Journal of Environmental Chemical Engineering 14 (2026) 120928

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

End of life permanent magnet recycling: State of the art and material flow analysis in the framework of potential substitution of RE-based magnets with ferrites

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ARTICLE INFO

Keywords:
Permanent magnets
Rare earth elements
Ferrite magnet
Recycling
Material flow analysis

ABSTRACT

Permanent magnets are crucial elements in many everyday technologies (e.g. green energy and mobilities). Neodymium-Iron-Boron (NdFeB) magnets are considered the strongest rare-earth (RE) based magnet available, due to their superior performances. Therefore, their global demand is expected to grow, together with the increased difficulties in raw materials supply due to geopolitical instability. Ferrite magnets represent a promising alternative and a significant share of the market due to their lower costs. Several reviews have addressed key aspects of permanent magnet processing, including recycling. Anyway, there is a lack of information concerning technological innovation change dealing with the recycling of both magnet types. To address this gap, the present review combines scientific literature with an analysis of available patents, which serve as a valuable indicator of the technological innovation. The analysis identified multiple experimental approaches for the extraction of RE from NdFeB, while ferrite recycling is still limited despite growing interest.

Moreover, with the aim to reduce reliance on critical raw materials, the benefit of RE-based magnets substitution with ferrites is quantified applying a material flow analysis. The substitution efficiency shows a decrease in RE magnets demand of about 40 % for the manufacturing of the products subjected to analysis (e-cars, e-bikes, e-motorbikes, e-scooter, pump drives) throughout 10 years. Results estimated that free-RE magnet substitution can save around 3400 tons of RE-based magnets, which represent around 20 % of the European demand. RE-free magnets offer a valuable opportunity for the European market through recyclability and reduced dependence on extra-EU raw materials.

1. Permanent magnets: current status and recent research trend

Permanent magnets (PM) are essential component in a wide range of technologies, including electric vehicle (EV) traction motors (35–40 %), wind turbines (15–20 %), household appliances (10–15 %), servo motors in robotic arms (5–10 %), and portable communication devices such as speakers (5–10 %) [1–3].

PMs are commonly classified into rare-earth (RE) and non-RE types. Among RE-based magnets, neodymium-iron-boron (NdFeB) magnets, commercialized during the 1980s, are the most widely used. Their composition consists of around 60–70 % of iron (Fe), 25–35 % of RE elements (REE), mainly neodymium (Nd), praseodymium (Pr) and dysprosium (Dy), and around 1 % of boron (B) [4–6].

The full production chain of RE-based magnets, from REE mining and beneficiation to cracking, separation, and final magnet fabrication, is well documented in the literature [7,8]. Significant material losses occur along this chain, particularly during ore flotation (30–50 %), hydrometallurgical treatment (6–10 %) and magnet manufacturing (10–15 %) [7]. Table 1 summarizes key information on the mining, refining and production of Nd, Dy and Pr. Mass quantities are expressed in metric tons, where 1 tons = 1000 kg.

NdFeB magnets exhibit the highest magnetic performance among

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https://doi.org/10.1016/j.jece.2025.120928
Received 11 November 2025; Received in revised form 24 December 2025; Accepted 26 December 2025
Available online 26 December 2025
2213-3437/

Table 1
Information about mining and refinery of Nd, Dy and Pr (in 2019).

	Nd	Dy	Pr
Main world reserves [9]	China 34 % Vietnam 17 % Russia 16 % Brazil 16 %	China 34 % Vietnam 17 % Russia 16 % Brazil 16 %	China 34 % Vietnam 17 % Russia 16 % Brazil 16 %
Primary producer [10]	China 93 % UK 3 %	China 68 % Japan 18 % UK 6 % [11]	China 93 % UK 3 %
Main refinery producer [10]	China 99 %	China 99 %	China 99 %
Main uses [10]	Magnet 71 % Ceramics 12 % Catalysts 10 % Batteries 3 % Others 4 %	Magnet 99 %	Magnet 24 % Ceramics 15 % Batteries 12 % Metal alloys 11 % Autocatalysts 10 % Others 28 %
Worldwide production	35,000 tons	2500 tons	11,000 ktons

commercially available PMs and are therefore the dominant technology in applications requiring high power density and compact design [1,6,12]. However, their production entails substantial environmental impacts associated with REE extraction and refining, as well as a high supply risk due to strong geopolitical dependency. China currently supplies about 80 % of global REE demand, due to its large reserves and dominant refining capacity [5,13–16].

As a result, all 17 REE are listed by the European Union as critical raw materials (CRMs) due to their high economic importance and a high supply vulnerability [13]. Ensuring long-term availability therefore requires mitigation strategies such as recycling and recovery from technological and industrial waste, especially considering the rapid expansion of the EV and wind energy sectors, which are expected to drive an annual growth of approximately 18 % in NdFeB demand [13,14,17,18].

On the other side, non-RE PMs are dominated by ferrites, primarily composed of iron oxide. Ferrites can be classified by structure (spinel, garnet, orthoferrites, and hexagonal ferrites) [19], or by magnetic behaviour (soft, semi-hard, and hard ferrites) [20]. PMs belong to the class of hard ferrites, specifically with a hexagonal structure (hexaferrites), made of ceramic with ferric oxide (Fe_2O_3) doped with strontium (Sr), barium (Ba), or lead (Pb). These materials have been used for decades in electric machines [5]. Despite they exhibit lower magnetic performance than RE-based magnets, ferrites remain widely adopted due to their low cost, corrosion resistance and stable raw material supply [1]. They are well suited for cost-sensitive, mid-performance applications such as small motors, pumps, fans, speaker and household appliances [21,22]. Growing concerns over REE supply have further increased interest in ferrites as viable substitute in applications where their magnetic properties are adequate. Consequently, the demand for hexaferrite is expected to increase in the coming years [23]. The global hexaferrite market, currently around $1.13*10^6$ tons per year, is dominated by Asia (~ 40 %), followed by North America and Europe, reflecting industrialization patterns [15,22,24–26]. Market forecasts predict an average annual growth rate of about 5.2 % by 2031 [26,27].

Research on PMs has expanded significantly over the last ten decades, driven by the need for high-performance materials for clean energy technologies. Several reviews have examined the main aspects of PM processing, including production, additive manufacturing, and recycling. Regarding synthesis routes, the literature covers both chemical approaches [28,29] and advanced metallurgical techniques [30,31]. Recent low-energy processing and nano structuring methods, such as cold sintering, flash sintering and high pressure torsion, have also been explored for hard ferrites [22]. In the field of additive manufacturing, multiple reviews have documented technological advances aimed at improving PMs density and coercivity [27,32–35]. Recycling represent another major research focus, particularly for NdFeB magnets, which are central to sustainability and CRMs supply-security strategies [6,14,36,11,37–39]. Overall, most reviews focus predominantly on NdFeB magnets, while developments in hard ferrite are discussed mainly in the context of identifying viable alternatives to RE-based PMs [22,40]. Beyond synthesis, manufacturing and recycling, several studies have also assessed the environmental implication of PM technologies through life cycle assessment (LCA), highlighting the importance of resource efficiency and sustainability in magnet development [41–43].

In recent years, the European Union has supported several research initiatives to reduce dependence on critical REE and strengthen industrial resilience [44]. Ongoing projects explore the development of new RE-free materials (REFMAG, CoCoMAG) [45,46], innovative and more sustainable production technologies (GREENE, MagNEO, MAG-TOOL) [47–49], and advanced recycling solutions (MAGELLAN, HARMONY, REEcycle, GYROMAGS) [50–53]. Within this framework, the EU-funded PASSENGER project adopts an integrated approach to reduce reliance on CRMs by developing and implementing RE-free magnets in components widely used in mobility and household sectors (e.g. compressors, fans, wiper motors, and pumps). These components generally have shorter operational lifetimes than the systems they serve, generating a mismatch that limits overall resource efficiency a [21]. Sintered ferrite magnets represent one of the most promising alternatives due to their technological maturity, scalability and compatibility with existing manufacturing and recycling infrastructures [21,23].

Recent comparative LCA show that the replacing of RE-based magnets with sintered ferrite can reduce key environmental impacts, such as global warming potential, ozone depletion and human toxicity, by more than 90 % [22,54].

Despite the growing number of reviews on PM, the literature still lacks a comprehensive overview of technological innovation trends, dealing with the recycling of both RE-based PM and ferrites. To address this gap, the present review, adopting the approach of Amato & Beolchini, combines scientific literature with an in-depth analysis of available patents, which serve as a valuable indicator of the technological activity [55]. Moreover, the effect of the substitution of RE-based PM with ferrites is quantified, applying a material flow analysis, focusing on the PM application to the e-mobility sector within the European context. Our outcomes are highly relevant to improve the awareness in the management of the PM value chain, in line with the broader European objectives to secure CRM supply and reduce environmental impacts, as laid out in the Critical Raw Materials Act [13].

2. Material and methods

With the aim of investigating the state of the art this review is organized considering the different recycling techniques applied to the 2 main type of PM, NdFeB or ferrite magnets, as reported in the roadmap in Fig. 1. In more details, chapter 3 focuses on the main recycling strategies for NdFeB PM and ferrite magnet, based on the literature analysis, taking into account direct recycling of magnets and metals extraction from waste. Chapter 4, on the other hand, analyses technological innovation, based on published patents, to understand emerging markets by examining how new inventions are adopted and diffused. More specifically, analysis of the most recent technologies of the last 5 years (2021–2025) for metal recovery from PM, was performed using the international free access Espacenet platform [56]. The analysis was conducted applying an advanced search query that combined specific patent classification codes (CP) for RE PM (H01F1/053), rare metal recovery (C22B59/00), together with technical keywords such as “recycling” or “recovery” and “NdFeB” or “neodymium iron boron” for NdFeB PM magnet and “ferrite magnet” combined to “recycling” for ferrite magnet. Chapter 5 provides a synthesis and critical discussion of the recycling technologies for PM, drawing together the key trends identified in the literature. Furthermore Chapter 6 describes a material flow analysis (MFA) carried out with the aim of providing an important baseline of background information to better address the future criticality of

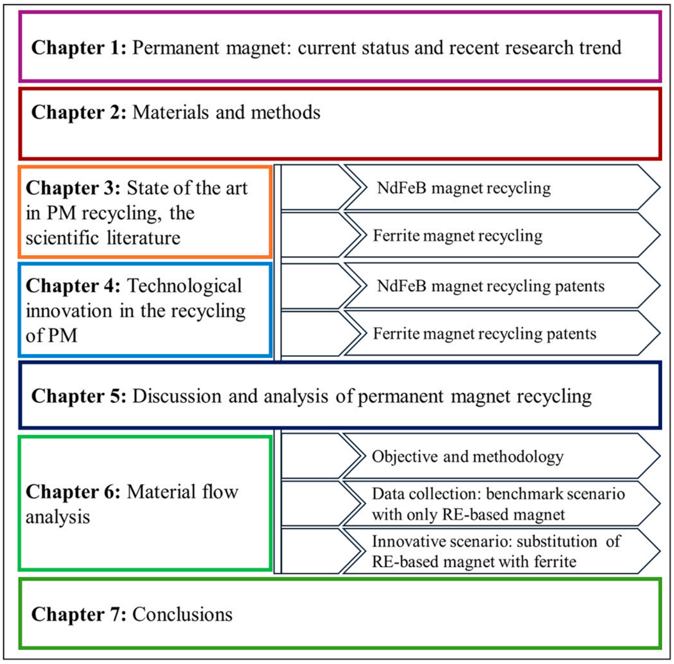

Fig. 1. Chapters roadmap.

materials in the field of PM. In this context, the first phase of MFA aimed at the identification of the scenarios to study, including the choices of the target elements, the PM life steps and the temporal geographical boundaries to include in the analysis. The collected data are showed with Sankey diagrams, built by the support of the free software STAN 2.7, developed at the Research Unit for Waste and Resource Management at TU Wien. More in detail, STAN allows the building of graphical models by using predefined components (processes, flows, system boundary, text fields).

3. State of the art in PM recycling, the scientific literature

In recent years, the rapid growth of high-tech industries and renewable energy application has led to an increasing demand for PM, which results in large volumes of production scraps and EoL products. Therefore, the environmentally friendly and efficient recycling of PM has become a growing research hotspot.

3.1. NdFeB magnet recycling

NdFeB magnets are primarily found in very recent products, which are not yet significantly present in current scrap streams, but will constitute the waste of the future. The growing attention for the development of efficient recycling methods is confirmed by Kumari and Sahu (2023), which reported 300,000 tons of REE stockpiled worldwide (considering all the magnet applications) [11]. Overall, the preliminary issue of spent magnet enhancement chain is the dismantling before crushing, since the recycling operations could cause the REE loss within ferrous or nonferrous scraps. The experimental approaches for REE recovery from magnets can be classified in: direct recycling of magnets and metal extraction from waste (pyrometallurgy, hydrometallurgy, electrometallurgy and biohydrometallurgy) [6,11,39].

3.1.1. Direct recycling

EoL magnets can be restored and used again, with the aim of maintaining the magnetic properties of PM, which can be deteriorated by excessive heating or oxidation [6,11]. This process, known as direct recycling of spent NdFeB magnets, "*magnet to magnet*", is suitable for clean and non-oxidized magnets and scraps [57]. The EoL magnets can be demagnetized by temperatures ranging between 300 and 500°C, and re-magnetized after cooling, but the effectiveness of the treatment decreases with increasing temperature and worsens in presence of air [58]. Furthermore, the EoL magnets can be remelted and re-casted into a master alloy. The oxygen level, which represents a drawback for the implementation of direct recycling at larger scale, since it causes the reduction of NdFeB magnets performance, can be reduced by induction-melting [59]. However, this method suffers from a 20–30 % efficiency loss [11,39]. Another process is the hydrogen decrepitation (HD), in which the hydrogen gas penetrates the spent magnets and fractures them into fine powder. By vacuum sintering at temperatures above 1000°C, the powder material is transformed into a sintered magnet and then adjusted in a suitable magnetic field [60–62]. The problem deriving from this technique is a decrease in the magnetic properties, compared to the fresh magnets [11,39]. HD was also tested in combination with Hydrogenation-Disproportionation-Desorption-Recombination (HDDR) process. The powder deriving from HD step is heated at high temperatures (around 800/900°C) under hydrogen pressure to reform a powder of finely divided Nd, Fe, B grains. This resulting powder can be used directly to produce resin-bonded magnets, with different magnetic properties [62–67]. Significant variability can occur, posing a challenge for large scale implementation [11].

Direct recycling methods for NdFeB magnets have shown partial success, and they are considered as the most cost-effective methods, since they do not require chemicals, and do not generate waste. Although most scientific studies focus on processes developed at laboratory scale, a few technologies are already implemented at the industrial scale. For example, HyProMag uses HD to recover magnets in powder form [68], while Noveon Magnetics has developed a direct recycling process, in which EoL magnets are crushed and reprocessed to produce new NdFeB magnets, without separating the individual elements [69]. However, they are only feasible for large and easily accessible magnets and restoring the full magnetic performance remains challenging. As a result, industries still prefer virgin materials, prompting growing interest in REE recovery from spent magnets, through either pyrometallurgical or hydrometallurgical techniques.

3.1.2. Pyrometallurgy

Pyrometallurgical methods are based on high temperature exploitation to recover REE in the form of alloy or mixed compound, which require further purification [6]. The main pyrometallurgical processes, reported in the literature, for the recovery of REE from spent NdFeB magnet are limited to a laboratory scale, and can be divided in (Table 2):

Table 2
Different pyrometallurgical processes for REE extraction.

References	Operating conditions	Process efficiencies
Liquid metal extraction		
[73]	Mg extraction through temperature gradients	98 % Nd
[70]	Mg extraction at 1000°C	97 % Nd
[71]	Mg extraction at 830°C	80 % Nd
[72]	Ag extraction at 1000°C	90 % Nd
Molten salt extraction/ selective chlorination		
[74]	Molten $MgCl_2$ – KCl salts at 1200°C under argon atmosphere	93 % REE
[75]	Molten LiF-NdF_3 salts at 1230°C for 72 h, electrolysis	Complete extraction of REE
[76]	$MgCl_2$ chlorination at 1000°C	80 % Nd and Dy
[77]	$FeCl_2$ chlorination at 1000°C	96 % $NdCl_3$, 94 % $DyCl_3$
[78]	NH_4Cl chlorination at 250–350°C	90 % $NdCl_3$
[79]	NH_4Cl chlorination at 285°C	84 % REE
Glass slag method		
[80,81]	Molten B_2O_3 at around 1377°C	Nd in final alloy $<$ 0.01 wt% and in the glass slag $>$ 25 wt%
[82]	FeO-B_2O_3 flux at 1300 °C	99.5 % REE oxide
[83]	CaO-SiO_2-Al_2O_3 slug systems at 1500°C	99 % REE

– Liquid metal extraction, where NdFeB magnet is immersed in a liquid metal (such as Mg) and the REE dissolve into the metal, producing an alloy and leaving Fe and B in the solids. After dissolution the liquid metal containing REE is mechanically separated and distilled to recover concentrated REE residues [70–73]. This approach is suitable for non-oxidized magnets and allow the direct extraction of pure REEs in metallic state. The main drawbacks are the high temperature and long reaction time, which cause high costs and energy consumption [37].
– Molten salt extraction, where NdFeB magnets are treated with molten salt (such as chlorides and fluorides) at high temperatures. REE form soluble compounds which can be recovered by distillation or electrolysis in metallic form [72,74,75]. Similarly, selective chlorination, in which magnets are exposed to chlorinating agents at high temperatures, allows volatile or soluble complexes to be formed which can be distilled [76–79]. These methods can be applied to both oxidized and non-oxidized scraps or magnets and allow a recovery of master alloys with efficiencies of 90 %. Anyway, they lead to the production of molten salts or toxic gases that must be managed, in addition to the problems related to the use of high temperatures.
– Glass slag method, where the oxidized scraps or shredded magnet residues are melted at high temperatures with glass flows. REE are selectively oxidized and incorporated into the glass phase (slag), while Fe forms a separate metal phase. After cooling the slag is crushed and leached, e.g. with sulfuric acid (H_2SO_4) to recover REE [80–83]. This process requires temperature higher than the others (around 1300–1500°C), to be applied in suitable plants with ovens and the management of large volume of slags, but allows to obtain high REE extractions in a single process and an effective separation of Fe [37].

Overall, the main drawbacks of pyrometallurgical processes are: high energy requirements to maintain temperatures above 1000°C, high costs due to reagents consumption, slag productions and complexity of the operational set-up [6] On the other hand, pyrometallurgical processes are applicable to all types of magnet compositions, require less steps than hydrometallurgical processes and avoid wastewater generation [6,37].

3.1.3. *Hydrometallurgy*

Hydrometallurgy offers the advantage to recover individual REE with high purities, less energy demand and lower gas pollution than pyrometallurgy. These techniques rely on the same processing steps used for the extraction of raw RE and are applicable to all types of magnet compositions [37].

Several hydrometallurgical techniques are reported in the literature, such as direct leaching, oxidative/chlorination/sulfation roasting leaching, organic acid leaching, ultrasound and microwave assisted leaching, for a wide range of NdFeB feedstocks (Table 3).

Direct leaching of magnets, followed by solution purification by iron precipitation, was used to recover critical RE metals from NdFeB magnets (mainly oxidized NdFeB magnets, spent magnets and oxidized powder) in several studies [84–89]. Although REE recoveries were reported to be high, the direct leaching process uses considerable amounts of acid and other chemicals during the leaching and iron removal steps. The discharge of acidic effluents is considered the major drawback of the processes, which could have a negative impact on the environment [37]. The development of selective leaching processes led to the avoidance of a separate iron removal step by selectively leaching RE from the NdFeB magnet [11]. Among them it was investigated the roasting at different temperatures as pre-treatment to the leaching process conducted with different agents, such as nitric acid (HNO_3), hydrochloric acid (HCl) or H_2SO_4, to selectively separate and recover the desired elements [92,93,95,96,90,97]. These techniques enable the processing of magnetic or roasted scraps, NdFeB powder and bulk spent magnets [92,93,95,96,90,97]. Hydrometallurgical processes were investigated also with organic acids, with or without previous roasting, on oxidized magnets and powders. The use of organic acids offers less environmental impact compared to mineral acids [100–106]. Furthermore, in recent years, ultrasound and microwave assisted leaching methods emerged as advance techniques to combine the reduction of reaction time and energetic consumption with high REE leaching efficiencies. More in details, ultrasound assisted leaching exploits the acoustic cavitation, which increases the solid-liquid contact surface improving dissolution [11,107,108]. On the other hand, microwaves allow a direct and uniform heating of scraps, which can be useful also as a pre-treatment technique. In this regard, Fironda et al. (2025) successfully combined the liquid metal extraction with microwave technology, resulting in 97 % of Nd recovery [110]. These techniques are reported for the processing of NdFeB powder and shredded spent magnets. The study of Emil-Kaya et al.

Table 3
Different hydrometallurgical techniques for REE recovery from NdFeB magnet.

References	Operating conditions	Process efficiencies
Direct leaching		
[84]	3 M HCl/H_2SO_4 at 27°C	96 % REE
[85]	4 M HCl at 40°C	99 % REE
[86]	0.4 M acetic acid at 80°C	99 %, high percentage of Fe
[87]	6 M HCl and 50 g/L tartaric acid at 40°C	99.3 % REE, 68 % Fe
[88]	1 M HNO_3 and 0.3 M H_2O_2 at 80°C	98 % Nd, 81 % Dy, 15 % Fe
[89]	1.3 M $(NH_4)_2S_2O_8$ at 75°C	98 % Nd
[90]	2 M H_2SO_4 at 50°C	95 % Fe
[91]	1 M H_2SO_4 at 70°C	99 % REE
Roasting + acid leaching		
[92]	Roasting at 800°C, leaching with 5 M HCl at 95°C	78 % Nd, 83 % Pr 76 % Dy
[93]	Roasting at 750°C, leaching with 14.5 M H_2SO_4 at 25°C	98 % REE, 0.02 % Fe
[94]	Roasting at 700 °C, leaching with $Fe_2(SO_4)_3$ at 25°C	96 % Nd, 99 % Pr, 0.01 % Fe
[95]	Roasting at 300°C, water leaching at 95°C	99 % REE, 99 % purity
[96]	Roasting at 950°C, leaching with 5 M HNO_3 at 80°C	> 95 % REE
[97]	Roasting at 800°C, leaching with 0.6 M HCl at 180°C	99 % REE, 97 % B, 0.1 % Fe
[98]	Roasting at 950°C, leaching with 0.5 M HNO_3 at 180°C	95 % REE, 0.3 % Fe
Roasting + organic acid leaching		
[99]	Roasting at 400°C, leaching with 1 M acetic acid at 90°C	94 % Nd, 93 % Dy, 1 % Fe
[100]	Roasting at 200°C, leaching with versatic acid 10 at 60°C	98 % REE
[101]	Roasting at 350°C, leaching with 1.6–10 M acetic acid at 60°C	90 % REE – not selective
[102]	Roasting at 400°C, leaching with 1 M glycolic/maleic at 25°C or 1 M ascorbic acid at 70°C	95 % REE
Organic acid leaching		
[103]	2 M oxalic acid at 90°C	93 % RE-oxalate, 94 % Fe
[104]	0.2 M HCl and 0.25 M oxalic acid at 25°C	95 % REE
[105]	1 M malic acid at 90°C	99 % REE
[106]	2.5 M citric acid 2.5 M at 25°C	89 % REE
Ultrasound/microwave assisted leaching		
[107]	Ultrasound and microwave assisted leaching with 0.4 M acetic acid, power 90 W	98 % REE
[108]	Microwave exposure (power 90 W) followed by leaching with 0.5 M HCl at 70°C	98 % Nd, Dy
[109]	Ultrasonic-assisted water leaching (power 60 W) followed by solution combustion at 200°C	98 % REE
[110]	Microwave-assisted liquid metal extraction with Mg, at 800°C	97 % Nd
Deep eutetic solvents		
[111]	Ethylene glycol-maleic acid DES leaching	97 % Nd, 0.8 % Fe
[112]	Tetraethylammonium chloride-levulinic acid DES leaching	98 % Nd, 0.4 % Fe

(2022) investigated the production of RE oxides by solution combustion synthesis as an alternative to conventional precipitation methods, to reduce the problems linked to conventional precipitation, such as loss of metals and reagents consumption. This process is based on the principle that an exothermic reaction initiated under heating undergoes self-sustained propagation. They presented a flowsheet for REE recovery based on first acid baking followed by ultrasound-assisted water leaching, production of RE oxides by solution combustion method, and calcination [109,113].

Overall, the main drawbacks of hydrometallurgical processes are related to the high consumption of chemicals, with the subsequent generation of large amount of wastewater, and the loss of RE during purification [6,11,37,114]. Furthermore, compared to the pyrometallurgical methods, these techniques require many steps before obtaining new magnets [6,37]. With the aim to increase process sustainability, Heo et al. (2024) propose an environmentally friendly alternative to inorganic acid using deep eutectic solvents (DESs) as leaching agents. Different solvents were tested combined with different pretreatment to increase the selectivity for REE. They reported that ethylene glycol (EG)-maleic acid (MA) DES displayed the highest leaching efficiency (97.3 % Nd and 0.8 % Fe) with NaOH digestion or NaOH digestion–roasting as pretreatment and the solvent could be reused twice, maintaining the efficiency [111]. As an alternative, Shuping et al. (2025) applied a novel tetraethylammonium chloride (TEAC) and levulinic acid (LA) DES, with a wide working temperature range, resulting in superior Nd/Fe separation performance and maintained leaching efficiencies after recycling 3 times [112]. This method can promote the sustainability of RE recycling processes, avoiding strong acid consumption and wastewater generation.

3.1.4. Electrochemical extraction

Electrochemical methods are based on the use of shredded spent magnet as an anode in an electrochemical cell (Table 4). These methods were proposed to limit the co-dissolution of Fe and REE: indeed, during hydrometallurgical processes, Fe leaches into the solution as Fe(II), which is stable at pH 6 and it is difficult to remove by precipitation, decreasing the selectivity for REE [115]. NdFeB magnet scrap can be used as an anode in an electrolytic cell with high-temperature molten salts, where RE metals dissolve as ions. These are then reduced to the cathode and recovered as metals or alloys, avoiding the use of strong acids [38,116,117]. Otherwise, the anodic dissolution selectively releases Nd, Pr and other REE into the electrolyte which can be recovered by precipitation or other chemical treatments. This technique avoids high temperatures, reducing the environmental impact compared to traditional techniques and allows the selective recovery of REE [6, 118–122].

Wet electrochemical leaching has the advantage of being a simple to implement and easily scalable technique, operable at room temperature and, if optimized, allows a selective recovery of both REE and Fe. However, it requires high acidity, with environmental implications [6, 115].

A novel circular electrochemical method for the recovery of REE was developed by Haque et al. (2024), ensuring 90 % recovery rates for Nd, Pd and Th, whit no Fe co-precipitation. The magnets were firstly leached in 2 M H_2SO_4 at room temperature and then separated as double salt precipitates with the addition of sodium sulphate. During the process, 77 % of Fe was removed for the leachate by electrooxidation or reduction, and the resulting solution with low Fe and Dy concentration can be recirculated to the dissolution phase of the magnet [123].

The closed loop recycling allows REE recovery coupled with Fe electrowinning and acid recycling and do not require further Fe oxidation as an additional step for Fe removal, with potential improvement in terms of recovery and energy consumption. Anyway, the simultaneous oxidation and reduction of Fe makes it difficult to implement the system at a larger scale [123].

More recently, Venkatesan and colleagues (2025) obtained more than 90 % REE recovery in a three chambers electrochemical reactor by combining extraction and purification in the same reactor. In this process they obtained the acid from its salts, without any acid addition. Fe was removed during electrolysis in the anolyte compartment, while RE cations were recovered as RE hydroxides in the catholyte compartment. The subsequent calcination of RE oxides produced pure REE [124]. Compartment systems allow physical separation between anode and cathode, have high selectivity and require less use of external chemicals. In particular, the process without the addition of external acid is more sustainable, with no wastewater production. The main drawbacks is that they are more complex and expensive to be implemented and less suitable for solid waste with impurities [6,115,124].

Table 4
Different electrochemical techniques for REE recovery from NdFeB magnet.

Refereces	Operating conditions	Process efficiencies
Molten salt electrolysis		
[116]	Electrolytic cell with molten salts LiCl-KCl (50–50 %) at 600–850°C	Not reported
[117]	Anodic dissolution in LiCl-KCl salts at 450°C, selective recovery via electrolysis	Not reported
[38]	RE converted into fluorides with fluorinating agents, dissolved in LiF salt and electrolyzed at 950°C	Complete extraction of REE
Leaching with HCl		
[118]	Leaching with 1.2 M HCl followed by in-situ electrochemical oxidation at 25°C. Selective precipitation with oxalic acid and calcination	99 % pure REE
[119]	Electrolysis pretreatment step, followed by leaching with 0.14 M HCl at 25°C. Precipitation with oxalic acid and calcination	99 % REE
[115]	Partial leaching with 0.1 M HCl followed by electrodeposition at 25°C. Selective precipitation with oxalic acid.	99 % pure REE
Leaching with H_2SO_4		
[120]	Electrochemical leaching with 0.25 M H_2SO_4 and oxalic acids at different current densities	> than chemical leaching (70 %)
[123]	Leaching with 2 M H_2SO_4 at 25°C followed by Fe electrochemical reduction. Selective precipitation with Na_2SO_4 and NaOH	99 % REE
Leaching with HF		
[122]	One-step precipitation in HF acid followed by Fe recovery by electrodeposition.	Not reported
Leaching with organic acid		
[121]	Electrochemical dissolution in 0.5 M citric acid at 25°C	Mixed RE oxides 99 % purity
In-situ electrochemical leaching (no acid addition)		
[124]	Electrochemical recovery of REE hydroxides in 3 compartment reactor by obtaining acid from its own salt at 25°C	REE > 95 % 99 % Fe removal

3.1.5. Biohydrometallurgy

Microorganisms such as bacteria, fungi and algae offer an environmentally friendly and cost-effective approach for the recovery of REE, due to their ability to thrive in extreme environments [125,126]. These microorganisms interact with REE through various biologically mediate processes, exploiting their metabolic activity to mobilize metal ions from the solid to the liquid phase [125]. During bioleaching the microorganisms convert insoluble metal compounds into soluble forms through biological oxidation and complexation, generating Fe(III) ions that concentrate at the interface between the material and the microbial cell, enhancing metal leaching [126]. In particular, the production of organic acids by heterotrophic microorganism not only facilitates REE solubilization but also decreases pH, creating favourable conditions for microbial survival in harsh environments [11,125]. Since these bio-based methods rely heavily on microbial metabolism, maintaining cell viability is essential for achieving high REE recovery, and factors such as medium composition, pH and temperature must be carefully optimized, particularly for large-scale industrial applications [125]. This process results to be more sustainable than pyro-hydrometallurgical method as avoids the energy-intensive pre-treatment steps, like roasting, and the usage of toxic chemicals [126].

Several studies have investigated the bioleaching of REE from a wide range of industrial and electronic waste materials, such as acidic solutions, red mud, coal fly ash or REE concentrates, using various type of microorganisms. These processes exploit several microbial mechanisms, including acidolysis, redoxolysis and complexolysis.

In acidolysis, microorganisms such as *Aspergillus niger (A. niger)*, *Penicillium sp* and sulphur-oxidizing bacteria produce organic and inorganic acids that dissolve REE [127,128]. Redoxolysis involves the oxidation of Fe(II) or elemental sulphur, generating an acidic environment that facilitates metal mobilization, and it is typically performed by *Acithiobacillus ferroxidans (A. ferroxidans)* and *Leptospirillum ferroxidans (L. ferroxidans)* [126,129,130]. In complexolysis, ligands or organic acids produced by fungi or heterotrophic bacteria form stable complexes with REE, promoting their solubilization [131–136].

These studies highlight the wide variety of microorganisms and mechanisms that can be applied to RE bioleaching from several electronic waste. However, to the best of our knowledge, only one work has focused specifically on the recovery of REE from NdFeB magnets. In more details, Auerbach et al. (2019) proved the feasibility and scalability of EoL magnets leaching with different type of bacteria [126]. They reported the highest leaching efficiencies (86 % Dy, 91 % for Nd and 100 % Pr) achieved by *A. ferrooxidans* and *L. ferrooxidans*. They tested different magnet alloys and particle sizes, reporting that the investigated process was feasible without losses in efficiency for different alloys, comparable to a chemical leaching.

3.2. Ferrite recycling

The advantages of ferrite compared to NdFeB magnets are related to their practical applications. The raw materials for ferrite synthesis are more abundant and cheaper, guaranteeing a reduced environmental impact in the extraction processing route. Furthermore, ferrite magnets are electrical insulators, chemically inert and have no corrosion issues, largely reducing operational costs [137].

Despite the growing interest and importance of ferrite magnets there is a lack of studies in the literature dealing with the possibility of recycling the EoL products. Ferrite magnet recycling is still limited to a few experimental demonstrations, almost exclusively based on direct physical reprocessing (closed loop) of manufacturing scraps [138]. Usually, scraps are re-used for further applications which require lower technical performance than PM. These processes apply conditions comparable to those used for primary ferrite magnet manufacturing and do not require chemicals addition. [137].In this regard, Bollero et al. (2017) worked on the recovery of residues from cutting machines used to shape magnets into strontium ferrite, which contains ferrite, water and coolant. This residue is treated by a calcination process in air at 1000 °C, either in a tubular furnace or, for comparison, in an industrial muffle, to evaluate the properties after heat treatment. Their results showed that the treatment increased remanence and coercivity, which resulted higher than the material purchased for magnet production [137].

Due to the absence of RE metals and the lack of valuable materials, pyro- and hydrometallurgical techniques have been less investigated. A leading global manufacturer of high-performance PM (Arnold Magnetic Technologies) reported that the limited efforts in ferrite recycling are due to the low commercial value of recovered raw materials which cannot offset the recovery cost [138].

Although the hydrometallurgical route does not find wide industrial application due to the high costs compared to the limited value of recoverable materials, some academic studies have explored its potential. Li et al. [139] proposed a recycling process combining H_2SO_4 leaching, reduction, purification and co-precipitation with traditional ceramic route (pre-sintering (850 °C), doping (Mo, Bi, Sn), sintering (1320 °C)) to process the Mn–Zn ferrite wastes. Through this method, most of Fe, Mn and Zn in the ferrite waste were recycled. The Mn–Zn ferrite prepared from waste by this route showed broader frequency characteristics, higher resistivity, lower loss coefficient and temperature coefficient as compared to the traditional product. Moreover, the technology offers a cost advantage over the traditional process. An industrial scalable process, which present a recycling method for strontium ferrite magnets from EoL household appliances, was proposed by Berja et al. (2025). This treatment is based on a wet milling step followed by annealing at a temperature of 900°C, which produces recycled powders for new bonded magnets manufacturing. They reported that the heat treatment at high temperatures (900–1000 °C) recovers magnetic properties, ensuring coercivity, remanent polarization and maximum energy product comparable to commercial ferrite bonded magnets [23].

Overall, ferrite recycling techniques have demonstrated their technical feasibility, but economic and operational challenges limit their large-scale application.

4. Technological innovation in the recycling of PM

Several scientific approaches have been applied into patent-protected processes, confirming their technological maturity and relevance. Patents analysis led to the identification of 268 patents related to the recycling of NdFeB magnets, confirming a strong interest in this topic. In comparison, the number of patents related to ferrite recycling was lower (78), but still significant.

4.1. NdFeB magnet recycling patents

In the case of patents related to the recovery of NdFeB magnets, a classification was carried out based on the employed technology. The initial query was refined by adding the clause “AND (hydrometallurgy OR leaching OR acid OR aqueous OR solvent extraction)” to search for hydrometallurgical processes and “AND (pyrometallurgy OR smelting OR roasting OR furnace OR calcination OR high temperature)” for pyrometallurgical processes. The results showed 246 patents related to hydrometallurgy (out of a total of 268) and 201 related to pyrometallurgy. However, this classification applied by Espacenet is affected by variability since patent that do not explicitly mention “leaching” or “smelting” in searchable fields may be excluded, while some hybrid or very generic patents may appear in both sets. For this reason, 20 patents, among those marked as “most relevant” by the Espacenet platform using the initial query without specific references to the method, were analysed and examined to identify the type of approach used (Table 5). Pyrometallurgical processes category is represented by 3 patents among the most relevant invention, mainly based on smelting with high temperature. *US12043882B2* [140] describes a high temperature treatment with oxidation to convert NdFeB into oxides and *CN115612851A* employs melting, thermal treatment under inert atmosphere and sintering [141]. *CN112553482A* combine oxidation, calcination and roasting with high temperature CO to selectively reduce Fe and to maximize REE extraction [142].

The dominant category was represented by hydrometallurgical processes with 14 patents falling into this category. Among them, *WO2024241335A1* describes a low-acid consumption process for the selective dissolution of REE through aeration, followed by precipitation with oxalic acid [143]; *CN113846221A* proposes an electrochemical recovery method in an acidic environment with subsequent REE precipitation [144] and *WO2024145995A1* exploits phosphoric acid and subsequent oxidation to separate Fe from REE [145]. On the other hand, *CN115537563A* exploits organic acids as an alternative to aggressive inorganic acids [146]. Patent *CN112375914A* [147] integrates oxidation, acid dissolution and multi-stage extraction, while patents *CN113584329A, CN112813269A, CN214496440U* and *CN113667823A* develop plant-scale or liquid-liquid separation technologies for controlled and cyclic extractions [148–151]. Patents *CN113667824A, CN113652539A, CN113652540A, CN113667819A* and *CN113667822A*, describe a similar approach that involve a key high-temperature

Table 5
Summary of the 20 most relevant patents for REE recovery from NdFeB magnet.

References	Number	Operating conditions
Pyrometallurgy		
[140]	US12043882B2	Oxidizing and heating NdFeB powder to produce oxide phase high-temperature solid-state conversion
[141]	CN115612851A	Smelting, thermal treatment under inert atmosphere, sintering and cooling
[142]	CN112553482A	Oxidation and calcination of NdFeB wastes, followed by selective reduction with high temperature CO. Fe is recovered as a high purity metal, RE are enriched in solid residues
Hydrometallurgy		
[143]	WO2024241335A1	Aeration leaching and REE precipitation using oxalic acid
[144]	CN113846221A	Electrochemical recovery in acidic electrolyte
[145]	WO2024145995A1	Leaching with phosphoric acid
[146]	CN115537563A	Organic acid leaching
[147]	CN112375914A	Acid extraction followed by hydrogen decrepitation and coating
[148]	CN113584329A	Recovery from three-phase extraction residues
[149]	CN112813269A	Dissolving solution extraction system with mixing and magnetic suspension adsorption
[150]	CN214496440U	Feed liquid extractor for controlling high-fluorine and high-cerium REE waste streams
[151]	CN113667823A	Sodium ferrate-based separation of Fe and REE using oxidation, water leaching and potassium hydroxide treatment
[152]	CN113667824A	Oxidation and roasting of NdFeB waste with additives, metals form oxides, RE oxides dissolve in dilute acid
[153]	CN113652539A	Roasting with calcifying agent, RE-oxide leached out through a leaching agent
[154]	CN113652540A	Roasting of NdFeB waste with additives, metals form oxides, RE oxides dissolve in dilute acid
[155]	CN113667819A	Roasting with zincing agent, RE-oxide leached through the dilute acid
[156]	CN113667822A	Roasting with magnetizing agent, RE-oxide leached with acid
Mechanical/process		
[157]	CN216550634U	Multi-stage device with leaching, stirring, extraction and clarification chambers
[158]	CN214881756U	Automated rust removal and recovery device for NdFeB waste magnets
[159]	CN112807768A	Filter press with dual-layer filtration structure; water separation through plate compression

treatment that chemically modifies the phases present (REE into oxides), followed by a targeted acid leaching step aimed at recovering the REE that have already been made soluble by thermal step [153–156,152].

Furthermore, 3 of the considered patents propose plant or mechanical setups to automate the recycling process. More specifically, *CN216550634U* proposes a modular multi-stage plant for leaching, filtration and extraction [157]; *CN214881756U* and *CN112807768A* include machinery for rust removal or filtration system with stacked pressure structures [158,159]. Even among the patents already classified as hydrometallurgical, patent *CN214496440U* claims a dual-phase extraction device with fluoride and cerium control and *CN112813269A* proposes a closed-loop circulation and separation system with magnetic adsorption [149,150].

The analysis of 20 of the most relevant patents, according to Espacenet, reveals a trend toward hydrometallurgy as the preferred approach for recycling NdFeB magnets, mainly for the easiest scaling up. Nevertheless, pyrometallurgical processes remain in use, particularly for magnets difficult to disassemble. Hybrid approaches and plant or mechanical solutions complete the picture, pointing to an increasingly sustainable industrial direction. Overall, the patented technologies reflect an evolution toward more sustainable, flexible processes adapted to the circular economy pillars.

4.2. Ferrite magnet recycling patents

Similarly, 20 out of 78 patents related to ferrite magnet recycling, identified as the most relevant to the query according to Espacenet platform, were analysed (Table 6). These 20 patents address topics related to the recovery, treatment and recycling of ferrite magnetic materials, and can be grouped into four main categories. The dominant category was represented by recovery and recycling of waste ferrite magnets, which includes 8 patents addressing the efficient recycling of ferrite waste. Patents *CN219702184U* and *CN212736484U* introduce structured systems for recovering ferrite scraps, ranging from magnetic sheets to green bodies, by removing impurities, drying and reclassifying materials to maintain the performance [160,161]. Liquid waste recovery is also tackled in *CN213610233U* and *CN213708040U*, which enable water reuse and sludge drying for ferrite mud, minimizing environmental harm and reclaiming usable materials [162,163].

CN116833906A and *CN117549462A* offer more advanced recovery strategies for grinding residues and rubber magnets, using ultrasonic sieving and optimized crushing to ensure better quality and environmental safety [164,165]. On the other hand, *CN112280096A* [166] details the production of regenerated rubber magnets via microwave desulfurization and stepwise mixing, while *US11524904B2* explores the treatment of heavy metal sludge to produce ferrite magnets, offering a novel route for industrial waste valorisation [167].

Table 6
Summary of the 20 most relevant patents for REE recovery from ferrite magnet.

References	Number	Operating conditions
Recovery and recycling		
[160]	CN219702184U	Automated recovery of ferrite magnetic sheet waste using impurity removal, sanding, drying
[161]	CN212736484U	Collection of magnetic green body scraps in buffer-equipped compartments
[162]	CN213610233U	Cleaning water recovery with sedimentation and replaceable filters
[163]	CN213708040U	Sludge separation and drying with air pump and electric heater
[164]	CN116833906A	Ultrasonic sieving, drying, and ball milling of strontium ferrite grinding residue
[165]	CN117549462A	Internal mixing and mechanical crushing of rubber magnets
[166]	CN112280096A	Microwave desulfurization and staged mixing for rubber magnet regeneration
[167]	US11524904B2	Pickling of sludge, NaOH neutralization, ultrasonic-microwave drying
Production of sintered ferrite magnet		
[168]	CN114141518A	Crushing to 2–5 mm, direct sintering
[169]	JP2024052568A	Multi-step processing including temporary sintering, recycling and mixing recycled heat-processed body
[170]	CN116102344A	Use of silicon and calcium gluconate to improve crystal alignment and magnetization
[171]	CN116619538A	Smart mold for wet pressing of magnetic shoes with sensor-based QC and assisted demolding
Grinding and polishing		
[172]	CN213704050U	Grinding device with air cylinders, multiple blades and roller sets
[173]	CN216678377U	Dual roller grinding with return mechanism and filter plate
[174]	CN117444813A	Grinding and polishing of magnetic shoes with hydraulic push rod and water spray system
Other applications		
[175]	CN118950183A	Building muck treatment with crushing, drying, magnetic chip separation
[176]	CN116408903A	Waste plastic cleaning with automatic compaction and water flow-based drainage
[177]	CN117046247A	Flare gas recovery with portioned cylinder and auxiliary damping
[178]	CN220882493U	Manual cutting system with magnet-assisted waste collection drawer
[179]	CN118186989A	Ferrite magnet-based anchored in slope reinforcement system

Research and development in ferrite magnets is reflected in 4 patents describing methods and devices for their production, sintering and shaping [168–171].

Complementary technologies also emerge in raw material processing, with patents *CN213704050U*, *CN216678377U* and *CN117444813A* presenting improved grinding and polishing solutions that increase productivity and material uniformity, key factors when working with recycled powders [172–174]. The other 5 patents (*CN118950183A, CN116408903A, CN117046247A, CN 220882493 U* and *CN118186989A)* are related with ferrite, but they are not specifically focused on their recycle [175–179].

The analysis of the 20 most relevant patents on ferrite magnet recycling, as identified by Espacenet platform, reveals several notable trends. Most of the patents focus on technologies designed to recover production-related ferrite waste through system for collecting, separating, or crushing residual powders with the main aim to improve the ferrite magnet value chain. Absent from the current landscape are chemical or hydrometallurgical approaches capable of extracting metals, as well as strategies for recovering ferrite from EoL products such as motors, in line with the prevailing trends in the scientific literature.

5. Discussion and analysis of permanent magnet recycling

The recycling of NdFeB magnets represents a highly active research field, characterized by a broad and articulated body of literature covering the entire technological spectrum, from established technologies to emerging approaches. To date, the main techniques investigated for RE recovery rely on pyrometallurgical and hydrometallurgical processes, while in recent years increasing attention has been devoted to electrochemical methods and low-impact solutions, in line with principles of green chemistry and circular economy.

Based on the works analyzed in this review, clear temporal and geographical patterns emerge for different NdFeB recycling approaches. Pyrometallurgical methods have been studied since the early 2000s, showing a relatively constant temporal distribution (Fig. 2a) and a strong geographical concentration in China and Japan, reflecting the presence of consolidated metallurgical infrastructure (Fig. 2b). In contrast, hydrometallurgical methods exhibit a marked increase in scientific output starting from around 2015 (Fig. 2a) and a more global geographical distribution, with significant contributions not only from China and Japan but also from Europe (Fig. 2b). Interestingly, within hydrometallurgical research, a further geographical trend can be observed: European studies are predominantly focused on REE recovery using organic acids, whereas direct leaching approaches are more extensively explored in Asia.

Electrochemical methods, although less represented overall, follow a similar temporal trend to hydrometallurgical approaches, with increasing attention since 2015 and a global distribution, albeit with a higher incidence of European contributions, indicating a particularly strong innovation drive in this region (Fig. 2). Bio-hydrometallurgical approaches, on the other hand, have also been proposed for NdFeB magnet recycling, however their presence in scientific literature remains extremely limited, indicating an early-stage research field.

A similar geographical pattern can also be observed at the industrial level. China and Japan host the majority of mature industrial activities, often integrated into existing metallurgical value chains and largely based on pyrometallurgical or hybrid processes, which enable the treatment of large volumes and heterogeneous feedstocks (e.g. Hitachi Group, Dowa Holdings, Zhongxi Tianma New Material, Shenghe Resources Holding) [180–182]. Europe and North America, by contrast, display a more recent and fragmented industrial landscape, dominated by pilot and demonstration plants and startups, which tend to prioritize hydrometallurgical and short-loop solutions (e.g. Ionic Technologies, REElement Technologies, MP Materials) [183–185].

In contrast, the scientific literature on ferrite magnet recycling is considerably less developed than that on NdFeB magnets. Available studies mainly focus on powder regeneration techniques or specific process steps, rather than on comprehensive industrial recycling strategies, indicating that ferrite recycling is not yet a dominant topic within the literature on magnet circularity.

This difference between NdFeB and ferrite magnets is also evident analysing the evolution of patent families in the period 2021–2025, where a "patent family" is a set of patent applications, filed in different countries, that protect the same invention. Two metrics were analysed (Fig. 3a and b):

1)patent families per year (orange), which indicates how many groups of patents were published for the first time each year;

2)cumulative patent families (blue), which shows the total accumulation of patent families over time.

Considering NdFeB magnet (Fig. 3a), the number of patent families per year showed a relatively constant trend, ranging between 40 and 60 across the analysed years. However, the cumulative number shows a significant increase, rising from around 70 in 2021–268 by 2025.

For ferrite magnets the trend was more fluctuating (Fig. 3b), with peaks in patent activity in the odd-numbered years (2021 and 2023). Nevertheless, the constant cumulative growth indicates that this technology continues to attract interest and development. In both cases, the apparent drop in 2025 may be due to the time of the analysis, since the year was still ongoing, and the data were updated at July 2025.

Patent families are also a way to track and analyse the global spread of an invention's protection. Concerning the global distribution of patent families, for both categories of magnets there is a clear dominance of China. In more details, among countries associated with more than one

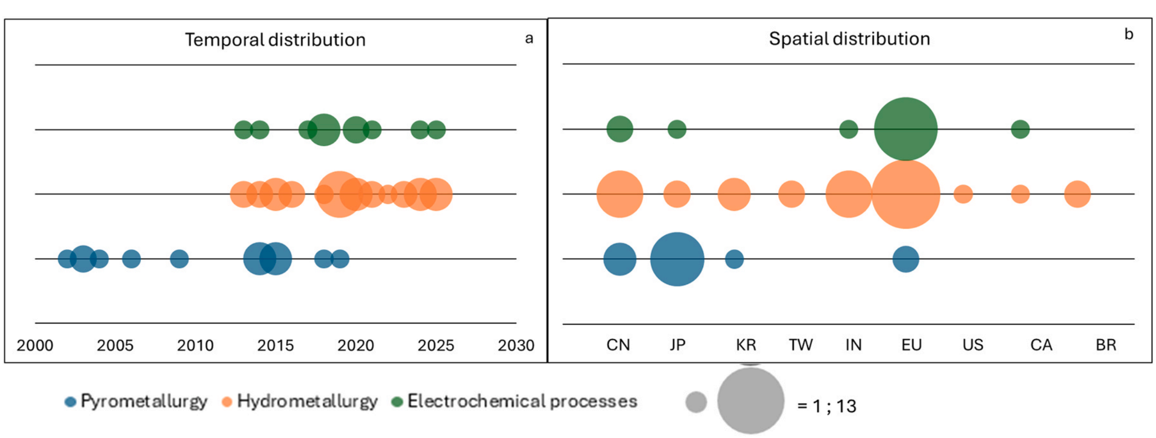

Fig. 2. Temporal (a) and spatial (b) distribution of the analyzed scientific literature on NdFeB magnet recycling.

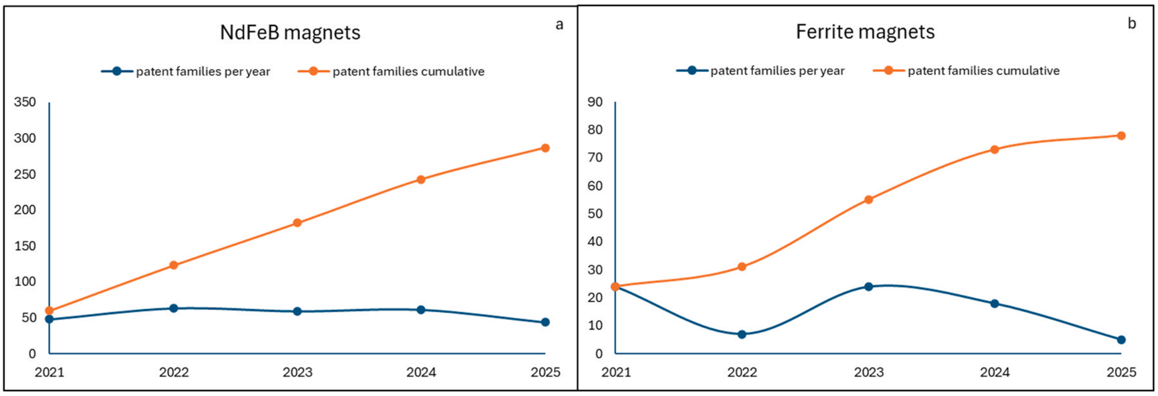

Fig. 3. Patent families per year and patent families cumulative for NdFeB magnets (a) and ferrite magnets (b), adapted from Espacenet platform Espacenet, [186].

patent family, for NdFeB magnets China (CN) leads with 200 patents, followed by WO, US, KR, EP, JP, AU, TW, DE, FR, CA and IL. In the case of ferrite magnets, patent distribution is less fragmented with China holding the monopoly (with 59 patents), followed by JP, KR, US, WO and EP.

Although the analyzed works represent a sample of the entire global literature, they provide a meaningful snapshot of the temporal and geographical evolution of NdFeB and ferrite recycling research and highlight consistent development trends across different technological pathways.

6. Materials flow analysis (MFA)

MFA is an excellent method to quantify material flows and stocks within a specific system. It applies the principle of mass conservation to trace the fate of matter throughout its entire life cycle in a given system and analyses the relationships among materials, human activities, and environmental changes [187]. Therefore, MFA is an important data provider for the identification of effective strategies of secondary raw material supply and the development of specific policies. It has the target to investigate the flows of valuable elements though the life of PM, to support the economy conversion with the emergence of new realities of industrial symbiosis, where the resulting flow from a facility becomes the raw materials from another one [188,189].

6.1. Objective and methodology

In this study, MFA was used as a supporting tool to estimate the potential benefits arising from the replacement of NdFeB magnets with ferrites. At the current stage, where substitution is still in the exploratory phase, this analysis provides a preliminary assessment that emphasizes the potential value of a transition in the magnet market, particularly in the context of high criticality in rare earth supply. Considering the multiple applications of RE-based magnets, this MFA focused on the technologies where the substitution is conceivable, choosing the results achieved within the European Project PASSENGER as reference. Indeed, the project goals include the improvement of ferrite performance, able to substitute the most common NdFeB magnets in specific applications (i.e. e-scooter, e-bike, e-motorbike, e-car, pump). The MFA results were represented by Sankey diagrams, in accordance with Schmidt (2008) [190]. To better understand the analysis output, some key terms were explained below:

- Goods, represented by the arrows in the diagrams, describe the flows of RE-based magnets in each considered product.
- Import and export of materials are indicated by the symbols 'I' and 'E'. Although not represented by proportional arrows, these symbols indicate the direction of flow across the system boundaries and are accompanied by numerical data for complete interpretation.
- Processes, represented by blocks, describe something which is changing in its quality (feedstocks become products and waste).
- Stocks, represented by a little block inside the process block, are the total amount of materials stored within a process at a given time. They are calculated as the difference between what enters and leaves the system in a certain interval of time.

A period of 10 years, between 2021 and 2030, was selected for the analysis. Some assumptions were considered:

- The market increase for each product was considered equally distributed among the considered ten-years period;
- The output flows were determined considering the estimated average lifetimes;
- Considering the key aspects of the young market and the longest lifetime of e-motorbikes, e-cars and pump drives, no output flows were reported up to 2027 for e-cars and 2030 for both e-motorbikes and pumps;
- No magnet material losses were considered in product production processes;
- A data error of 10 % was considered for all the estimated flows, considering the data variability observed on the available market information;
- The stocks in 2021 were estimated based on the following references: e-scooter [191,192], e-bike [193], e-motorbike [194], e-car [195], pump [196,197]. As concern the e-scooter, the estimation of the input flows and the stocks in Europe was based on the ratio between the number of e-scooter and the population reported in the literature for the Italian market.
- As concerns the pump stocks, a constant market in the previous 10 years was assumed, considering their application.

6.2. Data collection: benchmark scenario with only RE based magnets

The paragraphs below aim at explaining the information collected (divided in import, use and stock and export) included within the MFA related to NdFeB PM.

6.2.1. Import

In agreement with the application selected for PASSENGER technologies, the production processes include products from e-mobility sector. Since no magnet material losses have been assumed in the production processes, imports are estimated based on the weight of the magnet in the individual applications and on the quantities of that product sold over the years. The demand for year in these applications was evaluated as follows:

- *E-scooter.* The estimations reported an e-scooter number on European territory, in 2021, higher than 20 million with a growth forecast of

24.5 % between 2022 and 2029 [198]. Assuming an average magnet weight of 300 g (comparable with that in e-bikes), the REE consumption has been estimated around 2400 tons of Nd, 320 tons of Dy and 560 tons of Pr.

- *E-bikes and e-motorbikes.* According to the Confederation of the European Bicycle Industry (CONEBI 2021) approximately 5 million e-bike were sold in Europe in 2021 [193]. Market forecasts indicate a potential increase of about 60 % between 2021 and 2031 [199,200]. Each e-bike contains on average about 300 g of permanent magnet [201], with a RE composition of approximately 30 % Nd [202], 4 % Dy [203], and 7 % Pr [74]. Based on this assumption, e-bike production in 2021 required approximately 450 tons of Nd, 60 tons of Dy and 105 tons of Pr. On the other hand, the European Association of Motorcycle Manufacturers (ACEM) reported motorcycle registrations of around 16,800 e-motorcycles and 61,200 moped in 2021, considering only the greatest country in EU [194]. Between 2020 and 2030, the e-motorbike market is projected to have a compound annual growth rate of 7.4 %, with a whole increase around 50 % by 2031. Assuming an average content of 450 g of NdFeB per e-motorbike, and the same REE composition as for e-bike, the corresponding metal demand in 2021 is estimated at approximately 9 tons of Nd, 2 tons of Dy and 11 tons of Pr.
- *E-cars.* The European Commission reported 2.5 million e-cars in 2021 (54 % hybrid, 24 % battery electric and 21 % pug in hybrid vehicles) [195]. The forecasts for 2027 report an estimated vehicles increase around 27 %, mainly connected to the full-electric cars (around 14 % each year), which should reach a 70 % increase by 2031 [204,205]. The e-car quantity (weight of each NdFeB magnets 1.25 kg [11]) is translated into a consumption of 392 tons of Nd, 181 tons of Dy [195] and 65.8 tons of Pr, in 2021. The lowest quantity of Pr consumption is due to its (possible) role as partial substitute of Nd [54] (only in some cases) [206].
- *Pump drives.* The magnetic drive pump market in 2021 was estimated around 822,540 units, with an annual growth rate around 7.6 % (2021–2031) [196,197]. This kind of system has an average weight of 55 g with 25 % of Nd and 0.05 % of Dy [207], translated into a consumption of about 10 tons of Nd and 20 kg of Dy in 2021.

6.2.2. Use and stock

Considering the NdFeB uses, not relevant losses were identified during product life. The only losses can be due to product wear (with very low percentages), and for this reason they are excluded from the MFA. The characteristic of a stock is strongly correlated to the lifespan of products, which varies on NdFeB application basis. The average lifetime varies from around 3 years for e-scooters [74,203] and 5 years for e-bikes [202], to 16 years for e-motorbikes and e-cars and 20 years for pumps [208].

6.2.3. Export

Exits from the use cycle (export) are linked to the growth in demand and to the achievement of the end of the life of the considered products. Currently, however, these applications are so innovative that they do not contribute significantly to the current market with the recycling of secondary raw metals from NdFeB magnets, but they will represent the waste of the future. For example only 1 % from secondary resources have been reported for Nd supply [10]. Anyway, according to the European estimation, EU demand for RE-PM in 2030 could reach 40,000 tons, including all possible applications of these components and the demand for RE-PM for e-bikes, e-motorbikes, e-cars, e-scooters and pump drives is expected to represent more than 20 % of that amount (Fig. 4a and b). The information from this analysis, therefore, are useful for understanding the areas in which recycling should be applied, drawing on the technologies discussed in this review.

6.3. Innovative scenario: substitution of RE based magnets with ferrites

It is evident that the planning of a sustainable recycling strategy for RE-based magnets is a priority in the perspective of sustainable management of the growing export flows that will reach the market in next years (Fig. 4a and b). However, in agreement with the CRM action plan, the production of secondary CRM should be integrated with the possibility to decrease their consumption [13]. In this context the achievements of PASSENGER could play an important role. To estimate their positive effect, a survey with seven questions was submitted to PASSENGER partners to hypothesize the possibility of RE-based magnet substitutions in the different products (Supplementary materials, Figure S1). The questions were designed to be clear and simple for stakeholders, allowing everyone to respond regardless of the specific application, even in the absence of industrial-scale examples of magnet substitution and performance data. The survey format aimed at the identification of the alternative RE-free magnet evaluated (such as ferrites) exploiting the combination of partner expertise and technical results achieved within the project. The second and the third questions aimed at exploring the efficiency of substitution of RE-magnet, within specific products. Question 4 was relevant to evaluating the possible increase of product weight due to the ferrite use. Another key aspect of MFA is the definition of material stocks (i.e. the total amount of materials stored in a process), based on the product life cycle, compared to the current technology with RE-magnet (question 5). Questions 6 and 7 were relevant to evaluate the recyclability of the free RE-magnets (at the end of their life) and the possible use of the secondary raw materials within the same value chain. A space for comments was added to the survey to report possible thoughts.

We collected the interest from 5 partners and Table 7 was built on their responses. Partner answers are based on the best result achieved, integrated with hypothesis of their scale-up. Based on these inputs, the MFA provides an initial estimate of the potential effects of magnet recovery and reuse through substitution. The results represent a preliminary estimation rather than a performance-based assessment.

Data supplied by the PASSENGER project partners were integrated into the Sankey diagrams with the hypothesis of their implementation from 2026 (considered as a realistic assumption, given the end date of the project). It was set a growing introduction on the market of innovative products, with a RE PM magnet substitution of 10 % in 2026, 20 % in 2027, 30 % in 2028, 50 % in 2029, the maximum value in 2030 (Fig. 4c). The substitution efficiency estimated by the partners, 80 % for e-bikes, e-motorbikes, e-scooter, pump drives and 10 % for e-cars was considered during the whole period (2026–2030).

The results of PASSENGER implementation, despite being affected by a relevant variability (confirmed by the results of survey), show a decrease in RE PM demand of about 40 % for the manufacturing of the 5 products subjected to analysis. On the MFA result basis, the market for e-bikes, e-scooter and e-cars has a key role in the decrease in RE PM demand, with a contribution of 57 %, 23 % and 15 % respectively on the estimated reduction. The reason is the shortest lifetime of e-bikes and e-scooters (which justifies the quick substitution of these products), combined with the hypothesis of a complete replacement by innovative PASSENGER products, with an efficiency of 80 % (as hypothesized by partners). On the other hand, despite the lowest substitution efficiency in e-cars (10 %, reported by partners), their growing demand will play a key role in the decrease in REE demand in the perspective of the green transition.

The evaluation of input/output flows and the stocks trend are important to better understand the relevance of the integration of REE substitution and recycling strategies. Indeed, the observation of the Sankey diagrams suggests that:

- Among the considered products, the highest PM consumption is due to the manufacturing of both e-cars and e-bikes (followed by e-scooters). Therefore, the possibility of demonstrating the RE-based

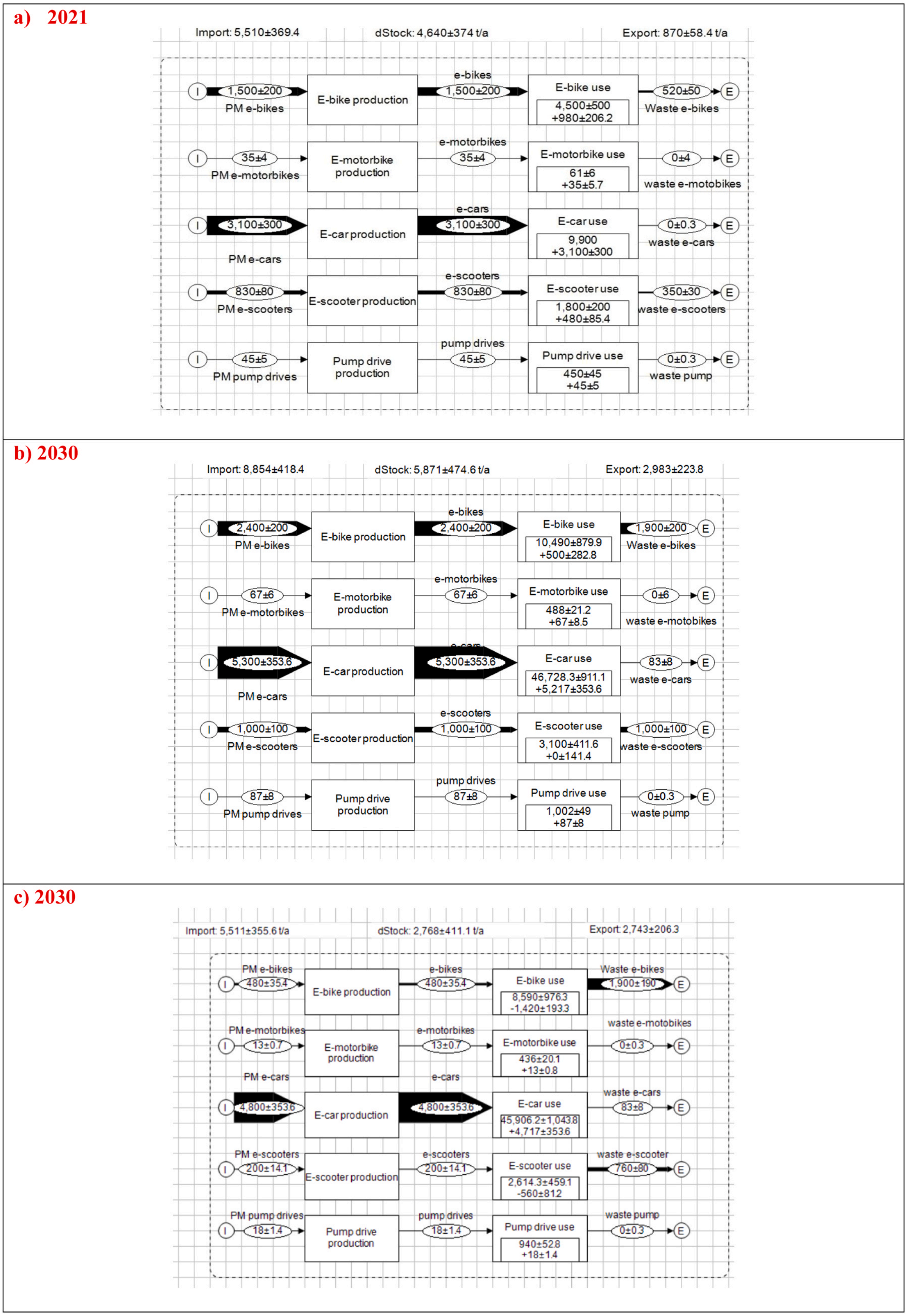

Fig. 4. Sankey diagrams describing the permanent magnets material flows in Europe from 2021 (a) to 2030 without (b) and with (c) the substitution of RE based magnets with ferrites, exploiting the outcomes of the HORIZON project PASSENGER in the e-mobility sector(i.e. PM *e*-bikes, PM *e*-motorbikes, PM *e*-cars, PM *e*-scooter, PM pump drives).

Table 7
Summary of the responses to the Survey.

	Question N°						
Product	1 **Kind of PM**	2 **Application**	3 **Substitution efficiency**	4 **Kg free-RE PM/kg RE PM**	5 **Lifetime**	6 **Recyclability**	7 **Possible use of secondary PM**
	Ferrite	E-bikes	80 %	1	5 (the same of REE-PM)	Yes	Yes
	Ferrite	E-motorbikes	80 %	1	16 (the same)	Yes	Yes
	Ferrite	E-cars	10 %	3–5	4–6	n.a.	Yes
	Ferrite	E-scooter	80 %	1	3 (the same)	Yes	Yes
	Ferrite	Pump drives	80 %	1	20 (the same)	Yes	Yes

PM substitution in both these products could have the greatest impact on material demand.

- Currently, low output flows of both e-motorbikes and e-cars were observed mainly due to the young technology, in the first case, and the longest lifetime in the second one.
- The short average lifetime of both e-bikes and e-scooters suggests constant output flows of these EoL products, available to feed recycling processes (not included in the Sankey diagrams).
- Winning strategies should focus on the integration of PM recycling strategy to enhance the future output flows of e-cars, and at least partial substitution of this kind of PM to reduce the future input flows.

Sankey diagrams showed the flows in specific reference year. However, the additional trend of RE PM input flow shown in Fig. 5 better represents the possible effect of the substitution on the European RE PM demand to produce e-bikes, e-motorbikes, e-cars, e-scooters and pump drives within the considered period between 2021 and 2030 (Fig. 5). Starting from 2026, the studied substitution benefit is gradual, but after 2029, the hypothesis of the fastest market entry of the products will allow the best expected outcome. The difference between the scenarios without and with the implementation of RE based substitution, according to the project PASSENGER, is around 3400 tons of REE PM, which represent around 20 % of rare earth oxide PM European demand, estimated by ERMA and EIT Raw Materials for 2030 [209].

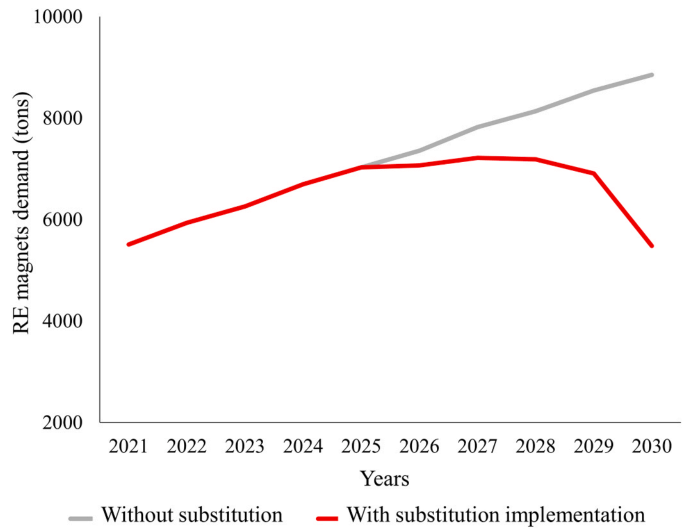

Fig. 5. Comparison of RE PM demand for PASSENGER products (i.e. PM e-bikes, PM e-motorbikes, PM e-cars, PM e-scooter, PM pump drives), from 2021 to 2030 between a European market with and without the implementation of PASSENGER results.

7. Conclusions

The sector of permanent magnets represents a rapidly expanding one, with constantly growing demand, which translates, in parallel, into an increase in waste streams containing such materials. MFA has highlighted that tracing the flows of magnets on the market constitutes a crucial strategy for identifying opportunities to integrate more efficient recycling processes and for promoting the reduction of RE-based magnet consumption.

Free-RE PM probably could not replace the RE PM in all the applications due to both the possible reduction in performance and the weight increase of the equipment (as confirmed by survey responses about e-cars). However, their contribution, integrated with the exploitation of RE PM stocks, estimated by the present MFA, represents an evident opportunity for the European market. It is evident that further integration of MFA with performance analysis will be necessary, once more data become available, in order to develop a stronger and more representative predictive model for studying the future of RE PM magnets across Europe. Furthermore, as highlighted in the survey response, the EoL ferrite PM will be recyclable and suitable to be reused in PM value-chain (aspect relevant to solve the possible decrease of lifetime reported for e-cars), reducing the EU dependence (currently almost complete) from extra-EU for primary raw material supplies. From a technological perspective, among the most promising options in terms of sustainability are hydrometallurgical processes, which emerge as less impactful alternatives to conventional pyrometallurgy. Bio-hydrometallurgy, on the other hand, although still at a predominantly experimental stage, emerges as a potential challenge for the future, opening up prospects for further innovation in the processes of recovery and enhancement of magnets.

CRediT authorship contribution statement

Maria del Mar Cerrillo-Gonzalez: Investigation, Data curation. **Ionela Birloaga:** Investigation, Data curation. **Francesca Beolchini:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Giulia Merli:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Valentina Innocenzi:** Resources, Project administration. **Francesco Vegliò:** Supervision, Project administration, Funding acquisition. **Maria Villen-Guzman:** Investigation, Data curation. **Alessia Amato:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Alessandro Becci:** Visualization, Formal analysis.

Declaration of Competing 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.

Acknowledgement

This research was performed within the European Union Horizon

2020 research and innovation programme through the project PASSENGER (Pilot Action for Securing a Sustainable European Next Generation of Efficient RE-free magnets) under Grant Agreement No. 101003914.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2025.120928.

Data availability

Data will be made available on request.

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