each fraction obtained through treatment in the facility and laboratory handling (e.g., screening and magnetic separation), we divided the percentage of Nd in the fraction considered by the percentage of Nd in the electric motor magnets, and then multiplied by the mass of that fraction using the following formula:

$$m_{\text{magnets fraction}} = (\%Nd_{\text{fraction}} / \%Nd_{\text{magnets}}) * m_{\text{fraction}}$$

Where:

$m_{\text{magnets fraction}}$ = mass of magnets present in the fraction considered

$\%Nd_{\text{fraction}}$ = percentage of Nd within the fraction considered

$\%Nd_{\text{magnets}}$ = percentage of Nd within the electric motor magnets

m_{fraction} = mass of the fraction considered

The concentration of Nd was chosen as the reference parameter for the presence of magnets, as it is the most abundant REE within the magnets. The ratio of $\%Nd_{fraction}$ to $\%Nd_{magnets}$ multiplied by 100 provides the mass percentage of magnets within the fraction considered. These percentages were used to evaluate the effectiveness of the enrichment process for magnets in the fractions subjected to magnetic separation at laboratory level.

3. Results

Figure 4 illustrates the components of the electric motor: stator (a), rotor (b), electrical cables (c), upper casing (d-e), and screws (f). Table 1 presents the composition of the motor in terms of materials, both before and after the filing process necessary for thermal demagnetization. The electrical cables within the motor were treated as a single material category, as they were not characterized in detail.

Figure 4: Main components of the characterized electric motors: a) Stator; b) Rotor; c) Electrical cables; d-e) Upper casing; f) Screws.

Table 1: Material composition of the electric motors studied before and after the disassembly.

Material	Percentage of materials in the motor (% w/w)	Percentage of materials in the motor, after filing and removal of cables (% w/w)
% Al	26.1	25.8
% Cu	11.2	11.6

https://doi.org/10.26434/chemrxiv-2024-x3sh7 **ORCID:** https://orcid.org/0009-0001-4652-2483 Content not peer-reviewed by ChemRxiv.

% Fe	51.5	53.2
% magnets	7.4	7.6
% plastic	1.6	1.7
% cable	2.1	Not present
Total	99.9	99.9

The reassembled motor after thermal demagnetization has a lower mass compared to its initial weight, as it does not include portions of the rotor and electrical cables. The total mass of the motors prior to disassembly was 170,6 kg, while the total mass sent to the industrial facility amounted to 164,6 kg.

The demagnetized electric motors were sent to an industrial recycling plant for processing, which included milling with a hammer mill and magnetic separation. After treatment at the facility, two fractions were obtained: one classified as ferrous, weighing 99,2 kg and attracted by the magnet, and the other classified as non-ferrous, weighing 77,4 kg and not attracted by the magnet. It was noted that the combined mass of the ferrous and non-ferrous fractions totaled 176,6 kg, which exceeds the initial mass input into the facility, recorded at 164,6 kg. This discrepancy can be attributed to foreign materials that accumulated in the plant during previous processing campaigns.

It is important to clarify that the ferrous fraction does not consist solely of ferromagnetic materials, and conversely, the non-ferrous fraction is not composed exclusively of non-ferromagnetic materials. The efficiency of industrial magnetic separation is influenced by the type of material being processed, which varies based on the nature of the waste and the degree of milling. Visually, a significant portion of NdFeB magnets, a ferromagnetic alloy, was found in the non-ferrous fraction. One of the aims of this study is to determine how NdFeB magnets are distributed between the two fractions, conducting a MFA study of the magnets within the industrial treatment process for electric motors.

In the non-ferrous fraction, coarse aluminum pieces were manually removed, totaling 36.1 kg. Subsequently, the non-ferrous fraction was screened at 0.1 mm, resulting in an undersized fraction weighing 3.3 kg. Both operations were conducted to facilitate laboratory characterization of the non-ferrous fraction. Below is block scheme (Figure 5) illustrating the distribution of the initial mass across the various fractions.

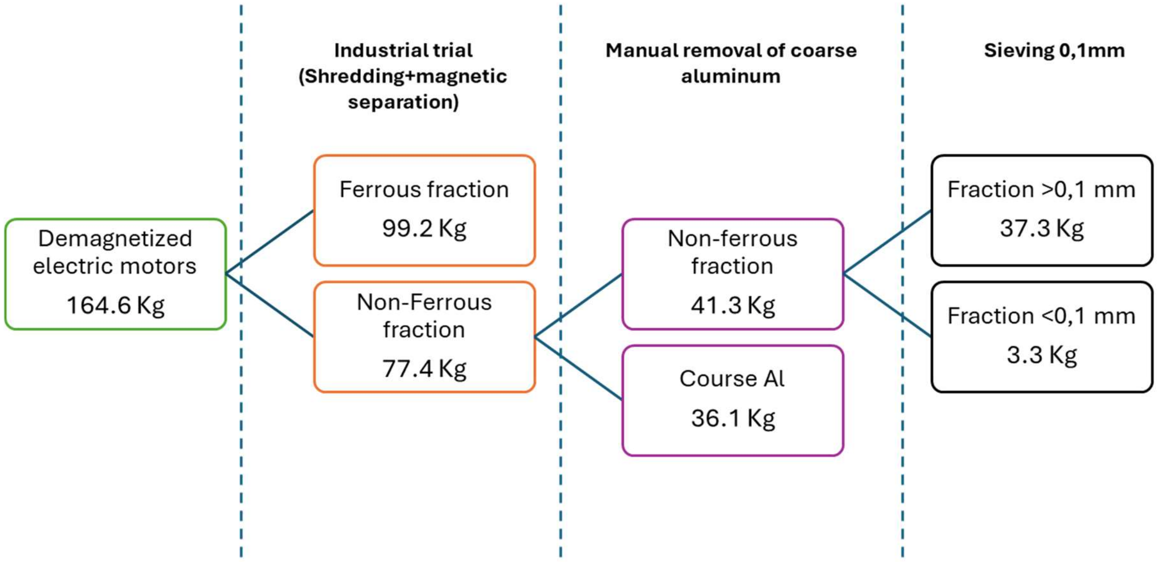

Figure 5:Block scheme (in kg) of the electric motors from dispatch to the facility to pre-treatment in the laboratory (removal of coarse aluminum and screening at 0.1 mm)

Subsequently, work focused on the non-ferrous fraction with a particle size greater than 0.1 mm, from which 12.6 kg were taken as a representative sample of the total mass. This sample was screened at 4 mm, resulting in two distinct fractions, which were then subjected to magnetic separation using manual screening with a magnet to divide the ferromagnetic component from the non-ferromagnetic one. This step aimed to obtain enriched fractions of NdFeB magnets, which are attracted to the magnet due to their ferromagnetic properties, thereby facilitating the digestion and analysis operations required for the MFA study of the magnets.

Subsequent MP-AES analyses allowed for the quantification of magnet presence in the different fractions of the process and the evaluation of the effectiveness of the enrichment achieved through magnetic separation. The goal was to assess the feasibility of integrating this process into the recycling of NdFeB magnets from electric motors. The ferromagnetic component with a particle size less than 4 mm was further screened at 1 mm to obtain homogeneous samples, thus simplifying characterization. Figure 6 presents a block scheme illustrating the masses of the fractions obtained at the various steps described above.

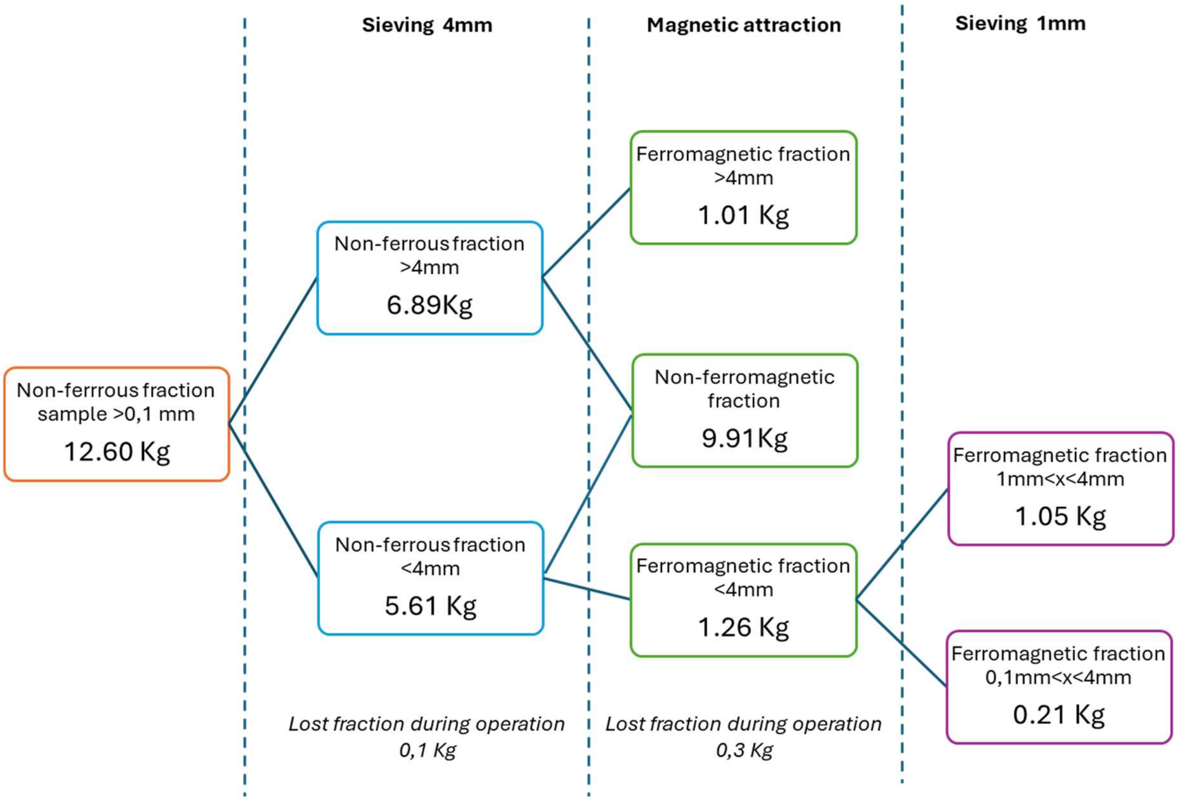

Figure 6: Block scheme of operation done on the non-ferrous fraction sample for laboratory characterization

The results obtained from the 12.60 kg sample of the non-ferrous fraction can be extrapolated to the total mass of the non-ferrous fraction. These results are illustrated in the block scheme presented in Figure 7.

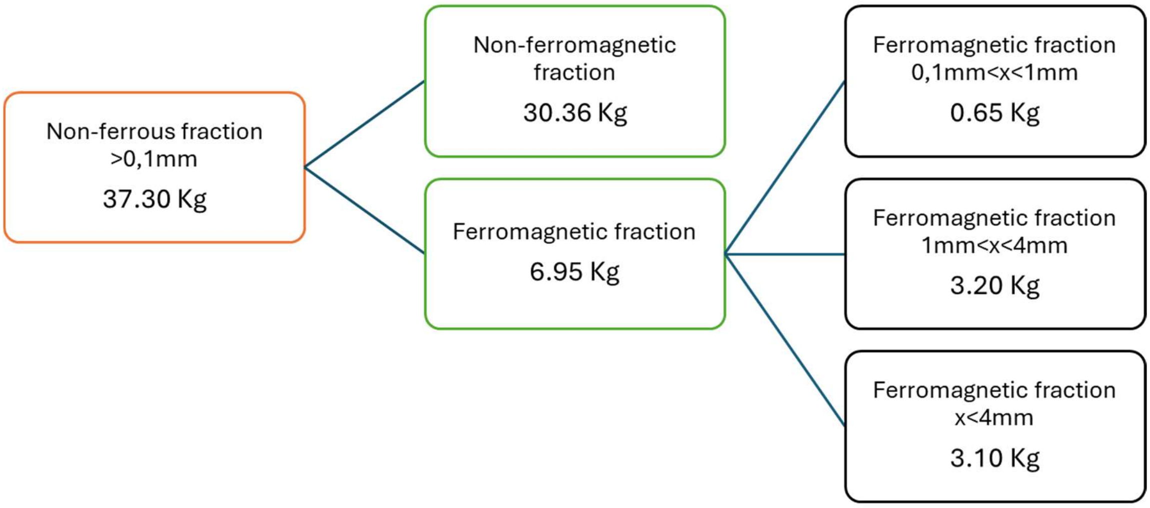

Figure 7: Distribution (in kg) of the various fractions relative to the total mass of the non-ferrous fraction.

Tables 2, 3, and 4 present the Total Organic Carbon (TOC) analyses for the ferromagnetic fractions with particle sizes ranging from 1 to 4 mm, from 0.1 to 1 mm, and the non-ferrous fraction below 0.1 mm. Each fraction was analyzed using three samples.

Table 2: TOC analysis results of ferromagnetic fraction with particle size between 1mm and 4 mm

Ferromagnetic fraction 1 mm<o<4mm	
Average carbon concentration (%)	0.633
Dev STD (%)	0.055
Dev. Std. relative (%)	8.65

Table 3: TOC analysis results of ferromagnetic fraction with particle size between 1mm and 4 mm

Ferromagnetic fraction 0,1 mm<o<1mm	
Average carbon concentration (%)	2.34
Dev STD (%)	0.191
Dev. Std. relative (%)	8.15

Table 4: TOC analysis results of non-ferrous fraction with particle size below 0.1 mm

Non-ferrous faction <0.1 mm	
Average carbon concentration (%)	17.4
Dev STD (%)	0.981
Dev. Std. relative (%)	5.63

The results indicate that the carbonaceous fraction, which can be considered as entirely organic carbon since there are no inorganic carbon components within the motors, is most prevalent in the fraction with a particle size of less than 0.1 mm, comprising approximately 17%. This higher concentration is likely attributed to the physical characteristics of the carbon-rich components present in the non-ferrous fraction, such as plastics, which easily break down.

To complete the MFA study of the magnets in the process, the various fractions obtained through sieving and magnetic separation, as well as the magnets contained within the electric motors, were analyzed using MP-AES. The elements examined included Fe, Nd, Pr, Dy, Ce, Gd, Cu, Co, and Al.

Table 5 presents the results of the MP-AES analysis conducted on the magnets found in the electric motors. Notably, a high concentration of Ce is observed; this element is used to partially replace Nd, resulting in reduced magnet performance at a lower raw material cost. The compositions of the fractions are then displayed from left to right: the ferromagnetic fraction with a particle size between 0.1 mm and 1 mm, with a size between 1 mm and 4 mm, and greater than 4 mm. It is important to note that the fraction above 4 mm does not exhibit a standard deviation, as its composition was determined both through MP-AES analysis of the finer fraction (< 2 mm) and visual characterization of the oversize fraction (> 2 mm).

Table 5: results of the MP-AES analysis conducted on the magnets found in the electric motors, the ferromagnetic fraction with a particle size between 0.1 mm and 1 mm, with a size between 1 mm and 4 mm, and greater than 4 mm

	NdFeB magnets within electric motors		Ferromagnetic fraction with a particle size ranging from 0.1 mm to 1 mm.		Ferromagnetic fraction with a particle size ranging from 1 mm to 4 mm		Ferromagnetic fraction with a particle size exceeding 4 mm
Element	% w/w	dev.std (%)	% w/w	dev.std (%)	% w/w	dev.std (%)	% w/w
Fe	63.2	3.2	60.3	0.2	61.7	2.2	67.05
Nd	14.7	1.3	5.72	0.09	8.71	0.24	6.41
Pr	4	0.4	0.685	0.072	2.89	0.08	4.87
Ce	7.9	1.6	2.51	0.48	4.73	0.72	1.35
Al	0.4	0.1	0.669	0.052	0.399	0.015	3.49
Co	0.2	0.1	0.109	0.009	0.181	0.004	1.72
Dy	1.2	0.2	0.498	0.009	0.769	0.027	0.162
Gd	0.2	0.1	0	0	0	0	0.292
Cu	1.4	0.1	3.93	1.25	2.39	0.59	0.067
Und*	6.8		25.58		18.23		14.59
total	100	6.9	100		100		100

*% of the fraction whose nature has not been determined

The results from the MP-AES analyses allowed for the construction of a mass flow diagram of the magnets, illustrating their distribution across the various fractions. The mass flow of the magnets is depicted in the diagram in Figure 8.

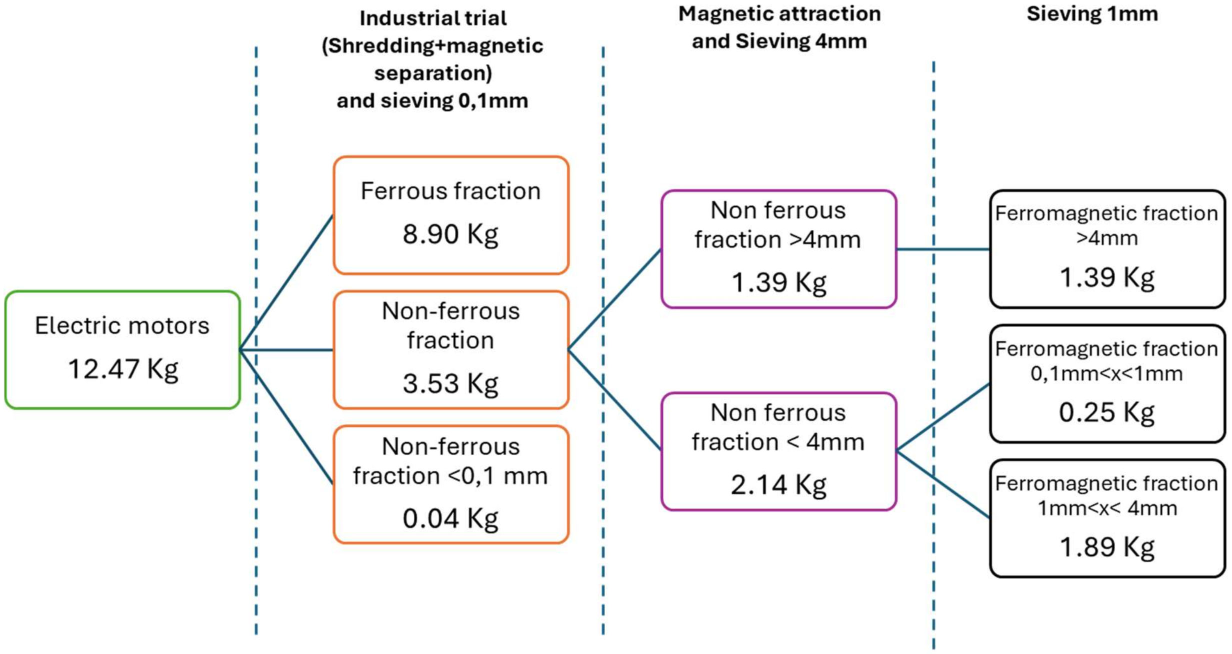

Figure 8: Mass flow (in kg) of the magnets from the motors throughout the treatment process and the laboratory treatment of the fractions.

It can be observed that most of the magnets (71.4%) ended up in the ferrous fraction due to their ferromagnetic nature. The demagnetization step eliminated any issues of magnet agglomeration during milling, allowing a portion of the magnets (28.3%) to remain in the non-ferrous fraction after magnetic separation in the industrial facility.

Table 6 presents the mass percentages of magnets across various particle size fractions, including the ferromagnetic fraction and the non-ferrous fraction (excluding aluminum). These values were calculated by dividing the mass of magnets present in each fraction by the mass of the corresponding reference fraction.

Table 6: Mass percentages of magnets across various particles size fractions

Fraction	Mass percentage of magnets (%)
Ferromagnetic fraction: 0.1 < x < 1 mm	38.9
Ferromagnetic fraction: 1 < x < 4 mm	59.2
Ferromagnetic fraction: > 4 mm	44.8
Total ferromagnetic fraction	50.8
Non-ferrous fraction	9.47

The magnetic separation conducted on the non-ferrous fraction sample resulted in a significant enrichment of magnets in the final composition. Specifically, the initial percentage of magnets in the non-ferrous fraction increased from 9.47% to 38.9% in the ferromagnetic fraction of size $0.1 < x < 1$ mm, reaching a maximum of 59.2% in the ferromagnetic fraction of size $1 < x < 4$ mm. Overall, the total ferromagnetic fraction exhibits a magnet content of 50.8%.

4. Conclusions

This study characterized electric scooter motors in terms of their content of copper, iron, aluminum, plastic, and NdFeB magnets. Approximately 160 kg of motors were thermally demagnetized at 310 °C for 25 minutes and subsequently treated in an industrial plant using a conventional recycling process for electric motors, which involved milling with a hammer mill and magnetic separation. This process yielded a magnetically attracted fraction defined as the ferrous fraction and a non-attracted fraction known as the non-ferrous fraction.

The non-ferrous fraction underwent a pre-treatment process at laboratory level involving sample homogenization and concentration, consisting of sieving and magnetic attraction using magnets, followed by MP-AES analysis to determine the content of REEs such as Nd, Pr, Ce, Dy, and Gd to assess magnet concentration. The collected data were utilized for a MFA study of magnet distribution throughout the process. The MFA revealed that 71.3% of the magnets entering the plant ended up in the ferrous fraction, while 28.3% were found in the non-ferrous fraction.

The thermal demagnetization effectively eliminated issues related to magnet agglomeration during milling; however, the ferromagnetic nature of the magnets ensured that the majority were attracted to the magnetic separator. The concentration of magnets in the ferromagnetic fractions obtained through magnetic attraction of the non-ferrous fraction showed a significant increase, rising from an initial mass concentration of 9.47% in the non-ferrous fraction to 50.8% in the attracted fraction. This indicates that the process represents a viable method for separating NdFeB magnets from a matrix of non-ferrous materials.

The introduction of a thermal demagnetization step prior to the treatment of the electric motor in the industrial facility enabled the recovery of a fraction containing approximately 50% NdFeB magnets, resulting in a yield of 28.3%.

The research conducted on electric motors demonstrated that a thermal demagnetization treatment, performed before sending the motors to the industrial treatment facility for milling and magnetic separation operations, significantly influences the behavior and distribution of NdFeB magnets within material flows. These insights will be crucial for developing an optimized mechanical process aimed at enhancing the value of the NdFeB magnet-containing fraction, thereby improving both the overall yield of the process and the concentration of magnets in the final enriched fraction.

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