Review

A circular economy approach for recycling Electric Motors in the end-of-life Vehicles: A literature review

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ABSTRACT

Increasing concerns over climate change have led to global decarbonisation efforts, in the form of new legislation, to phase out the sale of internal combustion engine (ICE) vehicles. As a result, the transition to electrified powertrain vehicles as the mode of transportation has never been greater. Electric motors (EMs), serving as the pivotal component of e-mobility, have gained much attention by policy makers and economic experts concerning the supply chain of raw materials needed for manufacturing. Permanent magnets (PMs), including rare earth elements (REEs), account for 40 to 60 % of the total EM cost. Given the importance of these materials to the e-mobility efforts, there has been a great impetus by leading economies to mitigate supply chain instability and mining operation constraints, by identifying and establishing a sustainable supply source through circular economy strategies. Although extensive studies on REEs recovery, via various techniques, have been undertaken by the research community, there remain underlying concerns over feed source, quality and technical challenges surrounding the retrieval of PM via a functional disassembly approach, all of which are yet to be elucidated. The present study serves to highlight state-of-the-art recycling of EMs from EoL electrified vehicles using a circular economy approach.

1. Introduction

With increasing concerns over climate change and inner-city air pollution, demand for alternative modes of transportation has never been more significant. This has resulted in global decarbonisation efforts, in the form of new legislations, by leading nations to phase-out the sale of internal combustion engine (ICE) vehicles, thus setting a precedent for enabling technologies such as batteries and EMs to pave the way for e-mobility. The UK society of motor manufacturers and traders (SMMT), estimates that 1 in 22 cars on UK roads is currently electrified (i.e., BEV, PHEV etc.) (SMMT, 2023). However, the latest statutory mandate set to reduce this gap to 1 in 3 by 2030 (Local-Government-Association, 2023; SMMT, 2023).

According to the international energy agency's (IEA) global electric vehicles (EVs) outlook analysis, the number of EVs on roads is forecasted to grow from 3 million in 2018 to 125 million by 2030 worldwide (IEA, 2018). Historically, the average age of a passenger vehicle has been 14 years (SMMT, 2022). Assuming this figure along with registered vehicles

on the road and EoL market size remains somewhat constant, it is estimated that 2 million electrified vehicles would reach their EoLs by 2040 and beyond in the UK alone (The-Scrappers, 2021). Furthermore, many of these vehicles may contain more than one EM. According to the EoL vehicle regulations (ELV Directive, 2000/53/EC), 95 % (by weight) of a vehicle must be reused, recycled, or utilised for energy generation, 85 % of which constitutes recycling or reusing and remaining 10 % for energy recovery mass (EUR-Lex, 2023). This represents a significant opportunity for the remanufacturing of components and closed-loop recycling of PMs in EMs. Remanufactured parts typically cost around 50–75 % of new components/parts (Colledani et al., 2014). Likewise, efficient recovery/recycling of critical elements such as REEs from e-machine PMs are equally important to sustain a healthy automotive industry. From supply chain point of view, this is particularly significant for countries that have no rare earth deposits of their own and are therefore vulnerable to supply market instabilities caused by geo-political shocks. REEs are estimated to make up between 40 and 60 % of the active material cost of an EM (Ma et al., 2021). To put things into perspective,

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the dry weight of EM57PM in Nissan Leaf (Shiro 2022) corresponds to about 3.50 % of the total kerb weight of the vehicle with a 40 kWh NCM 523 battery pack (EV-Database, 2023). Only 3 and 8 % of respective light and heavy REEs are currently being recycled at global scale (European-Commission, 2020). Equally, other metallic parts/components such as motor housing and/or transmission are either recycled or remanufactured depending on their condition following disassembly (Tiwari et al., 2021). Although remanufacturing has a strong presence within the automotive industry, the market for returned EMs (during warranty or at EoL stage) is highly complex, unstructured, and somewhat expensive to operate. This is primarily due to vast variations in terms of design, material, and manufacturing techniques that have been employed during assembly and production. In recent years, remanufacturing operations have started for both, battery packs and e-machines, since BEVs have grown in popularity. Remanufacturers have sophisticated end-of-line testing equipment to satisfy quality control requirements before returning parts back to OEMs. Nonetheless, there remain concerns over high operational costs and performance inefficiencies associated with current manual disassembly approaches that are being employed (Tiwari et al., 2021).

The automotive industry requires technology, knowledge, skills, and a resilient supply chain to enable net-zero production of cars. A net-zero vehicle can only be achieved by adopting circular principles to remanufacture moderately worn-out EoL parts for second lives and closed-loop recycling, when remanufacturing is deemed non-viable. EMs are identified to have the highest potential for reuse, remanufacturing, and closed-loop recycling. However, due to the ever-changing design, manufacturing approaches, and maintenance issues, EoL strategies of e-machines are not fully considered. This article reviews the status of the disassembly and recycling of EMs to provide directions in research and development to enable net-zero manufacturing from a circular economy point of view.

2. Electric motors

2.1. Types of EMs and their construction

Depending on the vehicle type and propulsion design, commonly used EMs in electrified vehicles include induction motors (IMs), permanent magnet synchronous motors (PMSMs) and wound-field synchronous motors (Gross J, 2019). Other machine types considered by designers include switched reluctance, and synchronous reluctance motors with or without magnet assistance (Fig. 1(a)). More recently, the use of induction and wound-field synchronous-motor designs have increased, primarily to reduce reliance on magnet materials.

EMs can be constructed in a wide variety of ways, but for the purpose of this review, it will be restricted to motors of 'permanent magnets (PMs)' architecture only (Ehsani et al., 2010). Broadly speaking, these motors are made from four main materials: aluminium, copper, steel, and REEs. This includes the construction of housing, stator with windings, rotor with PMs, and the driveshaft. PMSMs come in two main configurations: surface-mounted permanent magnet (SPM) machines where magnets are placed on the rotor surface, and interior permanent magnet (IPM) synchronous machines, where magnets are placed within the rotor. Due to their superior attributes such as, adjustable-speed operation, high efficiency, low heat emission, and reduced noise, IPM machines have become the preferred choice for traction motor applications (Cai et al., 2021). Like most EMs, IPMs have two main active parts: the rotor and the stator (Fig. 1(b)). Electrical power is supplied through the stator windings to generate a rotating magnetic field, which interacts with the rotor-assembly, causing it to rotate and thus create torque for propulsion (Ehsani et al., 2010). Magnets are embedded within a stack of electrical steel sheets (laminates), as opposed to solid metal which makes the handling of centrifugal forces more of a challenge. This requires careful design to guarantee high mechanical stability, even at high speed. IPM motors can use both the (alignment) torque due to magnets as well as (variable) reluctance torque due to special air features in the rotor laminates.

2.2. PMs and REEs: TEA, LCA and circular economy

EMs consist of several valuable materials including PMs, high-quality copper, and electrical steel, aluminium, cast iron, and polymers. Fig. 1 (c) highlights the material composition of typical 20 and 80-kW PM motors in electrified vehicles. Based on 2 million cars being scrapped each year (The-Scrappers, 2021), one can assume that around 69,600 tonnes of steel, 17,000 tonnes of copper, 28,200 tonnes of aluminium, and 4200 tonnes of PM will be generated by 2040 and beyond from EVs alone (Elwert et al., 2016). Some of these materials/elements are deemed critical: economically and strategically important but have a high-risk associated with their supply (CRM-Alliance, 2023). Of particular concern are the REEs found in PMs. It is worth noting that the amount of REEs in EVs is comparatively smaller than critical materials used in battery packs. However, REEs are rarely found in economic concentrations. Their mining and subsequent extraction from their ores are associated with higher cost burdens than metals such as nickel, cobalt, and lithium. As such, their values are reflected in the stock market accordingly. The current prices of nickel, cobalt and lithium carbonate are $16.97, $29.13, and $13.70 per kg, respectively. In comparison, respective current prices of neodymium and dysprosium are $115.60 and $583.20 per kg (LME, 2023; Strategic-Metals-Invest, 2023; Trading-Economics, 2023).

Neodymium-alloy (NdFeB) magnets have the highest energy density among commercial grades, therefore a preferred choice for the automotive industry. As the name implies, NdFeB magnets are largely composed of neodymium, iron, and boron (Fig. 1(c)), with small amounts of other REEs such as dysprosium and/or praseodymium to enhance magnetic and physicochemical properties of final sintered magnets (Elwert et al., 2016). Other PM alloys include ferrite, aluminium nickel cobalt (AlNiCo), and samarium cobalt (SmCo) (Elwert et al., 2016; Nordelöf et al., 2019).

Given that an average EV (BEV) contains around 2 kg of PM (Agamloh et al., 2020), it can be estimated that around 561 tonnes of PMs were placed on the market in 2022 by BEV alone (Best-Selling-Cars, 2023). In addition, to a few hundred tonnes of PM that would have been placed through hybrid and mild-hybrid EVs. Besides EVs, other applications of NdFeB magnets include wind turbines, particularly direct-drive offshore wind turbines. Such turbines contain up to 650 kg of magnets per megawatt capacity (Welzer, 2019). By the end of 2022, the UK installed 13.7 GW of offshore wind turbine capacity. This constitutes to around 9000 tonnes of rare earth PMs (Lynas-Rare-Earths, 2023; Renews.biz, 2023). These magnets will eventually need to be recovered to sustain the UK supply chain and infrastructure.

Historically, China has been the main producer and supplier of REEs globally, controlling 92 % of the global REE production market until 2010 (Visualcapitalist, 2021). Since then, other countries have increased mining and production operations to reduce reliance and supply chain disruptions that may occur because of geopolitical disputes (Nikkei-Asia, 2023). As of 2020, China's REE production represents 58 % of the total global REE production (Fig. 1(d)). A typical PM manufacturing process involves several hydrometallurgical and pyrometallurgical steps. Fig. 1(e) depicts a typical process flow diagram of PM production from initial REE ores. Fig. 1(f) illustrates global warming potential of 1 kg of NdFeB based on various LCA reports (Sprecher et al., 2014; Wulf et al., 2017; Arshi et al., 2018; Bailey 2019). The depicted scores show significant variations contingent upon factors such as raw materials, processing methods, and the chosen LCA methodology. It is notable that there is a lack of a standardised LCA approach that is specific to REEs. To enable a direct and quantitative comparison of processing routes, it is imperative to consider data from the same source as a consistent basis for comparison. Recycling emerges as a distinctively impactful strategy, that can potentially save more than 50 % of the equivalent carbon
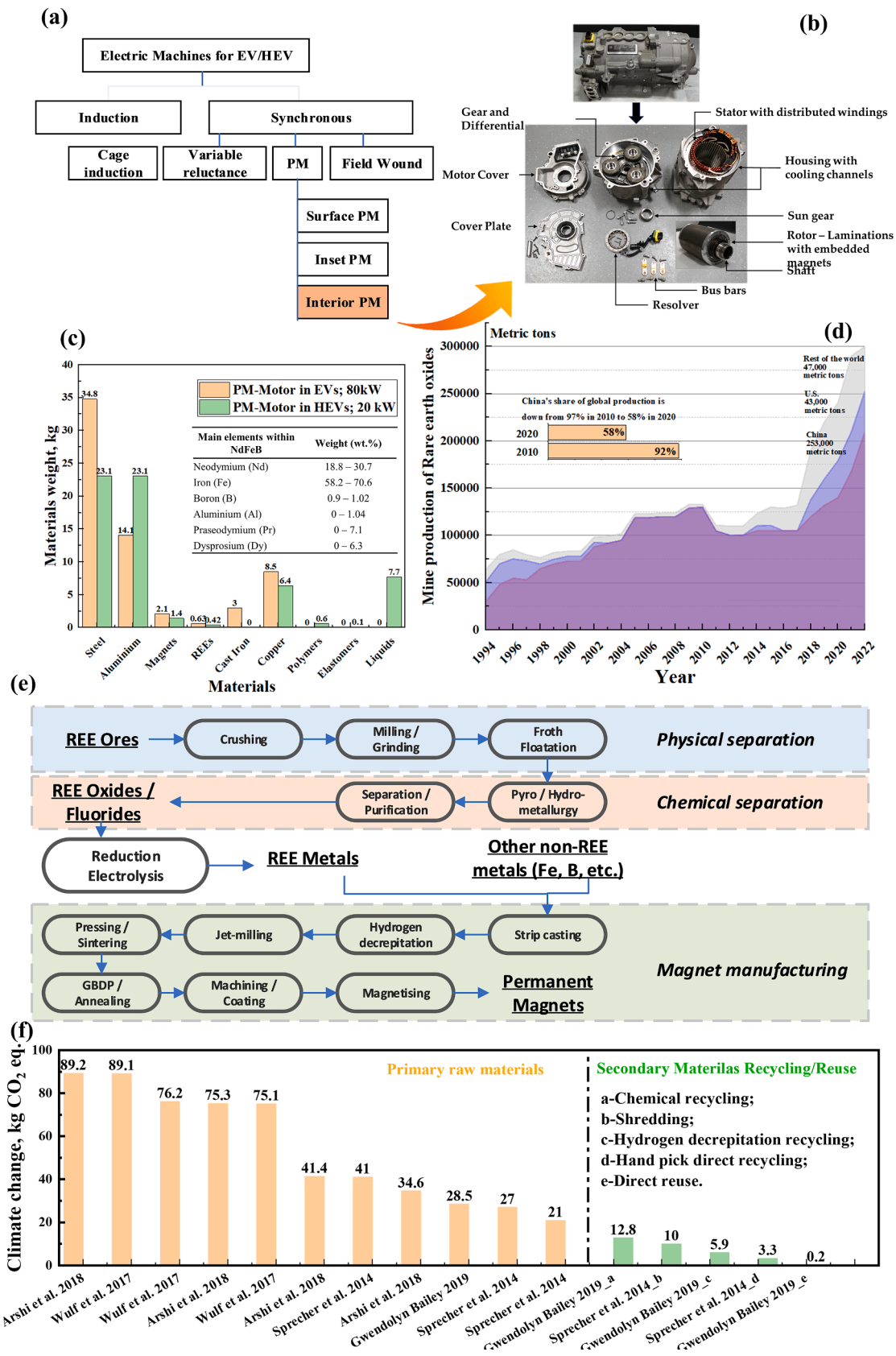
Fig. 1. (a) Tractions motors available for BEVs and HEVs. Inspired from (Agamloh et al., 2020); (b) Disassembled Jaguar I-Pace permanent magnet synchronous motor, with a planetary gear set and differential; (c) Typical material composition (kg) of PM synchronous motors and NdFeB magnet. Adapted from (Elwert et al., 2016); (d) Total global REEs production. Adapted from USGS National Minerals Information Center, 2023; (e) Flow chart of PM manufacturing process; (f) Climate change of 1 kg NdFeB (kg CO₂ eq.) according to various LCA reports.

footprint with substantial environmental benefits (Jin et al., 2016).

Circular economy can be broken down into three main routes, namely reuse, remanufacturing, and recycling of products and/or raw materials. **Reuse** refers to the use of a functional product in a similar application without substantial alterations. **Re-manufacturing** corresponds to the restoration/rebuilding of a product with new or repaired components, to achieve original OEM specification and functionality. **Recycling** refers to the destructive recovery of (raw) materials within a product so it can be used to make new products (Potting et al., 2017). In the context of EMs, recycling and remanufacturing routes ensure a product lifecycle that extends beyond conventional linear models. Both circularity routes require separation of components into materials, and in some cases into grade-specific waste streams. Systematic disassembly ensures that the value and quality of the recovered material remains at the highest value. A good example of circularity practice would be to replace the bearings of an EoL EM for a second life. According to the international standard for rotating electrical machines (IEC 60,034 23), replacing bearings of a 110 kW motor can double its lifecycle without the need for alterations to most of its structure (Tiwari et al., 2021).

3. Disassembly: destructive and non-destructive

Disassembly is defined as a systemic method for separating a product into its constituent parts, components, and subassemblies (Gungor and Gupta, 1999). Broadly speaking, disassembly process is generally categorised into destructive and non-destructive practices (Chang et al., 2017; Mitrouchev et al., 2015). Destructive disassembly refers to the removal of component(s) from a unit, at the expense of inflicting damage or destroying at least one of the connecting components, to gain access and enable joint separation. This includes techniques such as sawing, cutting, drilling etc. Non-destructive disassembly corresponds to practices where desirable components are removed without any damage or destruction (Bdiwi et al., 2016; Mitrouchev et al., 2015). However, in practice there will always be some degree of destruction or damage. Hence, disassembly practices overall can be better described as 'semi-destructive'.

3.1. Disassembly of EoL products

For EoL processing of consumer products, non-destructive disassembly practices are generally preferred. The process is largely manual primarily due to large variations in product design which serves to add complexity and, therefore, limits the scope for automation. Variation in product design means that steps, required for an appropriate disassembly sequence, ought to be specified carefully to accommodate each variant. According to Soh et al., factors that enable disassembly include simplification of the product design, low levels of assembly (i.e., few connection points) and product variability (Soh et al., 2016). It is also worth noting that for remanufacturing applications, complete product disassembly may not be necessary, just enough to recover the 'core' or target component in question. For example, Tiwari et al., outlined an eight-step process for the disassembly of a brake motor down to its copper windings, and seven steps to reach the worn bearings (Tiwari et al., 2021). Irrespective of the CE strategy at hand (remanufacturing or otherwise), non-destructive disassembly practices tend to be more labour-intensive and time-consuming with relatively higher operational costs. This is in contrast to destructive disassembly practices such as shredding that is currently being employed in the recycling industry, even though high levels of impurities are introduced in the material stream during such activities.

In recent years, numerous innovative attempts have been made to mitigate and find economically viable and technically feasible disassembly process solutions. This includes the use of automation, manipulators (robots), integrated product information (i.e., the use of product QR code), and technology-enabling framework (Industry 4.0) to provide methods and strategies that will help to generate an effective disassembly process paradigm (Chang et al., 2017; Mitrouchev et al., 2015). Within the framework, design concepts have been introduced which can be incorporated from the very initial stages of product design and development to reduce costs and facilitate disassembly of products at EoL stages (Chang et al., 2017; Soh et al., 2014). Such design concepts consist of, but are not limited to, design for disassembly (DfD)/disassembly embedded design, design for remanufacturing (DfReman) and design for sustainability (DfS) (Diehl and Crul, 2008; Masood et al., 2015; Soh et al., 2014) (Fig. 2).

For instance, commonly applied initiatives involving DfD concept include better product modularity, the minimal use of fasteners and tools required for disassembly, and the use of smart materials namely shape memory alloys and polymers to aide active disassembly. Modular drive units of Tesla Model Y and 3, are good examples of product modularity that are based on DfD and DfReman concepts. Components such as the complete gearbox set, differential, heat exchanger, oil pump, and oil filter are all interchangeable between the two models. The only difference between the two motor units is the inverter and associated electric motor type i.e., PM or induction.

3.2. Current challenges

From an economic standpoint, the industry considers disassembly a non-value-added activity for reasons mentioned above (Soh et al., 2016). However, with emphasis by the regulatory authorities on sustainable practices to mitigate environmental and climate concerns in addition to vulnerabilities imposed by limited supply sources of CMs, (systematic) disassembly to retrieve crucial components and/or materials has never been more important (Mitrouchev et al., 2015). This serves to encourage companies to pursue new/alternative CM supply sources, thus reducing dependency on already volatile, monopolised CM market with a small set of suppliers. This includes REEs required to produce PMs for e-machines in the automotive industry (European-Commision, 2020; Tiwari et al., 2021). Added to the complexity, designers are nowadays obliged to introduce simplicity in terms of
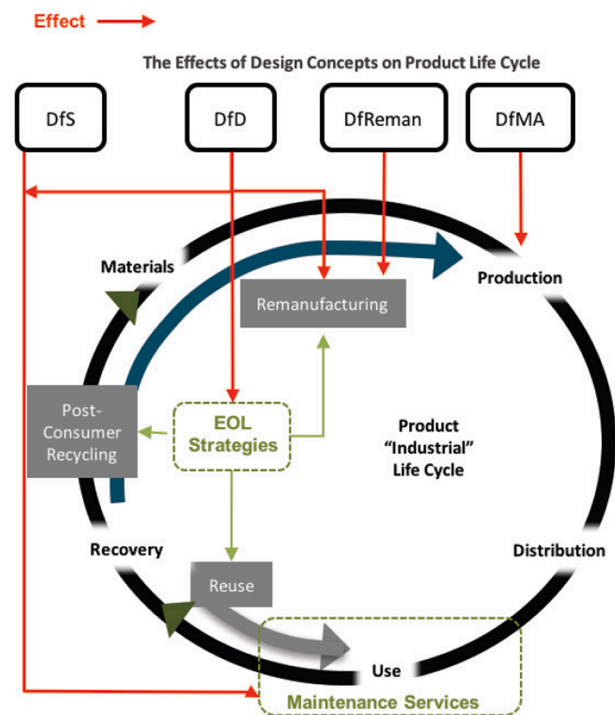
Fig. 2. Design approaches and their effects in a product life cycle. DfMA corresponds to Design for Manufacture and Assembly. Used under Creative Commons CC-BY-NC—ND license. (Chang et al., 2017).

component configuration and geometry to allow disassembly in a constantly evolving product design requirements, set to meet consumer market and manufacturing practices. This is particularly significant for e-machines in electrified vehicles (Zöhra and Akar, 2019; Chang et al., 2017; Soh et al., 2014) since the simultaneous implementation of sustainable design concepts mentioned above can be very challenging. Attention must be paid to product features to avoid design conflicts, i.e., DfD impacting manufacturing and assembly activities, and vice-versa. One way to avert such challenges would be to implement design concepts such as DfD on selected sequence routes only, since DfA needs to be applied to all parts that make up the product (Soh et al., 2016).

Majority of studies conducted on disassembly can be broadly divided into disassembly (i) process planning and (ii) sequence planning. The process planning aspect focuses on generating the optimal disassembly route. This includes establishing the extent to which disassembly of a given product at component level can be achieved. Sequence planning refers to task planning using product's inventory flow of information to generate optimal disassembly sequence for an individual product (Chang et al., 2017). Depending on product ontology, type, and the extent of disassembly etc., various mathematical models, are utilised to devise a disassembly procedure (Hatcher et al., 2011; Soh et al., 2014). The following section lists some of the recent noteworthy approaches that have been investigated to generate a workable electric motor disassembly sequence.

3.3. EM disassembly

Currently, different approaches are available to provide solutions for disassembly sequence generation. These approaches are categorised into (i) component-oriented approaches namely wave propagation (Srinivasan and Gadh, 2000), motional and directional analysis (Yi et al., 2008), and (ii) product-oriented approaches such as heuristic algorithms (Avikal et al., 2014), modularity analysis (Mitrouchev et al., 2015; Tseng et al., 2010). Major emphasis has been on generating optimal disassembly sequences to reduce the searching space and eradicate impractical solutions. This is in addition to reducing computational efforts and time using various methods such as geometric relationships and/or graphs, heuristic rules, genetic algorithms, petri nets and combination of thereof (Mitrouchev et al., 2015).

Soh et al. proposed a methodology to devise a disassembly sequence to retrieve target component(s) for remanufacturing applications (Soh et al., 2016). Using induction motor core as an example, the proposed methodology serves to assess part complexity and accessibility through a metric-based system and establish an optimal disassembly route to retrieve motor core (rotor). This was determined whilst considering both DfA and DfD constraints concurrently for remanufacturing. The proposed methodology offers a systematic approach to establishing a disassembly route for extraction of a particular component. However, the methodology is best suited to aid designers to incorporate DfD concepts on new or existing products that require design improvement for remanufacturing (Soh et al., 2016).

Mitrouchev et al., generated disassembly sequences for non-destructive, selective disassembly of an electric motor core using a graph method (Disassembly geometry contacting graph, DGCG) (Mitrouchev et al., 2015). More than one route was determined. The procedure was subsequently optimised for the quickest possible route by eliminating the searching process for unrelated components from the DGCG graph in favour of the target component. A 3D CAD of an electric motor and a robotic arm were used as models to illustrate the feasibility of the newly generated disassembly sequence for selected components at various levels (Mitrouchev et al., 2015). The proposed DGCG method is said to be computationally less expensive and time-consuming than wave propagation algorithm commonly used to generate sequences for selective disassembly (Chang et al., 2017).

More recently, Mangold et al. proposed a vision-based screw detection system to implement automated disassembly for remanufacturing

strategies (Mangold et al., 2022). Given that screws are standardised and normally on a unit, the proposed system was deemed highly adaptable in locating and classifying screws. The detection system reportedly worked satisfactorily on electrical motors in an automated disassembly line environment. The vision-based system consisted of an industrial robot (UR5 e-series) equipped with an integrated eye-in-hand camera system and one-stage object detectors known as YOLO (You Only Look Once). YOLO is a convolutional neural network that is specifically designed to detect and aggregate features in images. Using an initial training dataset, the system could locate and classify different screwheads to execute robot movements and configure a suitable tool for the end effector to perform the disassembly task on 'unseen' window lifter- and engine starter-motors. Fig. 3a illustrates the disassembly workflow (Mangold et al., 2022). Singh et al. quantified the potential of these artificial intelligence (AI) techniques by classifying 'split' features in physical sheet metal components using images captured by high-dynamic range cameras that were processed by YOLOv5. They reported that the algorithm required a training dataset of just 80 images to achieve a mean average precision of 0.978 for detecting these features. Their application was not strictly the disassembly of products, but they demonstrated the potential for AI to classify features quickly and with high accuracy (Singh et al., 2023).

The proposed vision-based screw detection system serves to offer a feasible alternative to commonly used approaches for disassembly applications in a somewhat industrial setting. The detection system can distinguish between different screws with a good deal of accuracy, particularly the screwheads that appear like the naked eye. However, the study is solely focused on image processing tasks and fell short of demonstrating the effectiveness of the system on an actual complete/ partial disassembly task involving complex products such as e-machines from EVs. Also, one of the major reported issues is the frequent False Positives (Mangold et al., 2022), which could be addressed with better imaging resolution to increase detection accuracy. The authors further highlighted the issue of screwhead misclassification (Mangold et al., 2022). In a real disassembly environment, this is deemed problematic since fixtures used to clamp disassembly products may contain screws or features that can be misinterpreted by the detection system (and indeed by the robot) for being part of the workpiece. In conjunction to better imaging and advanced detector systems, these shortcomings can be mitigated with increased computational power and larger dataset to augment detection accuracy and thus greater variety of application of the system.

Using a vision-based algorithm approach, Bdiwi et al. demonstrated a workstation concept for non-destructive automated disassembly of e-machines (Bdiwi et al., 2016). The workstation consisted of an industrial robot (KR 240–2) equipped with cameras (Kinect), a force/torque sensor, an environment light controller and a universal unscrewing toolset (as an end-effector) for the robot to automatically unscrew different types of fasteners (Fig. 3b). The proposed concept is based on an interactive partnership between a human and machine involving a learning phase, whereby the robot is essentially guided through a 3D space near the motor and screw locations to carry out disassembly. The procedure is logged via measurements recorded by the robot's sensors (e.g., vision, force, and displacement sensors) so it could perform the whole disassembly procedure on another identical motor autonomously. Vision algorithm has been used to improve the autonomy and cognition of the robot by compensating for any errors or changes in task sequence conditions that may have taken place since the learning phase. Using an imaging processing algorithm, the workstation has been designed to detect screws based on the grayscale, depth values, and hue saturation values (HSV) of images captured by the camera. The algorithm is reportedly capable of distinguishing screws not only from other structures such as holes and edges but also between different types of screws. This was made possible via the use of Harris corner detector to generate various features on structures, which were then filtered out at three optimisation levels to rule out false positives. Thus, leaving behind only
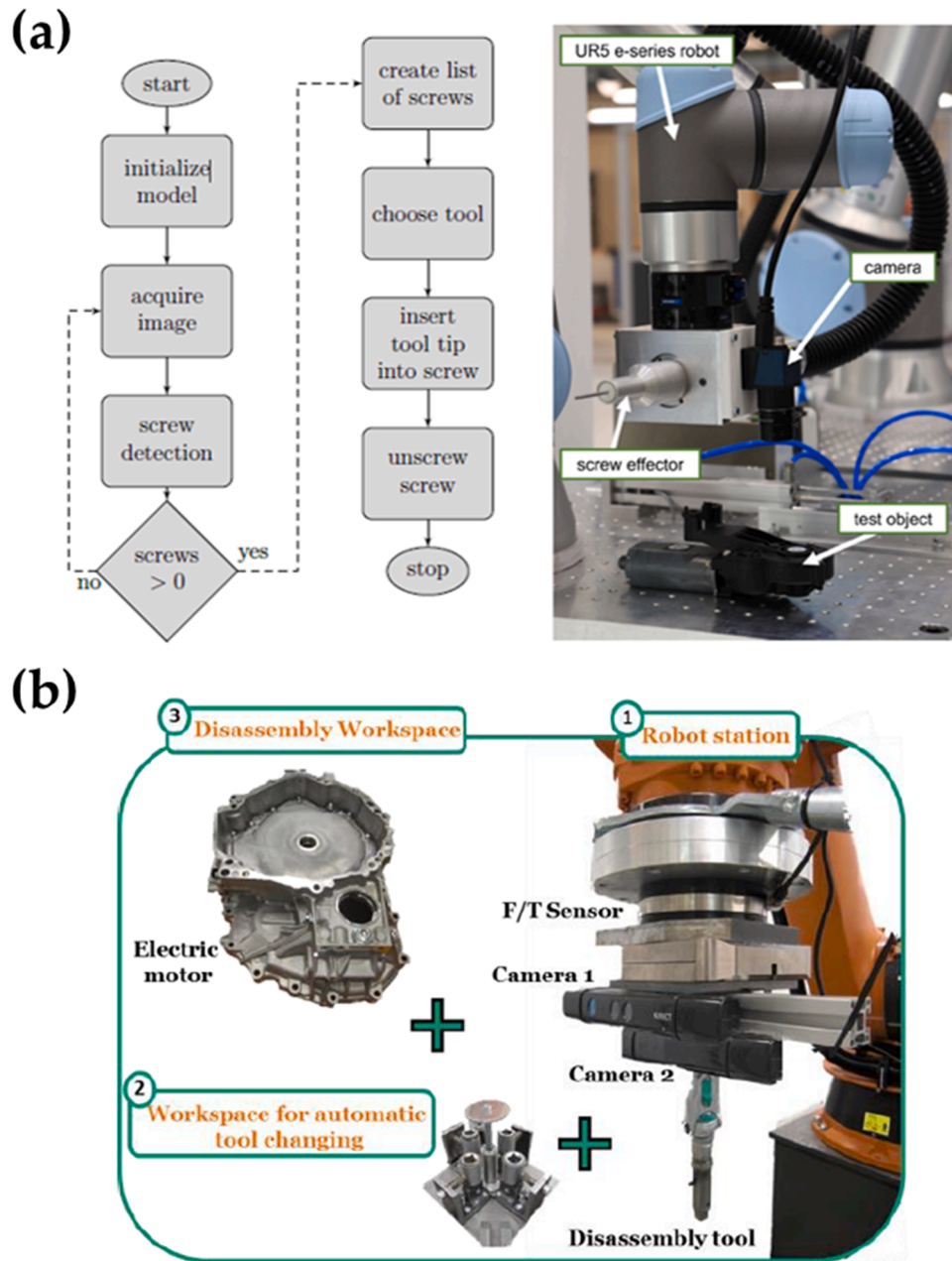
Fig. 3. (a) Vision-based screw detection and disassembly workflow (Left). Eye-in-hand effector system (Right). Used under Creative Commons CC-BY-NC—ND license. (Mangold et al., 2022). (b) KUKA robot with Kinect cameras and universal disassembly toolset. Reproduced under permission by IEEE (Bdiwi et al., 2016).

some of the features to be used to generate regions, which in turn utilised to establish the shape, size, and location of the structure/screw. The authors proposed that the filtering-out steps would help the system run faster by reducing the runtime, primarily due to HSV having a specific range at structures such as holes. By eliminating them, fewer features are left to compute for the region-growing algorithm (Bdiwi et al., 2016). The study has demonstrated the effective use of vision algorithms and industrial resources to design a workstation for automated motor disassembly. However, it falls short of depicting disassembly sequence and/or the extent to which automated disassembly is possible using the proposed robotic workstation.

A similar study conducted by Fleischer et al. proposed a robot-based flexible disassembly systems for both the battery module and EM (Fleischer et al., 2021). The proposed systems are based on morphological box methodology and reportedly serve to address disassembly flexibility to enable faster and cheaper remanufacturing of complex products.

The units were analysed to establish product-specific challenges and disassembly requirements. Four subsystems namely kinematic level, tool level, workpiece fixation and safety system were identified and captured to develop disassembly system concepts for both units. In the case of EM system, appropriate elements from each sub-system were selected from the morphological box. For instance, kinetic subsystem level involved two industrial robots (vertically articulated robot) that were jointly fixed on a workpiece bench by a flexible clamping system that could adapt according to the shape of the workpiece being disassembled. Similarly, tool level consisted of mechanical grippers along with a special disassembly end effector equipped with a screw driving tool to regulate applied forces and torques. Based on component arrangements and sequences, the disassembly process was divided into various steps namely product positioning, fixation, removal of screws and the removal of gearbox. Human intervention was incorporated to resolve any

disturbances that may occur on the disassembly line. For example, if a motor type is unfamiliar to the system, it would be directed to a human worker first to allow the system to learn from the human interaction and extract additional information such as disassembly precedence graphs and special points of interest on the product for future reference. Finally, as part of the disassembly line retrieved sub-units would go through a press station where remaining parts will be pressed out (Fleischer et al., 2021). The proposed conceptual system sets out a tool-guided approach for flexible disassembly based on product analysis and product-specific process requirements. When coupled with workpiece-guided approaches discussed above, the practicality of this proposed concept system can be realised in a real-world setting. Lastly, the authors proposed the disassembly system could be extended to include the retrieval of sub-components (i.e., PMs) from defected motor cores for recycling applications.

Klier et al. devised two prototype machines involving different (semi)-automated disassembly concepts to mechanically retrieve magnets from electric motors (Klier et al., 2013, 2015). This included both surface-mounted permanent magnets (SPM) as well as internal permanent magnets (IPM). Assuming the rotor is already separated from the stator, SPM disassembly steps consisted of thermal demagnetisation, followed by the manual removal of bandaging to expose magnet blocks before introducing the rotor to machine. Magnet blocks are essentially sheared off the surface to be collected through a carefully planned disassembly cycle loop. For IPMs, magnets are pressed out of rotor via a rotor-specific ejector. Using an unmagnetized slide, magnet blocks are then taken away via a conveyor belt to be stacked according to their magnetic polarity (Elwert et al., 2016; Klier et al., 2013). While these concepts have the potential, they serve to depict rather simplistic approaches with underlying constraints involving shape, dimensions, and the arrangement of magnet blocks in the rotor. This is significant particularly when magnet block configuration is constantly evolving within new rotor designs (Zöhra and Akar, 2019).

To recapitulate, the concept of disassembly involving EoL products has been widely studied and commercialised across many industries mostly for reusing and remanufacturing routes (ERN, 2023). In the case of EMs, even though modest attempts have been made by the research community for a viable universal disassembly solution, they do not truly justify the urgency to reflect the volume scale of EoL e-machines that are currently being disassembled manually, mostly for remanufacturing applications. However, given some of the major underlying challenges outlined in this survey, a 'workable automated disassembly' solution to retrieve (target) materials/components, is yet to be elucidated. It is worth noting that the two major challenges are product variability and manufacturing techniques employed during EM production. Product variability corresponds to e-machine design, which ultimately dictates manufacturing and assembly strategies of components into a working product. In both instances, OEMs bear the responsibility to ensure their products are designed and subsequently produced in a sustainable manner, particularly when design variation is anticipated with next generation e-machines. Similarly, it is mutually beneficial for both the OEMs and EoL industry (i.e., recyclers, remanufacturers) to work closely and 'constructively' to embrace and implement circular economy approach. This may include providing recyclers guidance on EoL e-machine design and components. Such collective effort would ensure that a viable disassembly route can be developed. Given the design complexity of EoL e-machines, it is proposed that augmented manual and/or flexible disassembly may serve as promising options for automation. Flexible disassembly refers to the use of collaborative robots (cobots) to aide and facilitate demanding disassembly steps, and to accommodate product variability.

4. PM recycling

Currently, research on recycling of NdFeB magnet scraps involves methods such as direct reuse, reprocessing following hydrogen

decrepitation, pyrometallurgy, hydrometallurgy, electrochemistry/ electrometallurgy, bio-metallurgy, and most often a combination thereof. It is worth noting that the condition of disassembled/dismantled rare earth magnets from a particular source dictates the technology that ought to be employed to retrieve and subsequently recover REEs. Although this paper focuses on REEs from EMs, this section summarises proposed recycling technologies that could potentially be employed to recycle and recover REEs from EVs and other sources. Fig. 4 highlights proposed methodologies for the reuse and recycling of PMs.
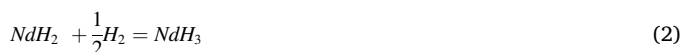
4.1. Direct reuse

Direct reuse involves taking used magnets and repurposing them for their originally intended use without significant (re-)processing or modification. This is under the assumption that magnets are still in good working condition and that their magnetic properties have been demonstrated and validated (Elwert et al., 2016). However, this is not always feasible especially when magnets are damaged or have lost their magnetic properties due to factors such as corrosion and/or demagnetisation. Obtaining magnets in good condition has significant importance, particularly during disassembly and subsequent quality assurance for reuse. This is particularly significant, since magnet blocks in EMs are firmly secured with structural adhesives that are difficult to remove (Mulcahy et al., 2022). As such their applications are deemed limited to remanufacturing (if functional and intact with the rotor) and recycling routes only.
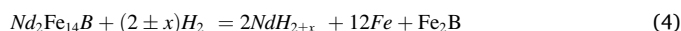
4.2. Reprocessing after hydrogen decrepitation

Walton et al. reported a novel method for extracting sintered NdFeB magnets from computer hard disk drives using a hydrogen decrepitation technique. The method involves exposing either the voice coil assemblies or cropped corner of the drive for hydrogen under ambient conditions (temperature and pressure), to react with sintered magnets and form interstitial hydride at grain boundaries. Two types of reaction are distinguished depending on the composition (Lalana E. H., 2016):

Between hydrogen and Nd-rich phase:

$$Nd + H_2 = NdH_2 \tag{1}$$

$$NdH_2 + \frac{1}{2}H_2 = NdH_3 \tag{2}$$

Between hydrogen and $Nd_2Fe_{14}B$ phase:

$$Nd_2\text{Fe}_{14}B + H_2 = Nd_2\text{Fe}_{14}BH_2 \tag{3}$$

$$Nd_2\text{Fe}_{14}B + (2 \pm x)H_2 = 2NdH_{2 \pm x} + 12Fe + \text{Fe}_2B \tag{4}$$

These reactions also cause around 5 % volume expansion, which results in magnets breaking apart to form hydrogenated powder of low coactivity. The process has also shown to be effective against nickel coating, by causing it to peel away from magnet surfaces in the form of thin sheets. The hydrogenated powder is subsequently separated using a porous drum and mechanical sieve to remove any remaining nickel particles (Walton et al., 2015). Piotrowicz et al. reported complete magnet disintegration following exposure to hydrogen atmosphere at 29 °C and 100 °C (Piotrowicz et al., 2020). In cases where disintegration was well-formed, peeled-off protective layers could be seen visibly. The hydrogen decrepitation process is considered a short-loop recycling of magnets. Currently, it is planned to operate at a pilot-scale to manufacture PMs from recycled materials close to the quality of virgin materials.

4.3. Pyrometallurgical methods

The main objective of high-temperature processing of NdFeB magnet scrap is to selectively convert REEs in magnets into a phase that can be
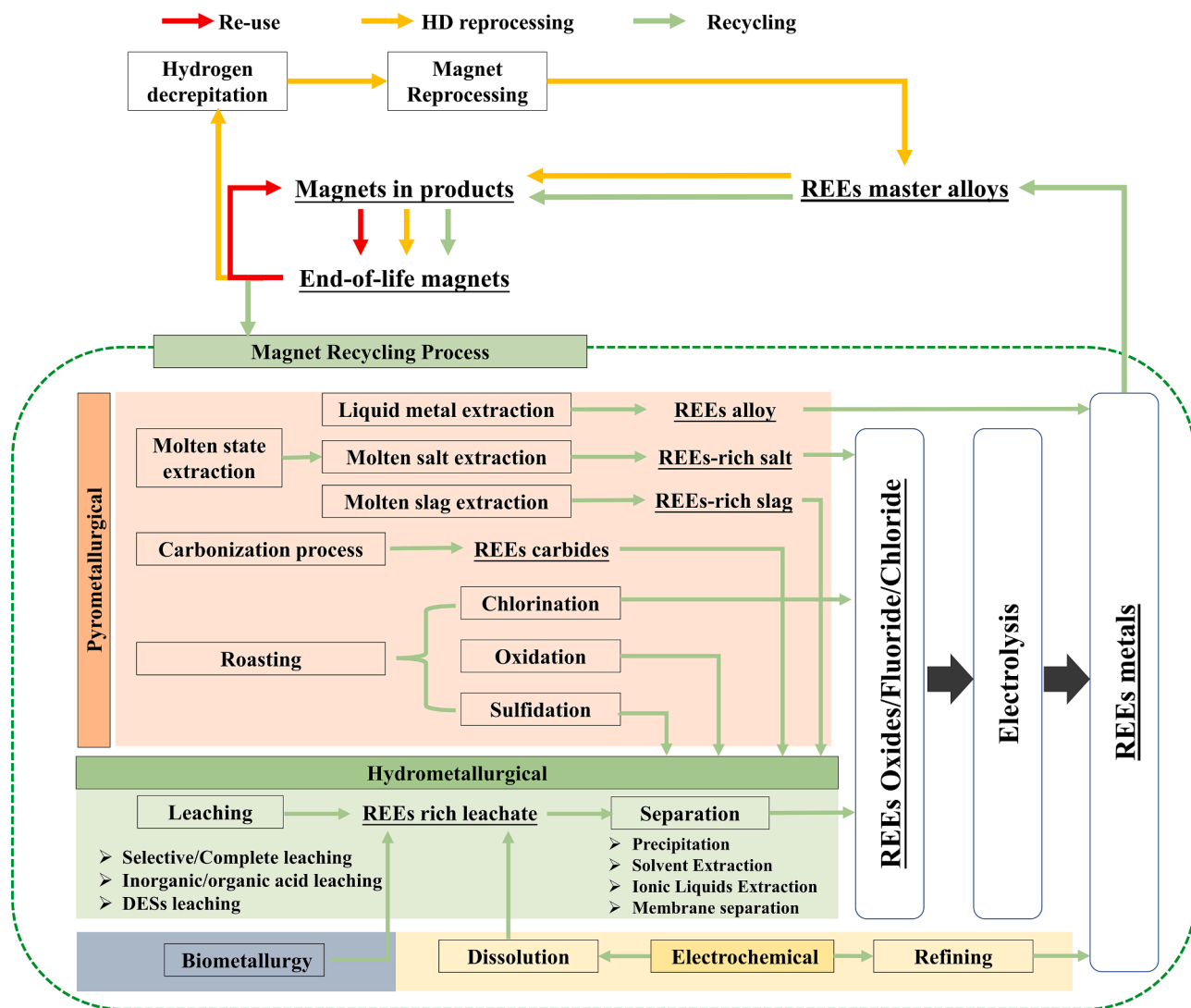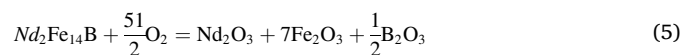
Fig. 4. Overview of recycling processes for permanent magnets. HD- hydrogen decrepitation.

easily separated from non-REE constituents. REEs in the separated phase are more concentrated and therefore can be used for RE metal production via molten salt electrolysis or metallothermic reduction. Different pyrometallurgical extraction methods have been identified, including roasting, molten state extraction, and carbon-hydrolysis. It is proposed that combination of methods may be necessary for complete recovery of REEs from magnet waste. Recent reviews provide a more detailed description of high-temperature recovery from NdFeB magnet wastes with an emphasis on high-temperature processing as an alternative route to minimise water consumption and hazardous waste production during a recovery process (Firdaus et al., 2016).
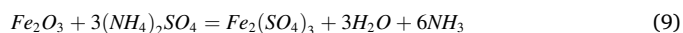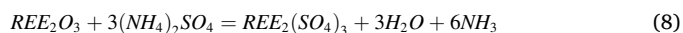
4.3.1. Roasting

Roasting transforms REEs into a new chemical form that is more amenable to selective dissolution during hydrometallurgical separation techniques, thus facilitating REEs extraction from the bulk magnet composition. Oxidation-, chlorination- and sulphation roasting are the main methods that have been explored, (Table 1). It is proposed that a suitable roasting technique can be combined with selective leaching (section 4.1.1) to improve overall REEs recovery. Techniques such as oxidation roasting converts all metallic elements, including REEs, into oxides (reaction (5)). This makes the subsequent leaching process easier, faster and/or more selective. However, Fe_2O_3 and Nd_2O_3 react to produce $NdFeO_3$ (Reaction (6)). This creation of mixed oxides poses issues

as these compounds are insoluble under mild conditions, leading to reduced rates of REEs leaching (Jakobsson et al., 2017).

$$Nd_2\text{Fe}_{14}B + \frac{51}{2}O_2 = Nd_2O_3 + 7Fe_2O_3 + \frac{1}{2}B_2O_3 \tag{5}$$

$$Nd_2O_3 + Fe_2O_3 = 2NdFeO_3 \tag{6}$$

Chlorination roasting refers to magnet powder roasting in the presence of a chloride compound. It commonly involves distilling $RECl_3$ (such as $NdCl_3$ and $DyCl_3$) at high temperatures to separate them from the iron-based residue. For example, when recovery of REE by $FeCl_2$ (reaction (7)), excess $FeCl_2$ could be separated from REE chlorides via vacuum distillation (Tetsuya Uda, 2002). However, current techniques have exhibited low reaction and REEs recovery rates, with added limitation of magnets of low oxygen content only. Equally, sulphation roasting involves exposing metallic elements to sulphate source to produce water-soluble sulphate-based complexes (reactions (8–9)).

$$2REE + 3FeCl_2 = 2REECl_3 + 3Fe \tag{7}$$

$$REE_2O_3 + 3(NH_4)_2SO_4 = REE_2(SO_4)_3 + 3H_2O + 6NH_3 \tag{8}$$

$$Fe_2O_3 + 3(NH_4)_2SO_4 = Fe_2(SO_4)_3 + 3H_2O + 6NH_3 \tag{9}$$

Table 1

REEs extraction based on combined approaches of oxidation roasting and chemical leaching.

| Roasting method	Sources	Method description	Products	Recovery rate	Comments
Oxidation	Yoon et al., 2003	Oxidative roasting + acid leaching + double salt precipitation: sintered scrap: 500 °C + H_2SO_4, 2 mol/L, 50 °C, 2 h; bonded scrap: 700 °C + H_2SO_4, 2 mol/L, 50 °C, 2 h	$Nd_2(SO_4)_3$	Nd > 99.9 %, Fe > 95 %	No selectivity of leaching
	Lee et al., 1998	Oxidative roasting + acid leaching + pH adjusting, 700 °C + H_2SO_4, 4 mol/L, 70 °C, 3h	$Nd_2(SO_4)_3$	Nd ~ 70 %	Formation of $NdFeO_3$ at higher temperatures hinders the dissolution of Nd.
	Koyama et al., 2009	Oxidative roasting + acid leaching + oxalic acid precipitation: 900 °C, 6 h + HCl, 0.02 mol/L, 180 °C, 2 h	$Nd_2(C_2O_4)_3$	Nd > 99.9 %, Fe < 5 %	Selectivity of leaching but Fe co-leached
	Yoon et al., 2004	Oxidative roasting + acid leaching + oxalic acid precipitation: 600 °C, 3 h, pulp density 35 %, acetic acid leaching, crystallization, and oxalic acid precipitation	$Nd_2(C_2O_4)_3$	Nd > 67.5 %	Leached with acetic acid followed by fractional crystallization for selective separation
	Vander Hoogerstraete et al., 2014	Oxidative roasting + acid leaching + ionic liquid impurity removal + oxalic acid precipitation: 950 °C, 8 h, 1.8 M HCl, 3.5 M HNO_3 leaching, and oxalic acid precipitation	$Nd_2(C_2O_4)_3$	/	REEs selectively leached into aqueous solution.
	Yoon et al., 2014	Oxidative roasting + acid leaching: 600 °C, 5 h, 3.0 M H_2SO_4, 70 °C, 4 h	$Nd_2(SO_4)_3$	/	Leaching kinetics, rare earth recovered in leach liquor in rare earth sulphate form.
	Kumari et al., 2018	Oxidative roasting + acid leaching: 900 °C, 5 h, 0.5 M HCl, 95 °C, 5 h	$Nd_2(C_2O_4)_3$	REE > 98 %	99 % purity was produced by oxalate precipitation
	Reisdorfer et al., 2019	Oxidative roasting + organic acid leaching: 900 °C, 8 h, Malic acid: 90 °C, 1 M, 50 g/l, Citric acid: 90 °C, 1 M. 50 g/l	Maleate Oxalate	Nd ~ 99 % (m) Nd ~ 72.8 % (c)	Formation of an iron complex with citrate, which created a thick sludge in the leachate solution
	Gergoric et al., 2019	Oxidative roasting + organic acid leaching + solvent extraction: 400 °C, 1.5 h, glycolic acid, maleic acid, L-ascorbic acid: 70 °C, 6.7 h, 12.5 g/l	/	REEs ~ 95 %	The leaching efficiency in glycolic and maleic acids found better than in ascorbic acid.
	Liu et al., 2020	Oxidative roasting + acid leaching + oxalic acid precipitation: 800 °C, 2 h, 0.6 mol HCl, 2 g/l NaNO₃, L/S 10, 180 °C, 2 h	$Nd_2(C_2O_4)_3$, Fe_2O_3	REEs > 98 %, B > 99.5 %, Fe < 0.1 %	NaNO₃ was found to significantly improve the separation of REEs and B from Fe
Chlorination	Murase et al., 1995	$AlCl_3$, Cl_2, 1323 K, 6–82 h	RAl_nCl_{3+3n} vapours	Nd > 59 %, Dy > 68 %	Owing to the relatively low formation rate of $RAlnCl_{3+3n}$ complexes
	Tetsuya Uda, 2002	activated carbon + $FeCl_2$ reacted at 1073 K for 12 h; vacuum distillation at 1273 K for 3 h	$NdCl_3$, $DyCl_3$, Fe-alloy	Nd > 96 %, Dy > 94 %	Only carbon and water are consumed, and there are no toxic pollutants
	Itoh et al., 2009	NH_4Cl 573 K 3 h in N_2	$NdCl_3$, $DyCl_3$, Fe/Fe-B	REEs ~ 90 %	Only works for magnets that with low oxygen content
	Shirayama and Okabe, 2018	$MgCl_2$ 1273 K 12 h under vacuum	$NdCl_3$, $DyCl_3$	Nd > 87 %, Dy > 78 %	$MgCl_2$ and Mg were removed by vacuum distillation
Sulphation	Önal et al., 2015	14.5 mol H_2SO_4, 750 °C, 1 h; 0.02 g/ml water leaching	REE oxides	REE > 95 %, Purity > 98 %	Most of the acid can be reused since sulphates decompose into their corresponding oxides thermally.
	Liu et al., 2021	$(NH_4)_2SO_4$ roasting, 1st: 400 °C, 1 h, Ratio (1:2), 2nd: 750 °C, 2 h, Water leaching: S/L = 1:20, 30 °C, 0.5 h	$RE_2(SO_4)_3$	REE > 96 %, Fe ~ 0.008 %, Al ~ 0.27 %, Co ~ 3.48 %	Waste gases from this process can be reused

4.3.2. Molten state extraction

Molten extraction methods are employed to separate REEs from iron at high temperatures in molten state. These methods encompass liquid metal extraction, molten salt extraction, and molten slag extraction. Table 2 provides a summary of molten state extraction techniques that have investigated to separate REEs from iron. Liquid metal extraction is based on the fundamental principles of traditional low-temperature liquid-liquid solvent extraction techniques. It entails selectively dissolving REE alloys in a liquid alloy system, which leads to the dispersion of REEs and transition metals between two immiscible liquid metal phases. Taking Mg as an absorbing metal as an example, the REEs captured by Mg to form a REE-Mg alloy (reaction (10)), which is then purified by removing Mg through vacuum distillation.

$$REE \ (in \ alloy) + Mg(l) = REE - Mg(l) \qquad (10)$$
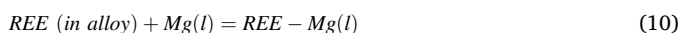
Molten salt extraction, on the other hand, focuses on selectively converting or dissolving REEs into a molten salt phase, whilst leaving behind iron, boron, and other constituent metals as unreacted solids. For example, in NaF-AlF₃ system (reaction (11)), the REEs react with AlF₃ to

form REEF3 and then absorbed by NaF-AlF₃ salt. Subsequently, the REE-rich salt phase undergoes electrolysis to extract REEs. Molten slag extraction involves the selective conversion of REEs into a slag phase, whilst leaving iron in the liquid metal phase. The REE-rich slag can then undergo hydrometallurgical extraction to obtain pure REEs, whereas the separated iron-rich alloy serves as a valuable raw material for steel-making. The ability to efficiently separate and recover both REEs and iron simultaneously makes slag extraction an attractive technique.
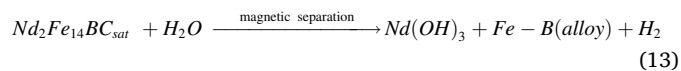
$$REEs \ (in \ alloy) + NaF - AlF_3(l) \rightarrow NaF - AlF_3 - REEF_3(l) + Al \ (l) \qquad (11)$$
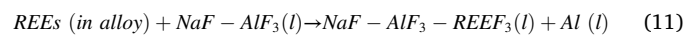
4.3.3. Carbon-hydrolysis process

Bian et al. used vacuum induction melting (VIM) followed by hydrolysis and magnetic separation (HMS) to recover REEs from clean NdFeB magnets without nickel coating. The process involves the melting of magnet at high temperature to form rare earth carbide alloys that are subsequently treated with water to produce rare earth hydroxides of high purity. Metallic iron and carbides are removed by magnetic separation (Bian et al., 2016). Similarly, Liu et al. proposed a process to recover REEs using biochar (derived from waste sawdust), as an

Table 2
Summary of the literature on separating REEs using molten state extraction.

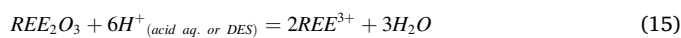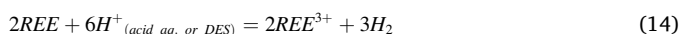| Methods	Sources	Method description	Products	Recovery rate	Comments
Liquid metal extraction	Xu et al., 2000	Mg melt to adsorb Nd; $T > 700$ °C,	Mg-Nd alloy; Fe-B alloy	/	Diffusion behaviour investigated
	Takeda et al., 2006	Mg catches the Nd, then evaporates Mg at high temperature zone; 24–72 h reaction time	Nd metal	Purity > 97.7 %	The mass ratio of Mg to scrap and temperature were investigated and the optimum extraction conditions
	Chae et al., 2014	Mg melt to adsorb Nd; T: 993 ~ 1073 K.	Mg-Nd alloy; Fe-B alloy	/	Diffusion behaviour investigated
	Na et al., 2014	Mg melt to adsorb Nd; T: 1073 K.	Mg-Nd alloy; Fe-B alloy	/	Scrap size, and holding time are investigated
	Takeda et al., 2004	1st: 1273 K, Ag melt to adsorb Nd; 2nd: oxidation of Ag-Nd in air	Nd_2O_3	Nd > 90 %	Wettability of Nd_2O_3 with molten silver caused some difficulties in the separation
	Moore et al., 2015	Arc melting about 1450 ~ 1500 °C; Cu melt to adsorb Nd	(Cu, Nd)-rich rim	Nd ~ 44 % in the rim	Cu is cheaper, how to separate Cu and Nd has not workout
Molten salt extraction	Tanaka et al., 2009	Fluoride system	/	/	Formed REE oxides –fluoride mixture can be used in molten salt electrolysis
	Takeda et al., 2014	ReF_3-LiF	1200 °C	/	Fluoride salts are suitable for the treatment of oxidized NdFeB magnet scrap only
	Hua et al., 2014	MgCl–KCl	600 - 1200 °C	REEs ~ 90 %	Produces a Mg-Nd alloy after electrolyzed
	Hua et al., 2015	AlF_3–NaF	800 - 1100 °C	REEs ~ 94.2 %	Obtained fluorides can be subsequently processed with molten salt electrolysis of Al-Nd alloy
Molten slag extraction	Saito et al., 2003	BN crucible with B_2O_3 at 1650 K in Ar atmosphere	Nd_2O_3, Fe_2B, Fe	Nd_2O_3-B_2O_3 slag	Acid leaching needs for further separation of Nd and B
	Nakamoto et al., 2012	Carbon crucible at 1550 °C in Ar atmosphere, 10–17 atm	REE oxides; Fe-C alloy	High-purity REE oxides	Fe and B in REE oxides can be magnetically separation
	Yang et al., 2013	CaO–SiO_2–Al_2O_3; CaO–CaF_2, at 1500 °C, 3 h	REE-rich slag; Fe metal	REEs ~ 100 %; Fe ~ 99 %	Hydrometallurgical extraction needs for further REE separation
	Tanaka et al., 2013	Oxygen control	REEs oxides; Fe metal	/	Formed REE oxides were converted to RE metal through conventional technologies
	Stopic et al., 2022	Peroxidation-smelting	REEs oxides; Fe metal	/	Further pyrometallurgical or hydrometallurgical treatment
	Lei et al., 2021	Si as a reductant to extract Nd from Nd_2O_3-slag; Si-Nd alloy separate by HCl leaching	NdOCl, NdF_3, $NdCl_3$, Si	/	Also increases the purity of Si from 99.2 to 99.997 %

extracting agent. In this method, NdFeB powder is layered over biochar, which is then carburised/hydrogenated at high temperatures to form NdFeB-C/H alloy. REEs are then recovered via subsequent hydrolysis and magnetic separation (Liu et al., 2019). This method is deemed less energy-intensive and uses waste material as an extracting agent, thus making it a more sustainable approach. Key processes of VIM-HMS are listed as follows:

$$Nd_2Fe_{14}B \ alloy + C \rightarrow Nd_2Fe_{14}BC_{sat} \ alloy \qquad (12)$$

$$Nd_2Fe_{14}BC_{sat} + H_2O \xrightarrow{\text{magnetic separation}} Nd(OH)_3 + Fe - B(alloy) + H_2 \qquad (13)$$

4.4. Hydrometallurgical methods

4.4.1. Leaching

Leaching processes include both, *selective-* and *complete leaching* using inorganic/organic acids or deep eutectic solvents (DESs). Selective leaching process is a common method used to recover REEs from NdFeB PM scraps. REEs recovery depends on the solubility difference between REEs and iron in solvent(s). Pre-treatments such as oxidation roasting are carried out to improve selectivity and recovery efficiency, though there remain concerns on preventing unwanted elements from entering the solution due to inherently low separation efficiency. Complete leaching process involves complete dissolution of magnets. It is deemed relatively simple and easy operation but at the expense of high leaching agent consumption and additional steps to remove impurities. DESs present a promising substitute for leaching of valuable metals from NdFeB magnets primarily due to their advantages including low cost and easy to prepare with lower biotoxicity. During the leaching process, REEs are easily dissolved by inorganic acid, organic acid, and DES via following reactions:
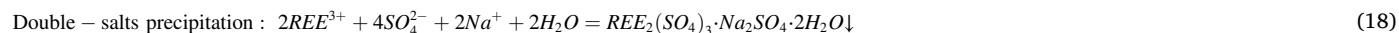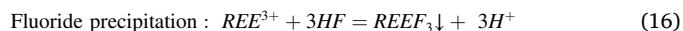
$$2REE + 6H^+_{(acid \ aq. \ or \ DES)} = 2REE^{3+} + 3H_2 \qquad (14)$$

$$REE_2O_3 + 6H^+_{(acid \ aq. \ or \ DES)} = 2REE^{3+} + 3H_2O \qquad (15)$$

Inorganic acid leaching: Leaching with HCl and HNO_3 in the presence of a concentrated chloride or nitrate matrix has been investigated to show if leachate could be used directly into a cheap solvent extraction system to further extract and purify the REEs (Vander Hoogerstraete et al., 2013). Rabatho et al. used 1 mol/L HNO_3 and 0.3 mol/L H_2O_2 for selective leaching. Up to 98 % and 81 % leaching of Nd and Dy was observed, respectively. Leaching of Fe was reportedly below 15 % (Rabatho et al., 2012). Kataoka et al. reported the pre-treatment of a corrosion process to increase selectivity between Nd and Fe at room temperature, and that almost 100 % of Nd can be recovered from NdFeB magnet scraps (Kataoka et al., 2015). Researchers (Liu et al., 2020, and Kumari et al. 2018.) successfully separated REEs and Boron from iron through selective pressure leaching. The process was notably enhanced with the addition of a $NaNO_3$ promoter to reduce iron levels in the leaching solution. Emil-Kaya et al. achieved over 90 % REEs leaching rate using 1 mol/L HCl at 60 °C. Subsequent iron removal process, via high pressure, was performed to obtain high-purity REEs solution (Emil-Kaya et al., 2023).

Organic acid leaching: The utilisation of organic acids as leaching agents could be a viable alternative to mineral acids due to ease of handling, reduced hazards, lower generation of toxic gas emissions, and better degradability. Behera and Parhi used acetic acid at a concentration of 0.4 mol/L to leach Nd from NdFeB scraps. The results showed > 99 % Nd leaching at a solid/liquid ratio of 1 % and a temperature of 80 °C (Behera and Parhi, 2016). Menad et al. confirmed acetic acid leaching of Nd, Dy, and Fe with over 90 % efficiency, and 0 % selectivity towards Ni (Menad et al., 2016). Gergoric et al. studied leaching of roasted NdFeB magnets using acetic acid and citric acid. Highest leaching yields were obtained with 1 mol/L citric acid and 1 mol/L acetic acid. More than 95 % of Nd, Pr, and Dy can be reached at a solid/liquid ratio of 3 % (Gergoric et al., 2018). However, no selective leaching was achieved between REEs and Fe, B, and Co. Reisdorfer et al. investigated leaching

of roasted and unroasted NdFeB magnets using maleic and citric acid to recover Nd. The results showed good leaching behaviour by both acids on unroasted NdFeB powder, and selective leaching from roasted NdFeB powder though at the expense of decreased Nd yield. Using citric acid at 1 mol/L under 90 °C and a solid/liquid ratio of 5 %; 73 % of Nd was leached after 1 h, whereas the use of maleic acid under same conditions

$$Double-salts\ precipitation:\ 2REE^{3+} + 4SO_4^{2-} + 2Na^+ + 2H_2O = REE_2(SO_4)_3 \cdot Na_2SO_4 \cdot 2H_2O\downarrow \tag{18}$$
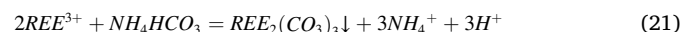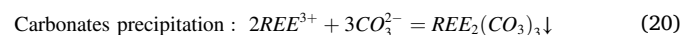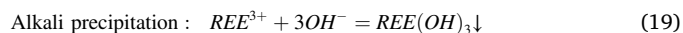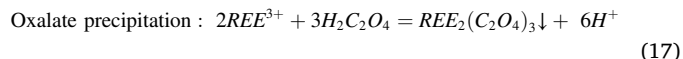
resulted in 99 % Nd leaching after 6 h (Reisdorfer et al., 2019). Belfqueh et al. studied the effects of organic acid type, concentration, and solid/liquid ratio on NdFeB magnet leaching. Acetic acid showed the highest leaching performance with leaching yields of over 90 % for Nd, Dy and Pr within acid concentrations of 1.6 to 10 mol/L and solid/liquid ratios of 0.5 to 5 %, under 60 °C (Belfqueh et al., 2023).

DESs leaching: DESs consist of a eutectic blend of Lewis or Brønsted acids with bases, thus comprising a diverse range of anionic and/or cationic species. Dissolution capabilities of DESs stem from their capacity to donate or accept electrons or protons, to form hydrogen bonds. Depending on the type of solvent being used, DESs can selectively dissolve different metal oxides. Riaño et al. employed a DES based on choline chloride and lactic acid (molar ratio 1:2) to leach out REEs from roasted magnet powder, at 70 °C for 24 h. Since highest leaching efficiency was achieved in the absence of water, DES was introduced to act as the more polar phase for further solvent extractions. This resulted in the overall recovery efficiency of 99.87 % and 99.94 % for Nd_2O_3 and Dy_2O_3, respectively (Riaño et al., 2017). Liu et al. proposed an approach which involved utilising guanidine hydrochloride–lactic acid (GUC–LAC) DES to achieve exceptionally high separation factor (>1300) between neodymium and iron, through dissolution of their respective oxide mixture. The resulting Nd_2O_3 product of 99 % purity was obtained in a dissolution step after a stripping process involving oxalic acid (Liu et al., 2020). Yu et al. introduced a method to selectively recovering REEs from spent NdFeB PMs, by utilising a hydrophobic deep eutectic solvent (HDES). A streamlined screening process identified the ternary HDES (DA: MA: TOPO = 5:5:4) for having the optimal extraction and separation efficiency for both, REEs and Fe with 99 % recovery rate. The stripped HDES demonstrated recyclability whilst maintaining stability even after five cycles (Yu et al., 2024).

4.4.2. Separation

Separation entails techniques such as precipitation, solvent extraction, ionic liquids (ILs) extraction, membrane technologies, and/or combination thereof required to selectively separate REEs from leaching liquor obtained through other routes.

Precipitation: Precipitation methods could be classified into two categories, namely selective precipitation, and co-precipitation. Nd can usually be precipitated by direct methods such as fluoride method with HF and oxalate method with $H_2C_2O_4$ (reactions (16–17)) (Abrahami et al., 2015; Lee et al., 2013). More than 99 % of Nd can be extracted from an Fe-Nd solution through selective precipitation, utilizing phosphoric acid (H_3PO_4) and ascorbic acid. (Onoda and Nakamura, 2014). Double salts precipitation ($RE_2(SO_4)_3 \cdot R_2SO_4 \cdot XH_2O$) may be an option for REEs within sulfuric acid media (reaction (18)) (Guzhov et al., 2023). NaOH has been used to adjust the pH to 3–4.3 to remove Fe as Fe(OH)$_3$, though at the expense of significant REE losses (reaction (19)) (Kikuchi et al., 2014; Rabatho et al., 2012). REEs have shown to readily precipitate with carbonate at high pH (reactions (20–21)). Carbonates are cost-effective and can easily dissolve in acids for subsequent purification processes. However, precipitation in acidic media is challenging as they require neutralisation prior to any effective carbonate precipitation (Han 2020). Furthermore, rare earth carbonates precipitated

using sodium carbonate exhibit a relatively reduced REE oxides purity of 94.2 wt. %, but with a higher impurities content, when compared with oxalic acid precipitation (Silva et al., 2019).

$$Fluoride\ precipitation:\ REE^{3+} + 3HF = REEF_3\downarrow + 3H^+ \tag{16}$$

$$Oxalate\ precipitation:\ 2REE^{3+} + 3H_2C_2O_4 = REE_2(C_2O_4)_3\downarrow + 6H^+ \tag{17}$$

$$Alkali\ precipitation:\ REE^{3+} + 3OH^- = REE(OH)_3\downarrow \tag{19}$$

$$Carbonates\ precipitation:\ 2REE^{3+} + 3CO_3^{2-} = REE_2(CO_3)_3\downarrow \tag{20}$$

$$2REE^{3+} + NH_4HCO_3 = REE_2(CO_3)_3\downarrow + 3NH_4^+ + 3H^+ \tag{21}$$

Solvent extraction: The recycling of REEs poses a significant challenge due to chemical similarities between them, especially during separation involving different sources. Acidic extractants, functioning as cation exchangers, represent the predominant choice for extracting REEs from aqueous solutions. The exchange of REEs between aqueous and organic phases occurs through a cationic exchange process, as described in reaction (22) (Judge and Azimi, 2020).

$$REE^{3+} + 3\overline{H_2A_2} = \overline{REE(HA_2)_3} + 3H^+ \tag{22}$$
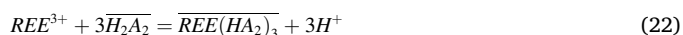
where A denotes an organic anion, and the overbar indicates species in the organic phase. Various acidic organophosphorus extractants have been used in REEs extraction processes. Organophosphorous compounds di-(2-ethylhexyl) phosphoric acid (D2EHPA), di-(2-ethylhexyl) phosphoric acid (HDEHP), saponified 2-ethylhexyl phosphonic mono-2-ethyl-hexyl ester (PC88A), and bis (2,4,4-trimethylpentyl) phosphinic acid (Cyanex 272) are some of the most widely used solvents. It has been reported that extraction capability for REEs by organophosphorus extractants decreases in the order of D2EHPA > PC88A (EHEPA) > Cyanex 272 (Yang et al., 2017; Zhang et al., 2020). However, separation factors between adjacent REEs have been shown to vary according to Cyanex 272 > PC88A > DEHPA (Banda et al., 2012). Saponified Cyanex 302 is another effective commercial reagent for Nd extraction. It was utilised by Padhan et al. to separate Nd and Dy (Padhan and Sarangi, 2015). They achieved a maximum separation factor (Dy/Nd) of 53.65 at pH = 1.2. Dy extraction reached 98 %, while Nd co-extraction was only 7.22 % after two stages of counter-current extraction in 0.125 mol/L NaCyanex 302 at A:O = 1:1. However, subsequent extraction in two counter-current stages with 0.2 mol/L NaCyanex 302 at A:O = 1:1 led to 99.79 % Nd recovery. Neutral and basic extraction of REEs is more effective in sulphate or nitrate solutions, due to a higher likelihood of ion pairing. For instance, the process of extracting REEs neutrally in a nitrate solution with tributyl phosphate (TBP) is demonstrated in reaction (23):

$$REE^{3+} + 3NO_3^- + 3\overline{TBP} = \overline{REE(NO_3)_3(TBP)_3} \tag{23}$$
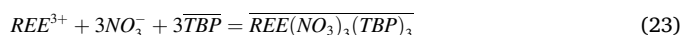
In basic extraction, anionic complexes are moved from the water-based phase to the organic phase. Compounds like tri-octyl methyl-ammonium nitrate (Aliquat 336), which are types of quaternary ammonium salts ($\overline{R_4N^+NO_3^-}$), have shown effectiveness in isolating rare earth elements. This extraction process is succinctly illustrated by the following reaction:

$$REE^{3+} + 3NO_3^- + x\overline{\left(R_4N^+NO_3^-\right)_n} = \overline{REE(NO_3)_3 \cdot xnR_4N^+NO_3^-} \qquad (24)$$
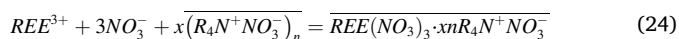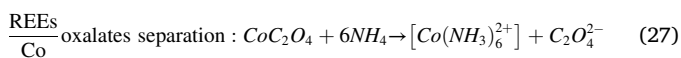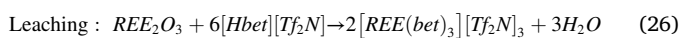
Aliquat 336 favours lighter over heavier rare earth in nitrate solutions, differing from many cations exchanger and solvating extractant that refer elements with higher atomic numbers. Lu et al. achieved high-purity Nd (>99 %) with 95 % recovery rate from a didymium nitrate solution using Aliquat 336 in a 45-stage tube-type mixer-settler (Lu et al., 1989). Equally, another study outlined a solvent-extraction method to recover magnet-grade Nd_2O_3 from a light rare earth nitrate solution. It involves employing a 0.50 mol/L Aliquat 336 nitrate in Shellsol AB through 8 extraction and 6 scrubbing stages (Preston J.S 1996).

Ionic liquids (ILs) extraction: ILs are entirely composed of ions. They have excellent solvating capabilities for various compounds, with high thermal, chemical, and electrochemical stability. Crucially, IL properties are tuneable, by selecting specific cation-anion combinations for a given application (*Kaim et al., 2023*). In a typical IL extraction process, a large volume of low-concentration REEs aqueous solution is contacted with a small volume of IL. Through various extraction mechanisms, REE ions form chelates with IL anions, cations, or both. These chelated REEs then move from the aqueous solution to the IL phase (Wang et al., 2017). Riaño et al. successfully synthesised and utilised trihexyl(tetradecyl) phosphonium nitrate ($[P_{66614}][NO_3]$) to demonstrate its effectiveness in separating and recovering REEs from NdFeB magnets. The process involved obtaining iron-free leachate using nitric acid followed by solvent extraction at pH 2. Cobalt was separated using $[P_{66614}][NO_3]$ alone, while Nd and Dy were extracted using $[P_{66614}][NO_3]$ with ethylenediaminetetraacetic acid (EDTA) as a selective complexing agent. Overall, the method resulted in the recovery of metal oxides with high purities (CoO (99.8 %), Nd_2O_3 (99.6 %), and Dy_2O_3 (99.8 %)), and offered potential benefits to industrial processes (Riaño and Binnemans. 2015). The general extraction mechanism for REEs extraction can be written as:

$$REE^{3+} + 3NO_3^- + n[P_{66614}]NO_3 \leftrightarrow REE(NO_3)_{3+n}[P_{66614}]_n \qquad (25)$$

Dupont proposed a novel recycling process for NdFeB magnets using carboxyl-functionalised ionic liquid known as betainium bis(trifluoromethylsulfonyl)imide ($[Hbet][Tf_2N]$). The process involves roasting NdFeB magnets to convert elements into oxides, before dissolving in $[Hbet][Tf_2N]$-H_2O systems. Leaching with $[Hbet][Tf_2N]$-H_2O at 80 °C separates valuable REEs/Co-rich aqueous phase from an iron-rich ionic liquid phase, whilst stripping with oxalic acid removes Fe to produce REEs/Co oxalates. Similarly, aqueous ammonia separates REEs and Co to produce REEs oxalates with over 99.9 % purity (Dupont and Binnemans 2015). The key process reactions are listed below:

$$\text{Leaching}: \ REE_2O_3 + 6[Hbet][Tf_2N] \rightarrow 2\left[REE(bet)_3\right][Tf_2N]_3 + 3H_2O \qquad (26)$$

$$\frac{REEs}{Co} \text{oxalates separation}: CoC_2O_4 + 6NH_4 \rightarrow \left[Co(NH_3)_6^{2+}\right] + C_2O_4^{2-} \qquad (27)$$

Nd and Pr separation can then be conducted from a chloride solution of NdFeB magnet leach liquor. In a comparative analysis of extractants, bi-functional ionic liquids (Bif-ILs) such as tri-octylmethylammonium bis(2,4,4-trimethylpentyl)phosphate (R_4NCy) and tri-octylmethylammonium di(2-ethylhexyl)phosphate (R_4ND) exhibit higher extraction efficiency, when compared with conventional extractants such as tri-octyl methyl ammonium chloride (Aliquat 336), bis (2,4,4-trimethylpentyl)phosphinic acid (Cyanex 272), and di-2-ethylhexyl phosphoric acid (D2EHPA) under identical experimental conditions. The extraction efficiency sequence for Nd and Pr is, $R_4NCy > R_4ND >$ Cyanex 272 > D2EHPA > Aliquat-336 (Padhan and Sarangi, 2017). In another study, Xue et al. created carboxylic acid-based ionic liquids with low viscosity, namely [A336][BTA] and [A336][OTA], to selectively extract Nd(III) from waste NdFeB magnets. The optimum extraction conditions for [A336][OTA] were fine-tuned using response surface methodology, to achieve an extraction efficiency of 99.1 % (Xue et al., 2022). The following reaction mechanism was proposed for the extraction of REEs via ionic liquids M, where M denotes R_4NCy, [A336] [BTA] or [A336][OTA]:

$$REE^{3+} + 3Cl^- + n[M] \leftrightarrow [M]_n REECl_3 \qquad (28)$$
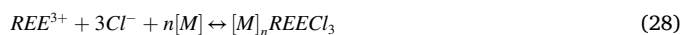
Equally, Nockemann and Ritesh, proposed a technology to both, extract and separate REEs from PMs in an aqueous IL medium. The technology has been patented and is currently seeking approval for commercialisation (Nockemann and Ritesh, 2018). ILs are recognised as environmentally friendly alternatives to organic solvents, primarily due to their low volatility and non-flammable properties. However, there remain challenges including scale-up limitations involving actual magnet waste, relatively high cost associated with predominantly fluorinated reagents, and the imperative need for reusability and recycling of ILs after extracting REEs.

Membrane technology: Membrane separation has received much attention in recent years for separation and purification owing to its benefits such as higher selectivity, lower energy requirements, with little to no liquid discharge. Yadav et al. conducted a study on the separation of REEs by employing a hollow fibre membrane supported with 2-ethyl-hexyl 2-ethyhexylphosphonic acid (EHEHPA). The process exhibited greater selectivity for Dy than Nd and Pr. Dy was subsequently obtained with a purity of 97 % at 94 % recovery (Yadav et al., 2018). In another study, Ni'am et al. tested hollow fibre supported liquid membrane with D2EHPA and Cyanex 272 to separate REEs from magnet recycling. In this system, respective purities of Nd, Dy, and Pr reached 58.62, 98.46, and 85.59 %, at 63.13, 15.21, and 56.29 % recovery, without iron co-extraction (Ni'am et al., 2020). In a separate study, Islam et al. investigated a membrane, supported by a neutral extractant tetraoctyl diglycolamide (TODGA), to separate REEs from scrap magnets. The concentration of REEs progressively rose in the permeated stream over time to produce recovered REE oxides with purity and yield exceeding 99.5 % and 95 %, respectively (Islam et al., 2022). To implement membrane techniques for large-scale REEs recovery, key challenges include improving ion selectivity in nanofiltration membranes, limited studies on economic feasibility for REE extraction, and membrane stability under aggressive environments involving acidic and/or alkaline conditions (Elbashier et al., 2021). Nanofiltration of solutions containing metal ions (e.g. REE) is performed using membranes with different molecular weight cutoff (MWCO) values in the presence of complexing agents (e.g. EDTA, DTPA). The addition of chelating agents increases metal rejection because the chelate species are larger than the free metal ions. The metal ions can then be further separated from the chelating agent for their recovery (Teresa et al., 2019).

4.5. Electrochemical methods

The separation and production of REEs using electrolysis have been studied extensively. Direct electrochemical refining: Kobayashi et al. investigated electrolysis using molten fluoride (LiF–CaF_2–NdF_3) with an iron group (RE-IG) alloy diaphragm. REE containing waste was used as the anode and was anodically dissolved by molten salt electrolysis (Kobayashi et al., 2012). The process was further developed by Yasuda et al. using molten NaCl-KCl-$RECl_3$ as the electrolyte to prepare REE-Ni alloy from magnet scrap (Fig. 5(a)). The process reportedly allowed for simultaneous extraction and separation of materials (Yasuda et al., 2016). However, this is yet to be elucidated since many issues ought to be resolved before treating the actual scrap. Yusheng et al. examined the potential for reclaiming Nd and Pr from waste materials containing rare earth PMs through an electrolysis process carried out in a molten LiF-CaF_2 medium (Fig. 5(b)) (Yusheng et al., 2020). Notably, this process stands out for its environmental appeal due to the absence of any released anode gases. Furthermore, this method allows for the direct transformation of separated rare-earth ions into rare-earth metals at cathode via an electrolysis process, whilst simultaneously generating a
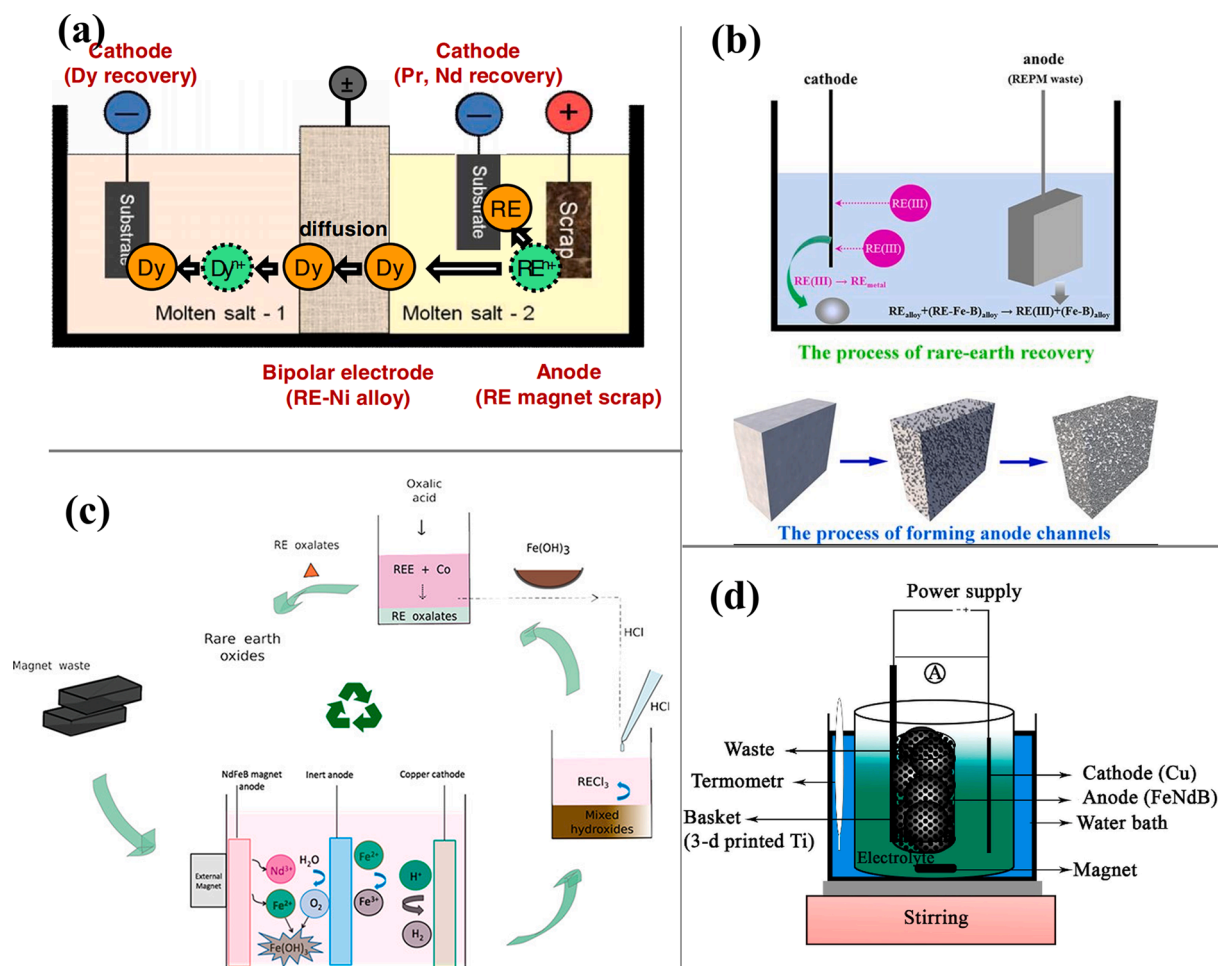
Fig. 5. (a) Separation and recovery process of rare earth (RE) metals from scraps using molten salt and alloy diaphragm to maintain the high separation ability of Dy in a continuous operation. Reproduced under permission by Elsevier (Yasuda et al., 2016). (b) REEs are selectively separated from REPM wastes. Reproduced under permission by Elsevier (Yusheng et al., 2020); (c) Anodic dissolution of NdFeB permanent magnet scrap. Reproduced under permission by Elsevier (Venkatesan et al., 2018). (d) Schematic of electro-leaching of magnet scrap in a Ti basket. Reproduced under permission by Elsevier (Makarova et al., 2020).

porous Fe_2B alloy and metallic Fe as byproducts

Similarly, Konishi et al. performed an anodic potential static electrolysis using Nd–Fe–B magnet as electrodes. REE ions were shown to have reduced on the anode compartment side of the alloy diaphragm. Reduced REE ions, on the bipolar diaphragm reacted with the bipolar electrode to form RE alloys and diffused into the diaphragm. The diffusing REEs on the electrode were anodically re-dissolved on the surface of cathode compartment side to be precipitated as highly pure metal via molten salt (Konishi et al., 2014). Martinez et al. investigated different combinations and compositions of salts under various temperatures and found that LiCl-based melt is a better electrochemical option than NaCl-based electrolyte. However, under-potential deposition (UPD) of lithium on neodymium made it difficult to deposit Nd free of Li. It was proposed that Li co-deposition could be avoided by increasing the activity of Nd ions in the electrolyte (Martinez et al., 2013).

Electrochemical dissolution: Venkatesan et al. investigated anodic dissolution to electrochemically separate REEs from non-REEs present in magnet scraps. By carefully controlling factors such as electrode and cell potentials, current density, and electrolyte chemistry, the authors managed to establish the dissolution of REEs and ferrous metals which can be reprecipitated as oxides/hydroxides in the solution or as metals on cathode (Venkatesan et al., 2016). As part of further studies, the authors also demonstrated selective extraction of REEs from magnet

waste under room temperature (Venkatesan et al., 2018). The proposed route consisted of partial leaching with an acid (HCl), followed by the transfer of (partial) leachate and undissolved magnet waste into anolyte side of a two-compartment reactor that was separated by an anion exchange membrane. Within the reactor, catholyte side consisted of sodium chloride solution. The Fe (II) present in the leachate was oxidised and precipitated as $Fe(OH)_3$, thus allowing for more than 95 % of REEs to be extracted into the solution. Oxalic acid was subsequently used to selectively precipitate REEs as rare-earth oxalates, as depicted in Fig. 5 (c). Makarova et al. used a 3D-printed titanium basket to leach metals from magnet scraps (Makarova et al., 2020) (Fig. 5(d)). Experimental results showed the concentration of acid and current density had a significant impact on the leaching of REEs. Moreover, the addition of oxalic acid reduced the energy consumption and improved REEs recovery.

4.6. Bio-metallurgical methods

Bioleaching is understood to be more efficient than chemical leaching in terms of costs, use of chemicals, and pollution due to emissions and contaminated residues. Auerbach et al., investigated recycling of EoL magnets using bioleaching involving different bacteria (Auerbach et al., 2019). The study entailed agitating batches of powder magnet samples of different alloy compositions and particle sizes. The study found that all samples can be successfully bioleached, with highest

leaching efficiencies achieved from *Acidithiobacillus* and *Leptospirillum ferrooxidans*. REEs were subsequently extracted from the media solution, using precipitation with oxalic acid and a two-step extraction method. Up to 100 % of REEs of 98 % purity, were reportedly achieved using these methods (Auerbach et al., 2019). Rasoulnia et al. have extensively explored bioleaching of REEs from primary (PMs) and secondary sources (Rasoulnia et al., 2021).

5. Concluding remarks

According to UK's EoL vehicle regulations (adopted from ELV Directive 2005/53/EC), 85 % of a vehicle's mass must be recycled or reused with the further 10 % ought to be used for energy generation. Therefore, efficient recycling of all components needs to take place, including the EMs for traction. It is particularly significant because, unlike batteries, there are no specific regulations aimed at increasing the recycling efficiencies of EMs. Therefore, such regulatory guidelines work in favour of facilitating the development of new technologies to recycle valuable REEs such as Nd, Dy and Pr which are crucial to the future of transportation's electrification. These elements are not native to UK and their recovery through recycling would facilitate a resilient supply chain. To date, only 3 to 8 % of REEs are currently being recycled globally. This is because, most recyclers focus on easy-to-recover, large-volume metals such as steel, aluminium, and copper. The magnets are difficult to retrieve from EM rotors and if left intact, they are lost during the shredding process since they stick to process units and eventually end up in various products in a very diluted form.

There is a significant opportunity for component remanufacturing and closed-loop recycling of CMs in EMs. However, current designs of EMs are biased towards performance and ease of manufacturing. Very few manufacturers have considered EoL and as a result, most EMs are currently being recycled sub-optimally with a large amount of intrinsic active material value (40 to 60 %) being lost as magnets. Obtaining magnets in good condition during disassembly is of prime interest, particularly if they are to be reused, however this is a very challenging undertaking. Disassembly workshops (for magnets) require high investment and operational costs and are limited in their ability to process different types of e-machines. As previously mentioned, recyclers tend to use easy and highly inefficient (destructive) methods such as shredding that prioritise speed over intrinsic materials value (i.e., REEs). Ever-changing EM design with little or no sustainable design concepts (DfD, DfReman etc.) and manufacturing techniques employed during assembly make EM disassembly practices unattractive and obsolete. Further complexity arises from the fact that NdFeB alloy magnets are brittle and difficult to protect from damage during disassembly. Coated sintered NdFeB magnets are assembled (in different shapes and configurations) and fixed in such a way that conventional disassembly techniques are deemed unsuitable. Thus, making the retrieval task extremely challenging and labour-intensive. Similar arguments can be extended to the retrieval of other components such as copper windings. Although some research on EMs disassembly has been reported, they are yet to be properly tested as commercially viable technique(s). To date, recycling of NdFeB PM scraps has mainly been focused on the recovery of REEs. The research community has been actively exploring various technologies in recent years, to efficiently recover REEs from EoL magnets, production wastes (e.g., swarf and turnings) and even REE-containing primary materials. Reported methods include direct reuse, reprocessing after hydrogen decrepitation, pyrometallurgy, hydrometallurgy, electrochemistry/ electrometallurgy, bio-metallurgy, and combination of thereof.

Direct reuse is not always feasible, especially when magnets have incurred damage or lost their magnetic properties due to factors such as corrosion or demagnetisation. The use of hydrogen to separate and recycle NdFeB alloy magnets has been developed and pilot-scale manufacturing, and recycling facilities have been established. These techniques are based on short-loop recycling steps to manufacture PMs

from recycled materials, with quality reportedly close to that made from virgin materials. However, such proposed techniques require relatively clean magnet scraps, and recycled materials from currently employed shredding-based processes may not be suitable.

To summarise, disassembly of EoL EMs and the subsequent recovery of PMs through recycling is yet to be established. As such, further research is still deemed necessary to deduce commercially viable solutions that not only address the recovery of REEs, but also the retrieval of other important materials such as copper, electrical steel, and aluminium alloys. Copper is another key metal for the electrification of transport, energy supply and industry. It is an essential material for low-resistive loss of most electric devices including EMs, batteries, solar panels, and wind turbines. Unlike iron and aluminium, which are both equipped with rather abundant ore deposits, copper supply on the other hand is limited, i.e., there are insufficient resources of accessible ores to meet the rapidly growing market demand. It is proposed that the global demand for refined copper will drastically grow in next decades due to the electrification of industry, transport, and households. The total demand for copper of about 16 Mt in 2010 is expected to grow to 23 Mt in 2030, at approximately 87 kt of CO_2 emissions per kt of copper depending on the technologies being used in the foreseeable future.

Equally, aluminium and its alloys are also considered to be an important metal group in terms of greenhouse gas emissions and environmental impacts (red mud), production volumes and energy (electricity) demand involving primary synthesis via electrolysis. The metal has one of the highest levels of embodied energy and emissions of all mass-produced metals, with a global average of $11\sim25$ tonnes of CO_2 per tonne of produced aluminium. The global per capita consumption of aluminium is growing partly due to demands for lightweight EV designs and other industrial and consumer products. This trend serves to amplify opportunities for the use of more recycled aluminium during production in the coming decades towards a greener and sustainable supply chain. The advantage of using scrapped aluminium is that up to 95 % of energy can be saved by (re-)melting, when compared with electrolysis technique(s) used to produce aluminium from ore (bauxite).

Life cycle assessment (LCA) of NdFeB magnets has been reported for primary production using major rare earth ores and the associated processes, for secondary production via magnet-to-magnet recycling processes, and for comparison between primary and secondary production routes. However, it is noticed that there is the lack of a standardised LCA approach specific to REEs and the insufficiency of consistent data for different processing routes. LCA of EMs recycling has not been reported yet, not only because reliable database is scarce for the current recycling routes which focus on easy-to-recover and large-volume materials, but also no circular economy-based approaches from the disassembly of EoL EMs to the recycling/ recovery of components and multiple materials have been established.

To conclude, the impetus of current endeavour is to work towards building a resilient supply chain of CMs for the net-zero production of EVs, for a country/region like UK as part of UK's electrification initiative. Firstly, an appropriate CE approach should be (i.e., reuse, remanufacture and/or closed-loop recycling) to replace the current approach adopted by the recycling industry which focuses on easy-to-recover, large-volume metals such as steel and aluminium, whilst failing to recover REEs-based components (i.e., Magnets) which account for 40 to 60 % of EM's value. Secondly, commercially viable and workable disassembly solutions should be developed to handle high-volume EoL EMs of varying design approaches. It is also equally important for OEMs to adopt CE-based motor design concepts to facilitate reuse, remanufacture and/or upcycling of parts/components at the EoL stage. That way the upcycling of valuable REEs and other metals such as copper and aluminium can be easily realised towards a sustainable economy. With only 3 to 8 % of REEs being currently recycled globally, attention must be paid towards developing commercially viable processes to efficiently recover REEs from different sources.

CRediT authorship contribution statement

Zushu Li: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Ahmed Samir Hamidi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Zhiming Yan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Anwar Sattar:** Writing – review & editing, Data curation. **Sumit Hazra:** Writing – review & editing, Writing – original draft, Supervision. **Juliette Soulard:** Writing – review & editing, Writing – original draft, Data curation. **Caroline Guest:** Writing – review & editing, Writing – original draft, Data curation. **Syed Hadi Ahmed:** Writing – review & editing, Data curation. **Friya Tailor:** Writing – review & editing, Data curation.

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.

Data availability

No data was used for the research described in the article.

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