UNIVERSIDADE FEDERAL DO PARANÁ

THAMIRES MARTINHO PRADOS

AVALIAÇÃO DO CICLO DE VIDA DA PRODUÇÃO DE ÍMÃS DE TERRAS RARAS DE ND-FE-B

JANDAIA DO SUL

2025

THAMIRES MARTINHO PRADOS

AVALIAÇÃO DO CICLO DE VIDA DA PRODUÇÃO DE ÍMÃS DE TERRAS RARAS DE ND-FE-B

Dissertação apresentada ao curso de Pós-Graduação em Engenharia e Tecnologia Ambiental, Setor de Palotina, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Engenharia e Tecnologia Ambiental.

Orientadora: Profa. Dra. Leda Maria Saragiotto Colpini

Coorientador: Prof. Dr. Giancarlo Alfonso Lovón-Canchumani

JANDAIA DO SUL

2025

DADOS INTERNACIONAIS DE CATALOGAÇÃO NA PUBLICAÇÃO (CIP)
UNIVERSIDADE FEDERAL DO PARANÁ
SISTEMA DE BIBLIOTECAS – BIBLIOTECA JANDAIA DO SUL

Prados, Thamires Martinho
Avaliação do ciclo de vida da produção de imãs de terras raras Nd-Fe-B. / Thamires Martinho Prados. – Jandaia do Sul, 2025.
1 recurso on-line : PDF.

Dissertação (Mestrado) – Universidade Federal do Paraná, Setor Palotina, Mestrado em Engenharia e Tecnologia Ambiental.
Orientadora: Profa. Dra. Leda Maria Saragiotto Colpini.
Coorientador: Prof. Dr. Giancarlo Alfonso Lovón-Canchumani.

1. Sustentabilidade. 2. Impacto ambiental. 3. Elementos de terras raras. 4. Mineração. 5. SimaPro. I. Colpini, Leda Maria Saragiotto. II. Lovón-Canchumani, Giancarlo Alfonso. III. Universidade Federal do Paraná. IV. Título.

CDD 628

Bibliotecário: César A. Galvão F. Conde - CRB-9/1747

MINISTÉRIO DA EDUCAÇÃO
SETOR PALOTINA
UNIVERSIDADE FEDERAL DO PARANÁ
PRÓ-REITORIA DE PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO ENGENHARIA E TECNOLOGIA AMBIENTAL - 40001016173P5

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA E TECNOLOGIA AMBIENTAL da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **THAMIRES MARTINHO PRADOS**, intitulada: **Avaliação do Ciclo da Vida da Produção de Ímãs de terras raras de Nd-Fe-B**, sob orientação da Profa. Dra. LEDA MARIA SARAGIOTTO COLPINI, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de mestra está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

Palotina, 28 de Fevereiro de 2025.

Assinatura Eletrônica
28/02/2025 11:48:38.0
LEDA MARIA SARAGIOTTO COLPINI
Presidente da Banca Examinadora

Assinatura Eletrônica
28/02/2025 13:20:58.0
LILIAN BECHARA ELABRAS VEIGA
Avaliador Externo (INSTITUTO FED. DE EDUC., CIÊNCIA E TECNOL. DO RIO DE JANEIRO)

Assinatura Eletrônica
28/02/2025 14:29:10.0
MARCELO GUIMARÃES ARAÚJO
Avaliador Externo (FUNDAÇÃO OSWALDO CRUZ - RIO DE JANEIRO)

Assinatura Eletrônica
28/02/2025 11:49:26.0
GIANCARLO ALFONSO LOVON CANCHUMANI
Coorientador(a) (UNIVERSIDADE FEDERAL DO PARANÁ)

TERMO DE APROVAÇÃO

Dedico esta dissertação aos meus avós, que partiram durante o caminho dessa jornada, mas cujas lições de vida, amor incondicional e força continuam a me guiar. Eles nunca pararam de acreditar em mim, e essa confiança foi um alicerce fundamental para que eu chegasse até aqui. Embora não estejam mais fisicamente presentes, sua presença em minha memória e coração foram essenciais em cada etapa dessa trajetória. Esta conquista é, em grande parte, resultado de suas inspirações e de todo o amor que sempre me ofereceram. Que o legado de sabedoria, carinho e dedicação deles seja sempre lembrado em tudo o que eu fizer.

AGRADECIMENTOS

Primeiramente, minha eterna gratidão a Deus, fonte de toda força e inspiração. Foi Ele quem me guiou nos momentos de incerteza, me concedeu a coragem para seguir adiante e me abençoou com a sabedoria necessária para vencer os desafios dessa jornada. Sem a Sua luz, nada disso seria possível.

À minha querida orientadora, Leda Maria Saragiotto Colpini, palavras não são suficientes para expressar minha gratidão por todo o apoio, dedicação e sabedoria que me ofereceu ao longo dessa caminhada. Em cada conversa, em cada conselho, você foi o alicerce que tornou os momentos de incerteza mais leves e as dificuldades mais superáveis. Sua paciência e atenção para comigo, além de me guiar com imensa sabedoria, fizeram de você uma mentora única, não apenas na esfera acadêmica, mas também na vida. Sou profundamente grata por cada ensinamento e por estar ao meu lado nas vitórias e nos obstáculos, fazendo parte das minhas conquistas diárias.

Ao meu coorientador, Giancarlo Alfonso Lovón-Canchumani, minha sincera gratidão por toda a sua contribuição para minha formação acadêmica e profissional. Durante todos os anos que passamos juntos nessa jornada, você foi um exemplo de dedicação, conhecimento e sabedoria. Seu apoio constante e os valiosos ensinamentos que compartilhou me ajudaram a crescer imensamente, tanto como profissional quanto como pessoa. Obrigada por acreditar em mim e por me ajudar a alcançar novos horizontes.

À minha mãe, que sempre foi meu pilar e minha maior fonte de força. Agradeço imensamente por nunca ter deixado que eu desistisse, por acreditar em mim mesmo quando as dificuldades pareciam insuperáveis. Seu amor incondicional, sua confiança e apoio constantes foram o combustível que me impulsionaram a seguir em frente. Seu sacrifício e carinho sempre foram a base do meu crescimento, e sou imensamente grata por tudo o que fez e faz por mim.

As minhas amigas e companheiras de caminhada, Thays Valeriano de Oliveira e Isadora Marcela de Campos, palavras de gratidão não são suficientes para descrever o quanto o apoio de vocês significou para mim. Durante toda essa jornada, vocês nunca soltaram a minha mão, sempre estiveram ao meu lado, oferecendo palavras de conforto, apoio e carinho, especialmente nos momentos de crise. A amizade de vocês tem sido uma fonte inesgotável de energia positiva, e a troca de experiências, conquistas e até as dificuldades enfrentadas juntas tornaram essa

trajetória ainda mais significativa. Nossa amizade é um presente que levarei para sempre comigo.

A todos que estiveram comigo, direta ou indiretamente, minha mais profunda gratidão. Cada um de vocês foram fundamentais na realização deste sonho, e sou muito abençoada por ter todos vocês ao meu lado.

“Palavras são, na minha nada humilde opinião, nossa inesgotável fonte de magia.’’ (ALVO DUMBLEDORE, Harry Potter e as Relíqueas da Morte)

RESUMO

Os elementos de terras raras (ETR) são fundamentais para diversas aplicações tecnológicas, desempenhando um papel estratégico na indústria brasileira, especialmente nos setores de energia renovável, eletrônica e mobilidade elétrica. A crescente demanda por esses materiais impulsiona a necessidade de um fornecimento sustentável e eficiente, considerando seus impactos ambientais e econômicos. Sendo amplamente utilizados na fabricação de ímãs permanentes de neodímio-ferro-boro (Nd-Fe-B). No entanto, a produção desses ímãs está associada a impactos ambientais significativos ao longo de sua cadeia produtiva, desde a mineração até a fabricação final. Este estudo tem como objetivo avaliar o ciclo de vida (ACV) dos ímãs de Nd-Fe-B, considerando a realidade brasileira. A metodologia seguiu as diretrizes das normas ISO 14040 e ISO 14044, que estabelecem princípios, requisitos e diretrizes para a ACV. A modelagem foi feita no *software* Sankey e tratamento dos dados no *software* SimaPro 9.1, permitindo a quantificação detalhada dos impactos ambientais ao longo da cadeia produtiva dos ímãs de Nd-Fe-B. Além disso, foram utilizados dados do banco EcoInvent e fontes da literatura para aprimorar a representatividade dos processos analisados, garantindo uma abordagem metodológica robusta. Os resultados indicam que a fase da mineração apresenta alto impacto ambiental, devido ao elevado consumo de energia, água e emissões de particulados. A fase de *roasting* destacou-se como a mais impactante, contribuindo significativamente para a formação de material particulado fino e emissões de gases de efeito estufa. Na fase de produção dos óxidos, a lixiviação e a pré-separação foram as fases mais críticas, com alto consumo de água e uso intensivo de reagentes químicos, como ácido clorídrico, aumentando a eutrofização marinha e a radiação ionizante. Já na fase de fabricação dos ímãs, a usinagem foi identificada como a etapa mais impactante, contribuindo para o aquecimento global, depleção da camada de ozônio e elevado consumo de água. Diante dos impactos observados, este estudo reforça a necessidade de medidas de mitigação, incluindo a implementação de políticas públicas voltadas para a regulação ambiental da mineração de ETRs, incentivos à economia circular e adoção de tecnologias emergentes, como processos hidrometalúrgicos mais eficientes e técnicas avançadas de reciclagem de ímãs. Além disso, investimentos em fontes energéticas renováveis podem reduzir a pegada de carbono da produção desses materiais, incluindo a otimização do consumo de recursos, o reaproveitamento de materiais e o uso de fontes energéticas mais sustentáveis. Além disso, recomenda-se a exploração de tecnologias de reciclagem para reduzir a dependência da extração primária e minimizar os impactos ambientais associados à produção de ímãs de terras raras.

Palavras-chave: Sustentabilidade. Impacto Ambiental. Elementos de terras raras. Mineração. SimaPro.

ABSTRACT

Rare earth elements (REE) are essential for various technological applications and play a strategic role in Brazilian industry, especially in the renewable energy, electronics and electric mobility sectors. The growing demand for these materials drives the need for a sustainable and efficient supply, considering their environmental and economic impacts. They are widely used in the manufacture of neodymium-iron-boron (Nd-Fe-B) permanent magnets. However, the production of these magnets is associated with significant environmental impacts throughout its production chain, from mining to final manufacture. This study aims to evaluate the life cycle (LCA) of Nd-Fe-B magnets, considering the Brazilian reality. The methodology followed the guidelines of ISO 14040 and ISO 14044, which establish principles, requirements and guidelines for LCA. The modeling was carried out using Sankey software and the data was processed using SimaPro 9.1 software, enabling detailed quantification of the environmental impacts along the Nd-Fe-B magnet production chain. In addition, data from the EcoInvent database and literature sources were used to improve the representativeness of the processes analyzed, ensuring a robust methodological approach. The results indicate that the mining phase has a high environmental impact, due to the high consumption of energy, water and particulate emissions. The roasting phase stood out as the most impactful, contributing significantly to the formation of fine particulate matter and greenhouse gas emissions. In the oxide production phase, leaching and pre-separation were the most critical phases, with high water consumption and intensive use of chemical reagents such as hydrochloric acid, increasing marine eutrophication and ionizing radiation. In the magnet manufacturing phase, machining was identified as the most impactful stage, contributing to global warming, depletion of the ozone layer and high water consumption. In view of the impacts observed, this study reinforces the need for mitigation measures, including the implementation of public policies aimed at the environmental regulation REE mining, incentives for the circular economy and the adoption of emerging technologies, such as more efficient hydrometallurgical processes and advanced magnet recycling techniques. In addition, investments in renewable energy sources can reduce the carbon footprint of the production of these materials, including the optimization of resource consumption, the reuse of materials and the use of more sustainable energy sources. In addition, it is recommended that recycling technologies be explored to reduce dependence on primary extraction and minimize the environmental impacts associated with the production of rare earth magnets.

Keywords: Sustainability. Environmental impact. Rare earth elements. Mining. SimaPro.

SUMÁRIO

1 INTRODUÇÃO

Os elementos de terras raras (ETR) são um conjunto de 17 elementos químicos, incluindo os 15 lantanídeos, além do escândio (Sc) e ítrio (Y) [1-3]. Esses elementos possuem propriedades físico-químicas semelhantes, tornando-se essenciais para diversas aplicações tecnológicas e industriais, especialmente no setor de energia renovável, eletrônica, catalisadores e manufatura de ímãs permanentes [4-6]. Os ETR podem ser categorizados em terras raras leves (cério, lantânio, praseodímio, neodímio, promécio, európio, gadolínio e samário) e terras raras pesadas (disprósio, térbio, hólmio, érbio, túlio, itérbio, lutécio e ítrio) [7].

Dentre suas principais aplicações, destaca-se a produção de ímãs de neodímio-ferro-boro (Nd-Fe-B) [8,9], amplamente utilizados em turbinas eólicas, veículos elétricos e dispositivos eletrônicos avançados [10-13]. A demanda por esses ímãs tem crescido exponencialmente, representando aproximadamente 20% do consumo global de ETR [14]. No entanto, essa dependência mundial é um fator crítico, pois a União Europeia classifica os ETR como matérias-primas estratégicas devido à sua alta importância econômica e ao risco de fornecimento [15,16]. Atualmente, a China domina a cadeia produtiva desses elementos, suprindo mais de 60% da demanda global, enquanto países como Brasil, Austrália, Uganda e Chile buscam alternativas para expandir suas atividades de exploração e produção [17,18].

A extração e o processamento de ETR geram impactos ambientais significativos, sendo caracterizados pelo alto consumo de energia e pela liberação de rejeitos tóxicos e radioativos [19-21]. Estudos indicam que a produção de uma tonelada de óxidos de terras raras (REO) pode resultar na emissão de 60.000 m^3 de gases de escape, 200 m^3 de águas residuais ácidas e 1,4 tonelada de rejeitos radioativos [22]. A mineração a céu aberto e subterrânea, frequentemente necessária para a extração de ETR, demandam grande quantidade de energia, água e produtos químicos, o que resulta na emissão de CO_2 e poluentes atmosféricos [23,24]. O processo de extração e o refino dessas substâncias envolvem processos químicos intensivos, como lixiviação ácida e extração por solvente, que resultam na contaminação do solo e dos recursos hídricos [20,25].

Diante desses desafios, a avaliação do ciclo de vida (ACV) surge como uma ferramenta essencial para quantificar os impactos ambientais dos ETR e propor estratégias de mitigação. Padronizada pelas normas ISO 14040 e ISO 14044, a ACV permite a identificação dos principais pontos críticos do ciclo produtivo, desde a extração da matéria prima até o descarte final, fornecendo subsídios para a adoção de práticas mais sustentáveis [26,27,13]. A recuperação de ímãs permanentes de terras raras tem sido considerada uma alternativa viável para minimizar os impactos ambientais e reduzir a dependência da extração primária [28]. Além disso, a economia circular tem ganhado destaque como um modelo de produção que busca reduzir o desperdício de materiais e incentivar a reutilização e reciclagem desses elementos [29,30].

Neste contexto, este estudo tem como objetivo avaliar o ciclo de vida da produção de ímãs de Nd-Fe-B no Brasil, considerando as especificidades do setor energético e de transporte no país. A partir dessa análise, serão propostas medidas mitigadoras para reduzir os impactos ambientais associados à sua produção, contribuindo para um modelo de desenvolvimento mais sustentável no setor de terras raras.

REFERÊNCIAS

[1] N. Krishnamurthy, C.K. Gupta, Extractive metallurgy of rare earths (1st ed.) (2004).

[2] A. Masmoudi-Soussi, I. Hammas-Nasri, K. Horchani-Naifer, M. Férid, Rare earths recovery by fractional precipitation from a sulfuric leach liquor obtained after phosphogypsum processing. Hydrometallurgy 191 (2020)105253. https://doi.org/10.1016/J.HYDROMET.2020.105253

[3] W. Nie, R. Zhang, Z. He, J. Zhou, M. Wu, Z. Xu, R. Chi, H. Yang, Research progress on leaching technology and theory of weathered crust elution-deposited rare earth ore. Hydrometallurgy 193 (2020) 105295. https://doi.org/10.1016/J.HYDROMET.2020.105295

[4] A. Greenfeld, T.E. Graedel, The omnivorous diet of modern technology. Resour Conserv Recycl 74 (2013) 1–7. https://doi.org/10.1016/J.RESCONREC.2013.02.010

[5] J. Wübbeke, Rare earth elements in China: policies and narratives of reinventing an industry. Resour Policy 38 (2013) 384–394. https://doi.org/10.1016/J.RESOURPOL.2013.05.005

[6] B. Zhou, Z. Li, C. Chen, Global potential of rare earth resources and rare earth demand from clean technologies. In: Minerals, 7 (2017) MDPI AG. https://doi.org/10.3390/min7110203

[7] L. Depraiter, S. Goutte, The role and challenges of rare earths in the energy transition. Resources Policy 86 (2023). https://doi.org/10.1016/j.resourpol.2023.104137

[8] H. Jin, K. Geada, I. Sousa, H. Ghaderi, A. Bevan, M. Zakotnik, C Handwerker, Life Cycle Assessment of Emerging Technologies in the Recovery of Hard Disk Drive Value. Resource. Conserve. Recycle 157 (2020). https://doi.org/10.1016/j.resconrec.2020.104781

[9] R. Eggert, C. Wadia, C. Anderson, D. Bauer, F. Campos, L. Meinert, P. Taylor, Rare Earths: Market Disruption, Innovation and Global Supply Chains. Anu. Environ. Rev. Resource. 41 (2016) 199-222. https://doi.org/10.1146/annurev-environ-110615-085700

[10] J. Amaral, Diagnosis of trends for accessing alternative sources of rare earths from fnished products: recycling of permanent magnets. UFRJ (2014).

[11] K. Habib, H. Wenzel, Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. J Clean Prod 84 (2014) 348–359. https://doi.org/10.1016/J.JCLEPRO.2014.04.035

[12] D.D Imholte, R. Nguyen, A. Vedantam, M. Brown, A. Iyer, B. Smith, J. Collins, C. Anderson, B. O'kelley, An assessment of U.S. rare earth availability for supporting

U.S. WIND ENERGY GROWTH TARGETS (2017).
https://www.sciencedirect.com/science/article/pii/S0301421517307383

[13] A. Schreiber, J. Marx, P. Zapp, Life Cycle Assessment studies of rare earths production—fndings from a systematic review. Sci Total Environ 791 (2021) 148257. https://doi.org/10.1016/J.SCITOTENV.2021.148257

[14] K. Habib, P. Schibye, A. Vestb, V. Dall, H. Wenzel, Material Flow Analysis of NdFeB Magnets to Denmark: A Comprehensive Sampling and Waste Stream Analysis Approach. Environ. Sci. Technol. 48 (2014) 12229–12237 https://doi.org/10.1021/es501975y

[15] Study on critical raw materials for the EU; European Commission, 2023.

[16] R. Gauß, C. Burkhardt, F. Carencotte, M. Gasparón, O. Gutfleisch, I. Higgins, M. Karajic,´ A. Klossek, M. Makinen, B. Schäfer, R. Schindler, B. Veluri, Rare earth magnets and motors: A European Call for Action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, 2021.

[17] M. Ezrati. How much control does China have over rare earth elements? https://www.forbes.com/sites/miltonezrati/2023/12/11/how-much-control-does-china-have-over-rare-earth-elements/?sh=62033e0f5b21 Forbes (2023).

[18] D.J. Packey, D. Kingsnorth, The impact of unregulated ionic clay rare earth mining in China. Res. Policy 48 (2016) 112-116 10.1016/j.resourpol.2016.03.003

[19] T. Eriksson, D. Olsson, The product chains of rare earth elements used in permanent magnets and NiMH batteries for electric vehicles (2011) 1–66.

[20] J. Navarro, F. Zhao, Life-cycle assessment of the production of rare-earth elements for energy applications: a review. In: Frontiers in energy research, 2 (2014) Frontiers media S.A. https://doi.org/10.3389/fenrg.2014.00045

[21] D.E. Al Momani, Z. Al Ansari, M. Ouda, M. Abujayyab, M. Kareem, T. Agbaje, B. Sizirici, Occurrence, treatment, and potential recovery of rare earth elements from wastewater in the context of a circular economy. J. Water Proc. Eng. 55 (2023) 104223 https://doi.org/10.1016/j.jwpe.2023.104223

[22] T. Xu, X. Zheng, B. Ji, Z. Xu, S. Bao, X. Zhang, G. Li, J. Mei, Z. Li, Green recovery of rare earth elements under sustainability and low carbon: a review of current challenges and opportunities. Sep. Purif. Technol. 330 (2024) https://doi.org/10.1016/j.seppur.2023.125501

[23] GM. Mudd, The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resources Policy 35, (2010) 98-115 https://doi.org/10.1016/j.resourpol.2009.12.001

[24] GM. Mudd, Global trends and environmental issues in nickel mining: Sulfides versus laterites. Ore Geology Reviews 38 (2010) 9-26 https://doi.org/10.1016/j.oregeorev.2010.05.003

[25] A. Kumari, R. Panda, MK. Jha, JR. Kumar, JY. Lee, Process development to recover rare earth metals from monazite mineral: a review. Miner Eng 79 (2015) 102–115. https://doi.org/10.1016/J.MINENG.2015.05.003

[26] ISO 14040 (2006) Environmental management: life cycle assessment—principles and framework.

[27] ISO 14044 (2006) Environmental management: life cycle assessment—requirements and guidelines.

[28] GG. Zaimes, BJ. Hubler, S. Wang, V. Khanna, Environmental life cycle perspective on rare earth oxide production. ACS Sustain Chem Eng 3 (2014) 237–244

[29] S. Bastianoni, G. Gofetti, E. Neri, N. Patrizi, A. Ruini, F. Sporchia, F. Pulselli, LCA based circularity índices of systems at diferent scales: a holistic approach. Sci Total Environ. (2023) https://doi.org/10.1016/j.scitotenv.2023.165245

[30] J. Brandstrom, M. Saidani, Comparison between circularity metrics and LCA: a case study on circular economy strategies. J Clean Prod. (2022) https://doi.org/10.1016/j.jclepro.2022.133537

CHAPTER I

Article published in the journal *Clean Technologies and Environmental Policy,* Volume 27, p.471-494, July 2024, https://doi.org/10.1007/s10098-024-02935-7

Life cycle assessment and circular economy in the production of rare earth magnets: an uptated and comprehensive review

ABSTRACT

Rare earth elements (REE) have applications in electric vehicles, wind turbines, trains, electronics, and agriculture. Nevertheless, in the mining process, waste production, such as thorium and uranium, harms the well-being of both people and the natural environment. This work provides a basis for studies that evidence research in the production chain of rare earth magnets throughout the life cycle and proposes an adequate circular economy (CE). The study reinforces the need for continuous research and innovation to develop more efcient and sustainable production technologies for REE and improve metal recycling and recovery practices. The innovation of this technology in industry and public policies contributes to the increased demand for REE and socioeconomic and environmental development. Also, the science citation index expanded (SCI-E) platform—Clarivate Analytics' ISI—web of science was used to fnd scientifc output to compile the bibliographic study. The systematic literature search revealed that 294 documents (237 articles and 57 reviews) were published in the research of words "rare earth elements, " closely associated with "life cycle assessment (LCA), " "life cycle inventory, " "mining," "leaching," and "solvent extraction" between 2010 and 2022. These associations indicate a pronounced interest in studies related to life cycle assessments, considering aspects of mining, leaching processes, and the solvents used in extraction. The areas "rare earth elements, " "recovery," and "metals" are situated within the basic themes but also are motor themes, distinguished by both high centrality and density, including "elements," "life cycle assessment," and "energy." This study provided a robust basis for future research and development of CE and LCA studies in the rare earth magnet production chain.

Keywords: Oxides · Mining · Environmental impacts · Recycling · Magnets · Rare earth metals · Life cycle assessment · Circular economy

1 INTRODUCTION

Rare earth elements (REE) are a set of 17 chemical elements composed of 15 lanthanides, such as scandium (Sc) and yttrium (Y) (Krishnamurthy and Gupta 2004; Masmoudi-Soussi et al. 2020; Nie *et al*. 2020). They can be subcategorized according to their atomic number, being light rare earth elements (atomic numbers 57–63) and heavy rare earth elements (atomic numbers 64–71, plus yttrium) (Greenfield and Graedel 2013; Hurst 2010; Pell *et al*. 2019). Due to their similar physical and chemical characteristics (Binnemans *et al*. 2013a, b), REE fnds diferent types of applications: electronic, optical (Binnemans *et al*. 2013a; Zhou *et al*. 2017), magnetic, nuclear (Voncken 2015), electrical, catalytic (Bradsher 2009; Chancerel *et al*. 2015; Greenfeld and Graedel 2013), in industrial sectors such as oil (Doronin *et al*. 2021; Jordens *et al*. 2013; Yurtaeva *et al.* 2021), agriculture, and metallurgy (Wang *et al.* 2022). Its importance has been growing in the field of green energy technology (Adibi *et al.* 2014; Bauer *et al.* 2010; Moldoveanu and Papangelakis 2012; Wübbeke 2013), such as wind turbines, electric vehicles (Amaral 2014; Habib and Wenzel 2016; Imholte *et al.* 2017; Schreiber *et al.* 2021; Yang *et al.* 2017a), batteries, and biofuel catalysts (Eggert *et al.* 2008; Fouquet and Martel-Jantin 2014). REE are the main enablers of technologies that aim to reduce emissions, minimize energy consumption, as well as increase performance, speed, longevity, and thermal stability, efficiency, seeking to make products lighter (Balaram 2019; Goonan 2011; Gosen *et al.* 2014, 2017; Reisman *et al.* 2013). These metals are also referred to in many countries as critical resources because of their growing importance in current technologies and their high estimated supply risk (Bauer *et al.* 2010; Moldoveanu and Papangelakis 2012; Tse 2011; Wübbeke 2013). All in all, the production of REE incurs substantial environmental harm due to their widespread occurrence in diverse regions and their low concentrations (Goodenough *et al.* 2018). Their extraction and refning processes are energyintensive and environmentally burdensome (Eriksson and Olsson 2011; Navarro and Zhao 2014; Schüler *et al.* 2011); its processing produces large amounts of waste and pollution-intensive materials, such as tailings, which is nothing more than the combinations of pulverized stones and processing liquids and focusing devices. These tailings often have highly hazardous contaminants accumulated from additional rocks and extraction reagents, with the substantial addition of acids, alkalis, and organic solvents at this stage (Kumari *et al.* 2015). China is currently the largest producer of REE (Arshi *et al.* 2018; Koltun and Tharumarajah 2014), with the rare earth oxides (REO) equivalent of 140,000 t in 2020 (U.S. Geological Survey 2021), with China's domestic industry consuming about 60% and rare earth elements being recovered as a byproduct of iron mining, consuming resources and generating environmental impacts (Jin *et al.* 2018b, a). Brazil is the holder of one of the largest reserves of rare earths. However, it does not have an established production. The utilization in 2021 was one thousand tons and, as a result, was obtained statistically the representation of 0.4% of the world production (U.S. Geological Survey 2021). According to (Wang and Kara 2019), limited research addresses the impacts of producing REE, especially regarding rare earth magnets. Therefore, evaluating REE magnets' production concerning environmental issues is important, making it necessary to know, quantify, and qualify the resources used, the waste, and the emissions generated (Zaimes *et al.* 2014). The recovery of elements from waste is the most appropriate strategy to fnd a possible solution to the problems of environmental impacts, thus ensuring the sustainability of the production of raw materials made of rare earth elements in the future due to its growing industrial demand. The circular economy (CE) is a model of production and consumption that is currently used to reduce waste of materials and energy by encouraging the reuse and recycling of resources (Bastianoni *et al.* 2023; Brandstrom and Saidani 2022; Blomsma 2018; Kirchherr *et al.* 2017). One of the models used is linear economy (LE), which is a "take, make, use, and discard" approach, thus limiting the sustainability of these materials (Blomsma 2018). To mitigate the environmental impacts generated, CE was introduced, aiming to maximize resource efciency and reduce the production of waste generated by the consumerism of the population (Habib 2019). CE principles, such as designing for reuse, remanufacturing, and innovative recycling methods, have been implemented by visionary organizations to maintain the highest value of materials, aiming for a zero-waste economy (Frost *et al.* 2020). According to (Vahidi *et al.,* 2016), life cycle assessment (LCA) is a tool based on standards (ISO 14040 2006; ISO 14044 2006) to fully evaluate and quantify the impacts of each stage of the life cycle of a product and/or process, as a result, identifes possible critical points, classifes them into impact categories, and is complementary to traditional environmental assessments, thus allowing a basic assessment of several primary routes of supply of REE (Schreiber *et al.* 2021). These steps range from extracting raw materials incorporated into the production system to disposing of the fnal product after use. According to studies by (Raspini 2021), the neodymium, iron, and boron magnet is under development, thus seeking to consider circular strategies in post-consumption, such as reuse and remanufacturing, in addition to utilization and the practical uses of rare earth magnets (Du and Graedel 2011; Honshima and Ohashi 1994; Thompson 2009). Bibliometric analysis, which involves quantitatively analyzing literature data, can contribute signifcantly to life cycle assessment (LCA) and circular economy eforts in the production of rare earth magnets. It is possible can help identify the key research areas related to rare earth magnets, such as material sourcing, manufacturing processes, usage, and end-of-life management. Rare earth magnets are essential components in many modern technologies. By analyzing bibliometric data, researchers can track technological advancements in magnet production, identifying innovations that enhance resource efciency, reduce environmental impacts, and promote circularity in material use. The bibliometric analysis could map the supply chains of rare earth magnets and identify barriers to advancing circularity in the industry.

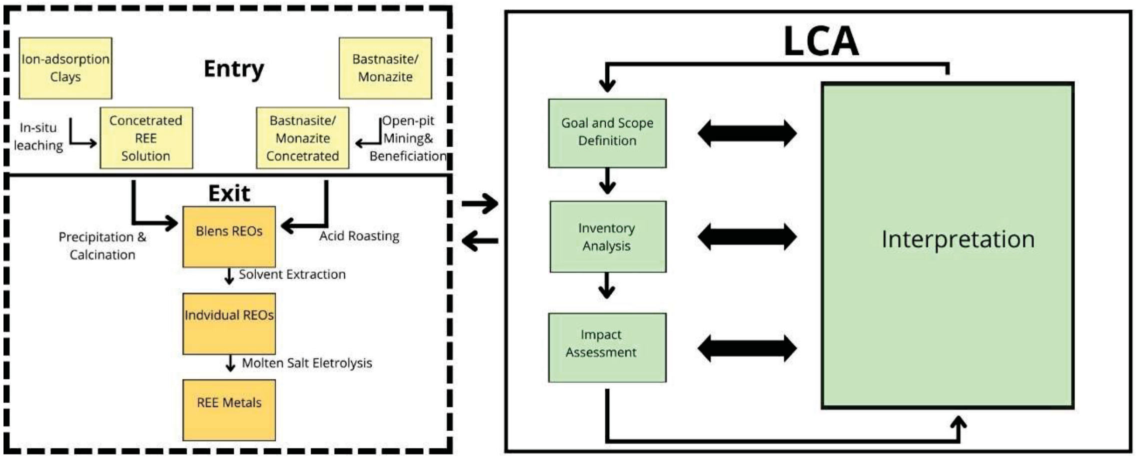
1.1 RARE EARTH MINING

As (Alonso *et al.* 2012; Zapp *et al.* 2022), the mining and production of REE involve techniques and processes linked to environmental impacts, such as many chemicals and waste materials. In addition, residues produced during the benefciation, extraction, and separation phase contain radionuclides such as thorium and uranium (Adibi *et al.* 2014; Huang *et al.* 2016). Knowledge about the environmental consequences associated with the production of REE is still incomplete (Lee and Wen 2017; Marx *et al.* 2018; Schreiber *et al.* 2016; Zapp *et al.* 2018). For (Holger *et al.* 2017), in the context of the production of REE, analyses of rare earth production were carried out in Australia, Malaysia (Mount Weld), the USA (Mountain Pass), and China (Bayan Obo). Social risks have been identified when producing REE for the manufacture of permanent magnets, and it is essential to develop strategies to mitigate these risks and protect the environment, avoiding CO_2 emissions and other pollutants. According to (Yan *et al.* 2011), REE production faces environmental challenges related to deposit geology, extraction methods (Koltun and Tharumarajah 2014), processing, and the measures adopted to mitigate environmental impacts. Already (Pell *et al.* 2019) have developed an environmental sustainability framework for the metallurgical industry using LCA, but it hasn't been applied to REE production yet. Several LCA studies have been conducted for REE, focusing on the mining and processing of bastnäsite ores in Mountain Pass, USA, and bastnäsitemonazite in Bayan Obo, China (Althaus *et al.* 2007; Du and Graedel, 2013; Haque *et al.* 2014; Sprecher *et al.* 2014a). Palle Paul Mejame *et al.* 2022 did a study where they provided a preliminary review of the consumption of REE within a sustainable management context in Australia, where they looked at the current state of research on REE in terms of environmental responsibility, including applications, uses, availability, mining sites, reserves, and governance policies (Haque *et al.* 2014; John *et al.* 2016; McLellan *et al.* 2014). It has been demonstrated how the concept of CE can be implemented to address the scarcity of REE resources by reducing environmental burdens (Balanay and Halog 2019), considering a system focusing on restoration and regeneration through its design, emphasizing longevity, ease of repair, reuse, maintenance, renovation, remanufacturing, recovery, and recycling principles (John *et al.* 2016; McLellan *et al.* 2014; Wang and Kara 2019). Technological advances in information and communication technologies (ICT) have intensified competition and reduced e-waste metal recovery lifespan (Işıldar *et al.* 2018). E-waste metal recovery typically employs pyrometallurgy and hydrometallurgy, with two stages: pre-processing (disassembly, sorting, shredding) and fnal processing (chemical separation) (Kaya 2016; Kumar *et al.* 2017). The study by Li *et al.* (2019) found that REE recovery through recycling is environmentally preferable except for the destruction of ozone, which was the highest compared to the pyrometallurgical process. Pyrometallurgical and hydrometallurgical processes were considered competitive in terms of environment (Bailey 2016). Despite the risk of sourcing REE, there is a signifcant knowledge gap regarding the systematic and comprehensive assessment of the environmental impacts and benefts of sustainable consumption of REE, highlighting the need for future research in this area (Alonso *et al.* 2012; Drost and Wang 2016; Jowitt *et al.* 2018; McLellan *et al.* 2014; Wang *et al.* 2017). Yuksekdag *et al.* 2022 assessed REE life cycle integration with CE steps, covering raw materials steps, REE use, the potential for demand in secondary sources, quantities generated, and recovery processes. Despite the potential, REE retrieval from secondary sources confronts technological challenges. Inadequate waste management and the lack of studies on recovery are the main challenges for closing the cycle, and there is a shortage of studies on the individual separation of REE (Bailey *et al.* 2020; Schreiber *et al.* 2021). Dang *et al.* 2021 explored the socioeconomic and sustainable aspects of the REE branch, focusing on the environmental impacts of activities related to these elements. Several REE recovery processes are not economically viable or environmentally amicable (Jally *et al.* 2021). Rising REE demand could disrupt the current supply chain, necessitating consumers' consciousness regarding the sustainability and human health repercussions linked to discarded electronics that enclose them (Hao *et al.* 2015; Liu *et al.* 2009; Oguri *et al.* 2018; Zhang *et al.* 2018). While REE hold potential for sustainable agriculture and the environment, further research is needed on their ecotoxicological impacts. Dutta *et al.* (2016) emphasize the importance of REE in manufacturing a wide variety of products and the need for a secure supply. Recycling is viable (Binnemans and Jones 2015; Machacek *et al.* 2015); the study aims to analyze the global REE scenario, supply chains, and environmental impacts of mining while highlighting the challenges in industrial recycling (Sun *et al.* 2016). Integrated approaches must consider ecological factors, resource management, mining techniques, production scale, market dynamics, and legislation. Waisman *et al.* (2019) highlighted the importance of decarbonization in reducing the consumption of nonrenewable energy usage and emissions. The study (Dudley 2018) reveals a rebound efect in REE life cycles, indicating that the rapid development of green energy technologies results in an unsustainable consumption of REE. Herrington (2021) has proposed the capability of replacing REE alternatives and implementing recycling policies to enhance circularity, while Golroudbary *et al.* (2022) observed noted market volatility of RE and the replacement of Nd, Fe, and B technology by others with lower demand for REE are essential factors. Sustainable methods, both environmentally and socially, must be established to acquire the necessary raw materials to meet emission reduction goals. Unfortunately, however, there is still no comprehensive analysis of the environmental impacts of the green energy value chain, including energy and water consumption in all processes related to REEs. Therefore, there is still a need for a comprehensive study of the environmental impact of all stages of the supply chain for green energy technologies, along with relevant decarbonization measures for the mining and global production of REEs, considering a long-term perspective. Studies conducted by (Weng *et al.* 2016) have raised concerns about the mining industry's sustainability due to the production of primary metals. These concerns include declining ore contents, mining waste, greenhouse gas emissions, hazardous wastewater disposal, high energy costs, irreversible land use, chemical pollution, and resource depletion (Mudd 2010a, 2010b; Norgate and Haque 2010). Increasing demand for REE has led to exploration and research of WWT mineral resource extraction capacity across the globe. This paper presents life cycle impact assessment (LCIA) data on a “cradle to gate” scale for 26 selected REO production projects, covering both operational and potential projects (Weng *et al.* 2015, 2013). The research analyzes essential factors in REOs production, including mineral deposit type, ore contents, mineralogies (Mudd 2010a; Norgate and Haque 2010; Weber and Reisman 2012), REE predominance, production configurations, individual concentrations of REE, and environmental impacts such as gross energy demand (GER) values and global warming potential (GWP). ALCI modeling quantifes interconnections between RE mineral resources, extraction technologies, and environmental interactions. The results show that the decrease in the contents of total rare earth oxides (TREO) (Weng *et al.* 2015) results in severe environmental consequences, with increased demands for GER and GWP (Weber and Reisman 2012; Weng *et al.* 2013; Wübbeke 2013; Xie *et al.* 2014; Xue and Lin 2011; Yang *et al.* 2013).

1.2 PRODUCTION OF RARE EARTH OXIDES

According to (Vahidi and Zhao 2017), China produces REE, providing about 85% of global demand (Duncan *et al.* 2017). The study (Fig. 1) presents the main operational steps involved in producing individual REE, mixed metals, and alloys from the reserves of these elements. All the process steps illustrated in Fig. 1 consume materials and energy intensively, generating signifcant emissions of air, water, and solid waste. While REE are essential for green and high-tech technologies, the production of REE themselves has substantial environmental impacts. Therefore, a comprehensive sustainability assessment is crucial to reduce the environmental impacts related to the production of REE, with LCA being the most commonly used method in sustainable product development (Adibi *et al.* 2014; Evans *et al.* 2009; McLellan *et al.* 2014).

FIGURE 1- SCHEMATIC OF HYDROMETALLURGICAL PROCESSES FOR PRODUCING INDIVIDUAL RARE EARTH METALS, MIXED METALS, AND ALLOYS



(a) (b)

FONTE: ISO 14040 (2006).

The study (Vahidi and Zhao 2017) addresses limitations and uncertainties in Ecoinvent 3 data for REO production, focusing on solvent extraction. The LCA study enhances the understanding of the environmental impacts, revealing that solvent extraction contributes 35% to the bastnasite/monazite route and 55% to ion adsorption clay route environmental impacts. Key chemicals like sodium hydroxide and hydrochloric acid require reduction or alternative pH adjustment methods (Sprecher *et al.* 2014a).

According to (Kanazawa and Kamitani 2006), the extraction of REE mainly occurs in China, using diferent methods, such as open-pit mining and leaching of ion adsorption clays (Talens Peiró and Villalba Méndez 2013). Specifcally, ion adsorption clays have a higher content of heavy REE (HREEs), considered valuable (Vahidi and Zhao 2016). Therefore, they are an essential source of REE, especially HREEs (Chakhmouradian and Wall 2012; Lusty and Walters 2010). The study (Vahidi and Zhao 2016) represents an LCA approach to producing REOs through ion adsorption clays through in situ leaching in southern China. Data from the Chinese literature were used to evaluate the environmental impacts of producing REOs from ion adsorption clays. The functional unit was defned as producing 1 kg of REOs with 92% purity

(Duncan *et al.* 2017). Results showed varying impacts, with ammonium sulfate as a major infuencer. In situ, leaching has a more minor impact on acidifcation but a signifcantly greater impact on eutrophication. In situ leaching of HREE-rich ion adsorption clays reduces environmental impact and constitutes 35% of China's HREE production, emphasizing LCA's role in evaluating tech's eco-efects. Nakamoto et al. 2012 conducted a study to investigate the extraction of REE as oxides from a neodymium-based magnetic sludge, focusing on oxygen affinity for REE. Carbon was used as a contact material to efciently separate the Nd, Dy, and Pr and the iron in the neodymium magnetic mud (Yoshizuka *et al.* 2010). Using a carbon crucible made it possible to separate the oxygen-containing and metal phases in the magnetic mud. The company of carbon creates a partial pressure of oxygen that allows REOs and metallic iron to coexist. Meng et al. (2020) introduced a cleaner method for producing REOs from RE chloride solutions. The traditional precipitation method (Gupta and Krishnamurthy 1992; Huang *et al.* 2015; LIU *et al.* 2008) has disadvantages, such as the introduction of impurities, excess waste, and greenhouse gas emissions. As an alternative, a new method was proposed, based on electrical transformation, simulating cationic membrane electrolysis (CME) technology (Savari *et al.* 2008), to obtain a cleaner production of REO. CME ofers advantages like no impurity introduction, no waste gases, and valuable by-products. In the study by Carrillo García *et al.* (2020), they investigated the production of REO from raw ore using a fluidized bed reactor. They processed minerals into leachable structures via cooking and hydrometallurgical steps, aiming for REO content above 90%. This process involves harsh conditions above 200 °C and a high ratio of acid to ore (Gupta and Krishnamurthy 1992; Krishnamurthy and Gupta 2004; Kul *et al.* 2008), such as the use of sulfuric acid to treat ore concentrate. An alternative to the hydrometallurgical process (cooking+hydrometallurgy) is using a pyrometallurgical process, such as calcination, followed by hydrometallurgical separation steps. Calcination, a pyrometallurgical alternative, reduces reagent complexity and cost (Criado and Ortega 1992; Padeste et al. 1991; Viczián, 2013). Combining monazite and calcite improved REO production. In another study, an experiment of calcination of a RE ore was carried out, focusing on the mineral association, aiming at the production of REO and analyzing its impact on the hydrometallurgical steps (Krishnamurthy and Gupta 2004; Xing *et al.* 2010). The researchers closely studied how particles change shape during calcination, which is important for selectively separating REE in the leaching step due to friction and particle clumping (Bemrose and Bridgwater 1987). Precipitating agents, such as oxalic acid (Rabatho *et al.* 2013), ammonium, sodium hydroxide, sodium sulfate, and hydrogen fluoride (Lyman and Palmer 1993), are commonly used in conventional rare earth oxide production processes. However, these agents have been problematic, especially HF, which can hinder NdF_3 fltration and cause iron contamination in the residue. Among the techniques explored for the recovery of REE, direct and selective leaching approaches have been proposed (Chung *et al.* 2022; Emil-Kaya *et al.* 2022; Honshima and Ohashi 1994; Polyakov and Sibilev 2015; Yang *et al.* 2017b). In the study by Emil-Kaya *et al.*, (2022), they proposed a direct and selective leaching approach for recycling Nd, Fe, and B magnets, intending to produce REO powders through combustion in solution. The recovery of REE from the scrap of these magnets presents a prospective resolution to meet the supply challenges of these elements due to their high demand in the high-tech industry (Du and Graedel 2011; Honshima and Ohashi 1994; Thompson 2009). Deng & Kendall (2019) address the lack of research on producing medium and heavy rare earth oxides (HREOs) production from ion adsorption clays in southern China to develop a new open-source LCI and perform a life cycle analysis (Schüler *et al.* 2011; SCIO 2012; Yang *et al.* 2013), with a purity of 90%. Data on HREO highlight the ecological impact, emphasizing the role of mining and extraction, with ammonium sulfate as the main contributor. Reducing chemical use and extending reaction times help mitigate efects. In situ leaching is similar to bastnasite/ monazite processing's environmental impact (Deng and Kendall 2019). Schreiber *et al.* (2021) reviewed LCA studies on REO production, addressing overestimation and underestimation of environmental impacts. The study was to identify suitable studies for systematic comparison, emphasizing key inputs and outputs afecting impact categories and highlighting the often-overlooked radioactivity released during REO production. The review revealed controversies in LCA studies, with no perfect study covering all necessary data adequately, leading to the use of various scenarios, analogous processes, or substitute materials in some cases to obtain information.

2 PRODUCTION OF RARE EARTH MAGNETS AND APPLICATION OF LCA AND CE

The work of (Bonfante et al. 2021) analyzed sustainability in the REM (rare earth magnets) supply chain and its contribution to the Sustainable Development Goals (SDGs). However, REE production involves significant socioenvironmental impacts (Ali 2014; Weng *et al.* 2015) due to the use of heavy chemical components, such as sulfuric and hydrochloric acid (Tharumarajah and Koltun 2011), and the generation of radioactive by-products like thorium and uranium (Weng *et al.* 2016), during the extraction of these elements. A study on the sustainability of the REM using strengths and threats (SWOT) analysis explored environmental impacts such as chemical (Marx *et al.* 2018) and energy consumption (Sprecher *et al.* 2014b), social consequences, economic aspects as recycling benefits (Hernandez *et al.* 2017), and CE. While REM sustainability strengths are evident, their implementation in emerging supply chains remains recent and uncertain (Arshi *et al.* 2018; Marx *et al.* 2018; Nordelöf *et al.* 2019; Schlör *et al.* 2018; Schreiber *et al.* 2019; Sprecher *et al.* 2014b; Wulf *et al.* 2017).

Bailey *et al.* (2020) stress the importance of REE in lowcarbon technologies but highlight the generation of toxic waste during permanent magnet production (Bailey *et al.* 2017; Koltun and Tharumarajah 2014). Despite multiple investigations, databases lack sufcient REE data (Althaus *et al.* 2007). In this context, the paper analyzes and evaluates 24 LCA studies on the production of REE, specifically addressing issues related to the incompatibility of inventory data, as with variable impacts noted for REO production from bastnasite ores. Bastnasite/monazite routes are similar but difer in waste management, infuenced by mineralogy, ore structure, and chemical reagent management, making direct comparisons challenging. According to the studies (Langkau and Erdmann 2021), electric vehicles are supported for reducing CO_2 emissions. However, it will drive demand for lithium, cobalt, and rare earths (Deetman *et al.*, 2018; Marscheider-Weidemann *et al.* 2016). To mitigate future environmental impacts (Amnesty International, 2016; Bodenheimer 2014; Bontron 2012; Walz *et al.* 2016), the study created scenarios related to the metals neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb). To perform this analysis, combined LCA with future demand scenarios for these metals, as proposed by (Van der Voet *et al.* 2019). In conclusion, reduction is possible with eforts like closing illegal mines and improving standards. Addressing future demand variations requires research on material efciency and alternative approaches for rare earth magnets. Schüler et al. (2011) conducted a process-based LCA on molten salt electrolysis for RE in China (Adibi *et al.* 2014; Evans *et al.* 2009; Golev *et al.* 2014). They collected energy and material data from rare earth refning facilities (Vahidi and Zhao 2017) to develop LCIs (Althaus *et al.* 2007). According to (Vahidi and Zhao 2018), dysprosium fuoride production has the highest environmental impact in all categories of TRACI (Toxicological and Environmental Risk Assessment for Impacts on Sustainable Systems). Molten salt electrolysis showed variations in life cycle impacts, with mining and chemical treatment and solvent extraction steps being signifcant in neodymium metal production. Kruse et al. (2017) analyzed the melting characteristics of Nd, Fe, and B-based production residues for RE compound recovery. Nd–Fe–B magnets have a high concentration in REE, ofer a precise composition, and lack radioactive elements. It has been observed by (Kruse et al. 2015) that grinding pastes with over 7% oxygen content can selfseparate during melting. Low-oxygen waste can undergo preliminary heat treatment to separate hydrocarbons, reduce carbon reactivity, and adjust oxygen levels, a crucial step for subsequent melting (Raulf 2016). A study conducted by Kaya *et al.* (2021) proposed a CE-focused process for REE recovery from used Nd, Fe, and B magnets, involving acid cooking, hydrolysis, and ultrasonic spray pyrolysis. This approach enhances resource efciency and produces spherical REE oxide particles. The process involved several steps, including cooking with nitric acid at 200 °C, leaching with water (Önal et al. 2017), and pyrolysis by ultrasonic spray at temperatures between 700 °C and 1000 °C. Higher temperatures increased crystallinity and particle size. In this way, he developed an environmentally friendly process to recover a mixture of nanometric powders of Nd_2O_3 and Pr_2O_3 from used magnets and reusing nitric acid. According to Magrini and Jagodzińska (2022), they analyzed the recovery of REE from neodymium magnet (NIB) residues. Diferent hydrometallurgical methods have been developed as possible alternatives for recycling these magnets. However, conventional methods require several steps to increase leaching selectivity and are costly due to complex pretreatment techniques and signifcant chemical consumption (Karal *et al.* 2021; Tanaka *et al.* 2013). An emerging approach in the recovery of REE from NIB magnets is bioleaching or biohydrometallurgy (Işıldar *et al.* 2019). It is the frst study (Magrini and Jagodzińska 2022) that addresses LCA and the cost and material fow analysis (MFCA) of bioleaching of NIB magnets on a pilot scale, focusing on the ecological and fnancial viability of bioleaching Nd, Dy, and Pr from NIB magnet residues. The study does not consider the benefts of recycling other components of data storage devices (Talens Peiró *et al.* 2020), such as printed circuit boards (PCBs) and aluminum. Early-stage

LCA results emphasized electricity consumption and oxalic acid production environmental impact, with bioreactor costs as a signifcant factor. Government subsidies may be necessary for process operation, highlighting the need for further research and development to improve this emerging technology. A study by Sprecher *et al.* (2014b) looked at the conditions under which RE metals are produced and conducted an LCA to compare the environmental impact of producing 1 kg of neodymium magnets from virgin material to recycling. A comprehensive analysis of the production chain of Nd, Fe, and B magnets (Binnemans *et al.* 2013b) revealed that most of the impacts are related to energy consumption. Two recycling processes were considered, one with manual magnet removal from hard drives and the other involving hard drive collection and destruction. Both reduced energy consumption and human toxicity but raised concerns about material losses during shredding, questioning the feasibility of recycling to address metal scarcity. Studies by Yang *et al.* (2017a) address the sources of permanent magnets at the end of their useful life (EOL), discussing their peculiarities, the technical hurdles, and possible methods of physical and metallurgical recuperation (Binnemans *et al.* 2013b; Firdaus *et al.* 2016; Takeda and Okabe 2014; Tanaka *et al.* 2013), magnets, and associated REE. In addition, the study includes an LCA for recycling the magnetic scrap of Nd, Fe, and B. Manufacturing permanent magnets from REE involves carefully selecting the starting material based on its intrinsic properties. Subsequently, these inherent traits are transformed into practical external attributes, including elevated retained magnetization and coercive force (Gutfeisch 2000). It is important to note that the consumption and annual demand for REE magnets is constantly increasing (Binnemans *et al.* 2018, Nakamura 2017; Sprecher *et al.* 2014a, b). Recycling these magnets is a complementary measure to address longterm supply shortages (Rademaker *et al.* 2013). Nlebedim and King (2018) recycle permanent magnets (PMs) and recover REE for resource sustainability and CE. However, challenges such as the use of hazardous chemicals, vapor generation, and energy consumption need to be addressed (Binnemans *et al.* 2013b; Vander Hoogerstraete *et al.* 2014). Tkaczyk *et al.* (2018) emphasize recycling REEcontaining waste like fuorescent powders (Tan *et al.* 2016), catalysts, and PMs. Although scraps, such as fuorescent powders and end-of-life fuid catalytic cracking catalysts (FCCC), contain many of these metals, sustainability aspects are often overlooked in the search for solutions (Amato *et al.* 2019). The study reinforces the potential benefts of producing REE from waste, both in environmental and economic terms (Amato *et al.* 2016; Cucchiella *et al.* 2016). They highlight the environmental and economic benefits of secondary REE production from waste, with costs significantly lower than primary production. Economic feasibility is confrmed under the baseline scenarios (Amato *et al.* 2016, 2017; Amato and Beolchini 2018; Baxter 2019; De Meester et al. 2019; Fiore et al. 2019; Latunussa et al. 2016; Menikpura *et al.* 2014; Rocchetti *et al.* 2013; Ruello *et al.* 2016), but can be afected by REE price volatility, energy, and raw material costs in alternative scenarios (Geissdoerfer *et al.* 2017). A study by Ueberschaar and Rotter (2015) aimed to identify REE, particularly Nd, Fe, and B magnets, in hard disk drives (HDDs) to promote recycling. They categorized information into general, physical, and chemical levels (Chancerel and Rotter 2009; Rotter *et al.* 2013). HDDs contain valuable metals, but magnet separation is challenging. It is essential to employ sequential hydro or pyrometallurgical recovery techniques needed (Elwert and Goldmann 2014). Standardized alloys for magnetic materials could facilitate magnet reclamation. Implementing selective collection and treatment systems for laptops and desktop PCs is crucial for maximizing magnet and REE recovery. The study of Frost *et al.* (2020) analyzed the relationship between HDDs and RE magnets in transitioning from a linear economic model (PwC 2015) to a circular one. Engaged stakeholders formulated the problem and developed CE strategies for HDDs. Decision support tools and a comprehensive analysis using the PESTEL+structure (Political, Economic, Social, Technological, Environmental, Legal+Financial/Organizational) were used to identify the barriers and opportunities associated with each circular business model, focusing on returns management and supply chain integration. This study ofers a model for assessing circular business models in other electronic products. Wang *et al.* (2022) address the rising demand for sintered Nd, Fe, and B magnets in energy and environmental protection industries. However, signifcant waste, such as oil mud, leftover residual materials, and fawed products, resists efcient recycling. In this sense, the study evaluates the potential for environmental improvement by utilizing repurposed REE and magnets employed in manufacturing sintered Nd, Fe, and B magnets, replacing part of the original materials. The LCA methodology was sintered (Curran *et al.* 2010), showing substituting virgin materials with oil mud and post-consumer magnets reduces environmental impact, with raw material choices and electricity consumption being critical factors (Binnemans *et al.* 2013b; Jin *et al.* 2018b, a; Schüler *et al.* 2011). Habib (2019) sought to explore resource circularity options for critical elements, such as Nd and Dy, present in the magnets of Nd, Fe, and B along its value chain. A product classification approach has been proposed to understand the circularity potential of these features better (Ghisellini *et al.* 2016; Jawahir and Bradley 2016), using Nd, Fe, and B magnets as a case study (Habib 2015; Habib *et al.* 2014, 2015, 2016; Habib and Wenzel 2014, 2016). This approach allows you to group products according to the most feasible way to achieve resource circularity. The next step is to develop a theoretical framework for classifying anthropogenic resources (Winterstetter *et al.* 2016) inspired by the United States Geological Survey's natural mineral resources classification system (Gambogi 2016; USGS 1976). This classifcation allows you to identify and group products based on the varying economic and technical feasibility of recovering resources from them, considering current and future conditions. The study by Raspini *et al.* (2022) provided a sectoral viewpoint regarding the factors infuencing and hindering the adoption of CE in Brazil’s Nd, Fe, and B industries, particularly within the REM production complex. Identifying these drivers and barriers is crucial for fostering circularity in the sector and leading the transition to more sustainable production, involving companies (Jin *et al.* 2018b, a), governments, and the scientifc community. The fndings of this study may drive the implementation of circular economy practices within the REM sector (Amato *et al.* 2019; Diehl *et al.* 2018; Nlebedim and King 2018; Ueberschaar and Rotter 2015; Xu *et al.* 2019; Zhang *et al.* 2018) and ofer insights into strategies for resource conservation. The main drivers are related to external factors, while the main barriers combine internal and external factors (Maqbool *et al.* 2020). It is important to highlight the interconnection and possible interaction efects between drivers (Ritzén and Sandström, 2017; Rizos *et al.* 2016) and barriers (Sharma *et al.* 2011), improving competitive advantage and fnancial proftability (Gue *et al.* 2020; Gusmerotti *et al.* 2019). Diehl *et al.* (2018) addressed the recycling of materials for the production of magnets to reuse the magnetic alloys in a new manufacturing cycle, highlighting their competitive advantages, lower environmental impact, and relevance with the transition to a Green Economy. Recycled magnets closely match primary material magnets in magnetic properties. However, one of the main challenges is the custom manufacturing of reclaimed magnets to meet specifc design and engineering criteria, which is a key challenge (Binnemans *et al.* 2013b; Yoon *et al.* 2016). Silvestri *et al.* (2021) verifed the circularity potential of REE in the vehicle battery industry, focusing on a closed-loop recycling system in Europe. They conducted a comprehensive study involving literature review, policy analysis, and modeling. Results indicate that current recycling tech and policies can reduce future REE demand. Still, the risk of scarcity remains due to growing green tech adoption, particularly nickel-metal hydride (Ni-MH) batteries (Binnemans *et al.* 2013b), which will lead to a rise in the REE demand. Table 1 presents studies that apply the methodology of life cycle assessment and circular economy in producing rare earth magnets, from the extraction of raw materials to the manufacture, use, fnal disposal, and recycling. It illustrates the interconnection between these phases and the diverse environmental and socioeconomic impacts associated with each of them. By examining aspects such as energy consumption, greenhouse gas emissions, water consumption, and natural resource use throughout the life cycle, the framework offers a comprehensive overview of the environmental implications of producing rare earth magnets, including recycling and applying circular economy models. This holistic analysis serves as the basis for informed decision-making to minimize negative impacts and promote more sustainable practices in the magnet and related materials industry.

TABLE 1- LIFE CYCLE ASSESSMENT AND CIRCULAR ECONOMY APPLICATIONS IN MAGNET PRODUCTION

	Reference	OBJECTIVE	METHOD	RESULTS
1	Magrini, C.; Jagodzinska, K. (2022).	Evaluating the environmental and economic feasibility of bioleaching Nd, Dy, and Pr from NIB magnet residues in the circular economy; without considering the recycling of other HDD components such as PCBs and Al.	LCA	The LCA highlights the need to reduce electricity consumption, which impacts the environment, and suggests that government subsidies may be necessary due to the high costs of the bioreactor.
2	Pell *et al* (2019).	Develop a framework of indicators for benchmarking the environmental sustainability of products manufactured by the metallurgical industry.	LCA	The results indicate a positive relationship between decreasing content and the impact of global warming, but there are also patterns between ore composition and global warming potential.
3	Weng *et al*. (2016).	A “cradle to gate” scale life cycle impact assessment for 26 operating and potential REE mining projects, focusing on the gross energy requirement and	LCA	The declining ore grades of REE significantly increase the environmental impact of REE production.

		the global warming impacts of the primary REE production stage.		
4	Wang *et al.* (2022).	Conduct an LCA of three regeneration technology routes for sintered NdFeB magnets using actual industrial data to determine the key processes and environmental hotspots of different production processes, thereby providing data support for the clean and sustainable development of the sintered NdFeB magnet industry.	LCA	The results showed that the preparation of rare earth metals and power consumption were major contributors to the observed environmental impacts during NdFeB magnet production.
5	Deng, H.; Kendall, A. (2019).	Collect and publish primary data related to mining ion adsorption clays producing mixed HREOs.	LCA	The results show that 1 kg of mixed HREOs emits 258–408 kg of CO_2 and consumes 270–443 MJ of primary energy. Comparisons indicated that some environmental impacts for in situ leaching of ion adsorption clays fall within the same processing range as bastnasite/monazite.
6	Jin *et al.* (2016).	Evaluating the environmental impact of recycling NdFeB	LCA	The magnet-to-magnet recycling approach has significantly lower environmental impacts than the production of virgin magnets,

		magnets versus producing new magnets using virgin materials.		while recycled magnets offer stronger magnetic performance and better microstructure compared to virgin magnets.
7	Li *et al.* (2019).	Evaluate the environmental impacts of different methods for recovering precious metals from electronic waste.	LCA	The LCA for recovering 1 kg of REEs was conducted, and the results indicate that REE recovery through the RE process has fewer environmental impacts than in-situ extraction.
8	Yuksekdag *et al* (2022).	Each stage of the CE model can be integrated with the life cycle of elements to understand better how their use can be implemented within the CE concept.	CE	The first obstacle to closing the loop is improper waste management. Another challenge arises in the recovery stage, which is the final step of the CE. Recent studies have focused on the efficiency of the process and the development of more eco-friendly methods.
9	Mejame *et al* (2022).	An initial review of REEs consumption within a sustainable management a framework in Australia; as a strategy for global acceptance.	CE	A material flow analysis from the life cycle analysis of critical material usage suggested magnets and phosphors as the applications with the highest demand for these critical metals. It should be noted that all of these applications are used in the clean energy sectors for low-emission energy production.
10	Spreafico, C. (2022).	A quantitative assessment of the environmental impacts reductions arising from the application of	CE	The obtained results have been used to evaluate the different design strategies for CE and to hierarchize them based on the environmental sustainability of the associated solutions. In addition, an economic evaluation of the strategies, based on the

		some common design strategies for implementing different CE options (e.g. reuse, waste to energy, remanufacturing); by using some standard indicators.		life cycle costing methodology and exploiting the data available in the same articles, was also provided.
11	Dang (2021).	This is to provide an overall socioeconomic and environmental perspective of the REE industry with a central focus on the environmental impacts of various REE-related activities.	CE	Some of these REE recovery processes are not yet economically profitable and environmentally-friendly.
12	Silvestri *et al* (2021).	Assess the circularity potential of REEs in the vehicle batteries industry, investigating the potential of a closed-loop recycling system in the European context.	CE	Provide the evidence that an appropriate circular economy system for the vehicle battery industry can lead to benefits not only in terms of supply risk reduction but also concerning the preservation of natural resources, implying one step further towards sustainable mobility.
13	Frost *et al* (2020).	A case study of HDDs and RE magnets was presented to demonstrate the use of DSTs in	CE	Barriers to HDD CBMs were highlighted, including reverse logistics and coordination with the existing supply chain.

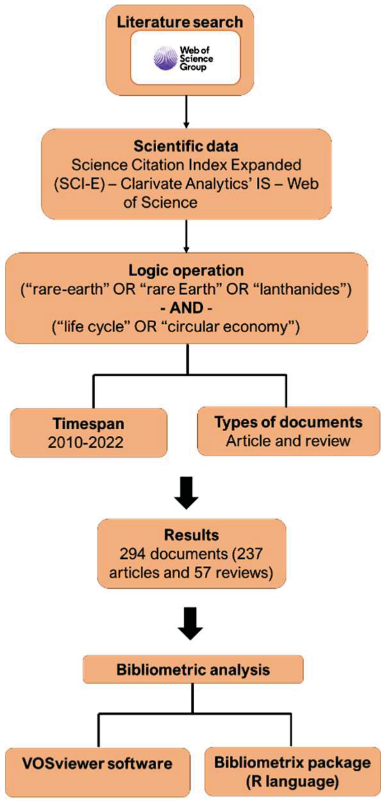
		assessing the complex interaction of variables.		
14	Alecu, G.; Kappel, W. (2021).	Describe, in a conclusive example, the defining elements of the CE.	CE	Waste and resource use are minimized to the fullest extent, and resources, once they reach the end of their life cycle, do not exit the economic system but are reused, generating revenue to meet national/international demands for specific metals.
15	Holger *et al* (2017).	Assess the future development of social conditions for producing permanent magnets resulting from the human development index using social LCA scenarios.	LCA social	The three RE production sites in the four countries pose social risks when producing REE for the permanent magnets used in wind turbines. These social risks stem from the overall manufacturing conditions within the industrial sectors producing these components.
16	Qiu, Y.; Suh, S. (2019).	Analyze the effects that the scale of recycling operation and REO prices have on the economic feasibility of REO recycling using dynamic material flow analysis and technology learning curve approaches.	Dynamic material flow analysis	End-of-life REOs from lighting technologies are expected to peak between 2020 and 2027.
17	Wang *et al* (2020).	Adopt the standard LCA approach to assess the	LCA	HTNC and GWA are the two main environmental impacts caused by scandium oxide production. At the same time, Fe (II)

		environmental impacts of scandium oxide production from rare earth tailings at the Bayan Obo mine.		separation and oxalic acid precipitation contribute more to the overall impacts in the beneficiation process.
18	Adibi, N.; Lafhaj, Z.; Payet, J. (2019).	Tackle the issue of missing characterization factors (CFs) for REEs in Life Cycle Assessment (LCA).	ADP, LCA	The results reveal that REEs have a relatively high resource impact; therefore, they should be included in the assessment of resources. In addition, the applicability of the provided CFs is checked in a NdFeB permanent magnets case study, and some recommendations are provided for the practice.
19	Golroudbary *et al* (2022).	The first global analysis of the environmental impact of using rare earth elements in green energy technologies.	Integrated dynamic systems modeling with LCA and geometallurgical approach.	Between 2010 and 2020, the use of permanent magnets has resulted cumulatively in 32 billion tonnes CO_2 equivalent of GHG emissions globally.

3 LIFE CYCLE ASSESSMENT AND CIRCULAR ECONOMY APPLICATIONS IN MAGNET PRODUCTION

The Science Citation Index Expanded (SCI-E) platform— Clarivate Analytics' ISI—Web of Science was used to fnd scientific output to compile the bibliographic study. The search was conducted using the advanced search mode and the search logic making use of keywords in the feld of rare earth research, namely “rare-earth,” “rare earth,” and “lanthanides,” restricting documents that jointly present the keywords “life cycle” or “circular economy.” Through the following search logic: “TS=[(“rare-earth” OR “rare earth” OR “lanthanides”) AND (“Life cycle” OR “circular economy”)].” The search also excluded “Keywords Plus,” which are supplementary keywords automatically identifed in an article based on its semantic content during indexing. Therefore, the search was confned to information contained in the title, authors, source, abstract, and references. Only reviews and articles from the 12 years between 2010 and 2022 were chosen for data fltering. In total, 294 materials were chosen, of which 237 were articles and 57 were reviews (Fig. 2).

FIGURE 2- METHODOLOGICAL STEPS FOR EXECUTING THE BIBLIOMETRIC ANALYSIS



Data extracted from the selected documents were exported and analyzed using the Bibliometrix package in the R programming language in conjunction with the VOSviewer software. VOSviewer was employed to ascertain the primary study keywords and their clustering, facilitating the constructing a network that elucidated the prevalent terminologies employed within the chosen papers. Conversely, Bibliometrix was utilized to generate a graphical representation illustrating the temporal evolution of scholarly production (citations) by key authors and to construct a thematic map classifying primary keywords into three distinct categories: authors, keywords, and geographical regions. The primary objective of this comprehensive analysis was to gain insight into the signifcance and far-reaching implications of the pivotal publications in the realm of life cycle and circular economy within the context of rare earth production. Following the well-established framework of Brocke *et al.*, 2009, the systematic search aimed to summarize the results within the specifed search flters outlined above, which can be outlined as follows:

1. Defnition of review scope: Focused on the rare earth elements área;
2. Conceptualization of topic: Bounded in searches involving life cycle studies and circular economy;
3. Literature search: Conducted in the Web of Science database;
4. Literature analysis and synthesis: Utilizing the VOSviewer and Bibliometrix tools;
5. Research agenda: Summarized in Table 2, further detailed descriptions are provided in the subsequent sections.

TABLE 2: IDENTIFCATION OF KEYWORD CLUSTERS USING VOSVIEWER SOFTWARE

Cluster	Number of items	Keywords on VOSviewer Network
1	13	Cobalt, critical materials, hydrometallurgy, lca, leaching, life cycle assessment, life cycle assessment (lca), life cycle inventory, metals, mining, permanent magnet, rare earth elements, and solvent extraction.

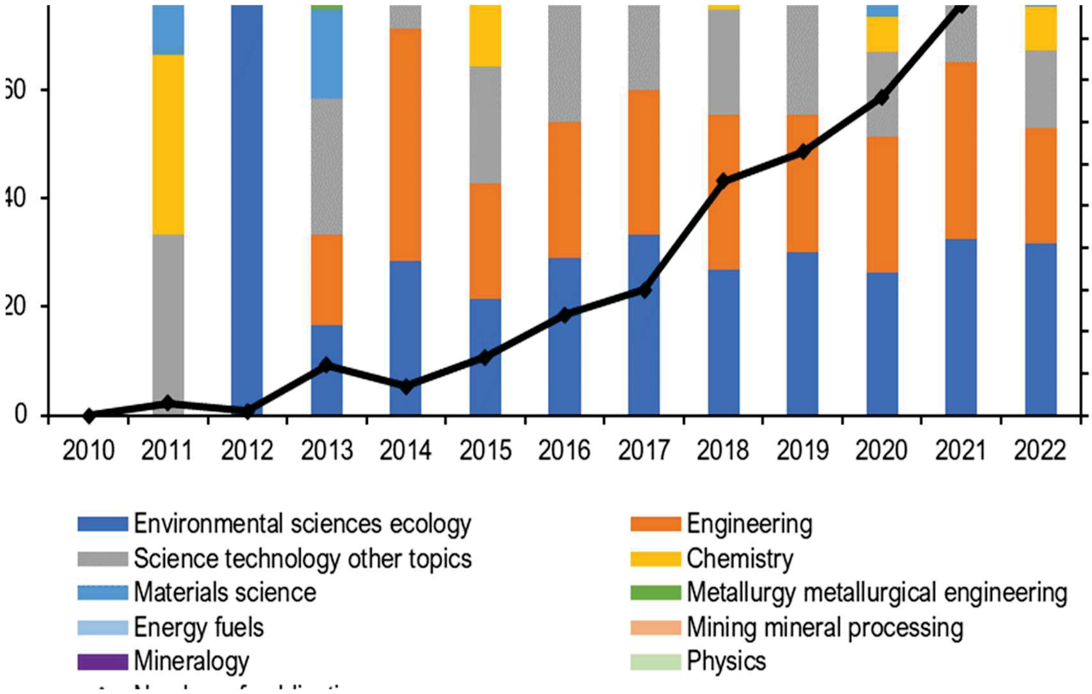
2	11	Adsorption, biosorption, characterization, circular economy, critical metals, critical raw material, life cycle, phosphogypsum, rare earth element, rare earth elements (rees), and recovery.
3	8	Bioleaching, critical raw materials, e-waste, electronic waste, metal recovery, rare-earth elements, recycling, and weee;
4	7	Dysprosium, industrial ecology, material flow analysis, molten salt electrolysis, neodymium, rare earth, and rare earth metals.
5	7	Rare earths, red mud, resource recovery, scandium, sustainability, urban mining, and valorization.
6	2	Waste electrical – and - electronic equipment and waste management.
7	1	Supply chain.

4 BIBLIOMETRIC ANALYSIS OF THE LIFE CYCLE AND CIRCULAR ECONOMY WITHIN THE CONTEXT OF RARE EARTH PRODUCTION IN THE LAST 12 YEARS

4.1 THE DEVELOPMENT OF PUBLICATIONS AND SUBJECT ÁREAS

Figure 3 illustrates the evolution of publications between the years 2010 and 2022. Initially, it can be observed that among the 10 most relevant felds of study, no documents were reported in the year 2010, possibly due to the emerging nature of the research segment, which had not yet piqued the interest of the scientifc community. The frst signifcant increase in the number of publications began to occur in 2013, with a total of 12 documents. Graphically, Table there is evidence of a second phenomenon of increased publications in 2018, when 56 documents were recorded. This phenomenon indicates a growing interest in studying rare earth related to life cycle analysis and circular economy. Regarding the areas of study, certain patterns can be inferred. In 2011, when document records within this research feld commenced, the most prominent area was not yet present. The records were distributed across the felds of “Materials Science,” “Chemistry,” and “Science Technology Other Topics.” However, next year (2012), only one document belonged to the feld of “Environmental Sciences Ecology.” At the end of the assessed period in 2022, it can be observed that the “Environmental Sciences Ecology” sector represents 31.75% of the documents, followed by “Engineering” at 21.43% and “Science Technology Other Topics” at 14.29%.

FIGURE 3: EVOLUTION OF PUBLICATIONS IN THE LIFE CYCLE AND CIRCULAR ECONOMY WITHIN THE CONTEXT OF RARE EARTH FROM 2010 TO 2022



Analysis of the key terms

In Fig. 4, the author’s most frequently utilized keywords are consolidated into a network map comprising seven clusters arranged following their significance and relevance, as outlined in Table 3 The 49 keywords were selected based on a minimum criterion of 4 occurrences. In Fig. 4A, which presents the term map based on the obtained clusters, the keyword “rare earth elements” is closely associated with keywords such as “life cycle assessment,” “life cycle inventory,” “mining,” “leaching,” and “solvent extraction.” These associations indicate a pronounced interest in studies related to life cycle assessments, considering aspects of mining, leaching processes, and the solventes used in extraction. Across the other clusters, various trends within the research feld can be observed. These trends encompass other terms related to rare earth and associated research domains, including the adoption of processes such as “adsorption” and “biosorption,” as well as concerns about environmental impacts such as “electronic waste,” “recycling,” “resource recovery,” “sustainability,” “waste management,” and “supply chain.” Furthermore, when checking cluster 2 (Table 3), which corresponds to the green color in Fig. 4A, the keyword “economic circular” exhibits strong correlations with terms related to adsorption processes, recovery, and characterization. This suggests the prominence of these terms within the context of circular economy studies. In turn, Fig. 4B depicts the usage of keywords over time, indicating trends or their decline. In 2018, represented by the blue color, keywords such as “metals,” “industrial ecology,” and “life cycle” are already noticeable. Moving to 2020, indicated by the green color, we observe a greater prevalence of keywords such as “rare earth elements,” “life cycle assessment,” “life cycle inventory,” “sustainability,” and “urban mining.” This suggests a continued focus on environmental concerns and life cycle studies within the subject area, along with advancements in developing new niches and expanding research fields. Finally, in 2021, marked by the yellow color, a more in-depth direction is apparent, with keywords like “phosphogypsum,” “e-waste,” “leaching,” and “neodymium.”

FIGURE 4: KEYWORD CLUSTERING BY AUTHORS: A MAPPING TERMS INTO DISTINCT CLUSTERS; B MAPPING THE AVERAGE YEAR OF TERM USAG

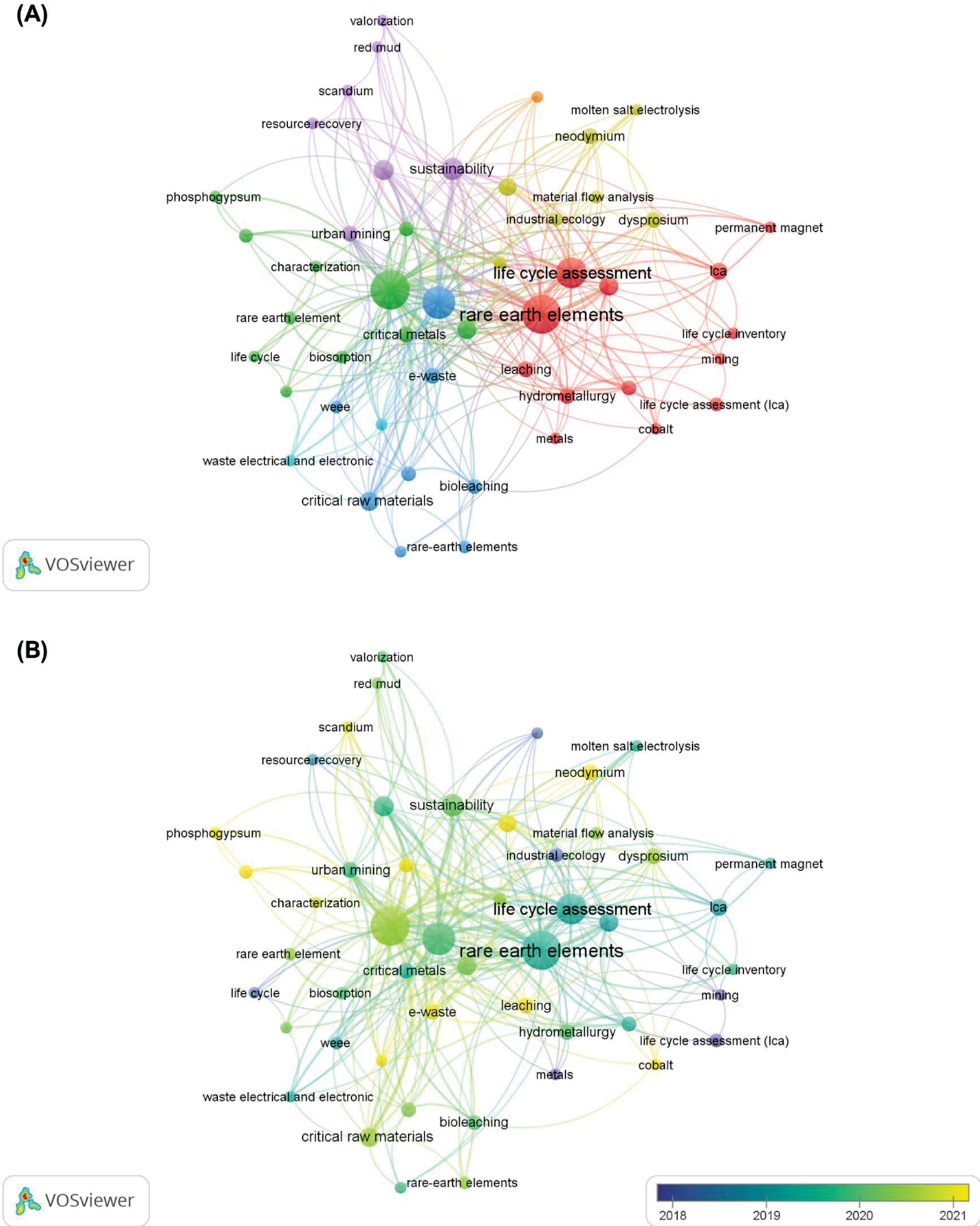


TABLE 3: TOP 10 RANKINGS IN THE FELD OF RARE EARTHS RESTRICTED TO THE STUDY OF LIFE CYCLE AND ECONOMIC CIRCULAR STUDIES OVER THE LAST 12 YEARS: PUBLICATION

AREAS, AFFILIATIONS, COUNTRIES, JOURNALS, AND AUTHORS BASED ON PUBLICATION COUNT.

Ranking	Parameters	Number	%
Research areas			
1st	Environmental sciences ecology	151	51.36
2nd	Engineering	132	44.90
3rd	Science technology other topics	89	30.27
4th	Chemistry	40	13.60
5th	Materials science	25	8.50
6th	Metallurgy metallurgical engineering	20	6.80
7th	Energy fuels	16	5.44
8th	Mining mineral processing	15	5.10
9th	Mineralogy	13	4.42
10th	Physics	10	3.40
Affiliations			
1st	Helmholtz Association	22	7.48
2nd	United States Department of Energy Doe	18	6.12
3rd	Purdue University System	17	5.78
4th	Purdue University West Lafayette Campus	17	5.78
5th	Chinese Academy of Sciences	17	5.78
6th	Research Center Julich	14	4.76
7th	Leiden University	10	3.40
8th	Leiden University Excl. Lumc	9	3.06
9th	Delft University of Technology	9	3.06
10th	Idaho National Laboratory	8	2.72
Countries			
1st	United States of America	61	20.75
2nd	Germany	45	15.31
3rd	China	45	15.31
4th	England	30	10.20
5th	Italy	22	7.48

6th	Netherlands	22	7.48
7th	France	20	6.80
8th	Finland	17	5.78
9th	Sweden	17	5.78
10th	Canada	16	5.44
Journals			
1st	Resources Conservation and Recycling	26	8.84
2nd	Journal Of Cleaner Production	25	8.59
3rd	ACS Sustainable Chemistry Engineering	15	5.12
4th	Chemosphere	8	2.72
5th	Environmental Science Technology	8	2.72
6th	Waste Management	8	2.72
7th	Journal Of Sustainable Metallurgy	7	2.38
8th	International Journal of Life Cycle Assessment	6	2.04
9th	Science of the Total Environment	6	2.04
10th	Hydrometallurgy	5	1.70

The keyword analysis enabled us to identify the most commonly used terms among authors who have published in this feld. In Fig. 5, we presented the 15 most frequently employed keywords and their respective percentage to the entire sample. The three keywords that stood out most frequently were “rare earth elements,” “circular economy,” and “recycling,” with the first two being selected as keywords during the literature search. However, the third suggests studies focused on recycling, which correlates with research in the feld of circular economy. Furthermore, a closer examination of this keyword group revealed a consistent thematic orientation in research publications. Concepts such as “sustainability,” “leaching,” “recovery,” and “e-waste,” among others, exhibited notable prominence. This aligned with our earlier fndings from network mapping and cluster analysis, reinforcing the signifcance of these topics. Another powerful tool for keyword evaluation is depicted in Fig. 6. By employing thematic map assessments, we can gain valuable insights within the research field by evaluating the relevance and development of keywords. Keywords such as “rare-earth elements,” “recovery,” and “metals” are situated within the basic themes, signifying high centrality and low density. These are research areas that, with increased occurrences, hold the potential to evolve into motor themes. Conversely, motor themes, distinguished by both high centrality and density, encompass keywords that already bear established signifcance in the research feld, including “elements,” “life cycle assessment,” and “energy.” Within the niche themes, marked by high density but low centrality, we encounter topics of importance, albeit confined to specific research niches. These encompass “removal,” “behavior,” and “waste water,” signifying the research domain related to wastewater treatment, with a specifc focus on techniques and processes for removing pollutants and wastewater residues. Finally, the emerging or declining themes, characterized by low centrality and density, constitute a group of keywords that may follow two scenarios. They either have such low occurrence that their utilization might diminish or represent a burgeoning feld of study that could potentially increase in frequency over the years. Keywords in this category encompass “printed-circuit boards,” “copper,” and “electronic waste.”

FIGURE 5: 20 MOST FREQUENT FELD KEYWORDS RANKED BY OCCURRENCE

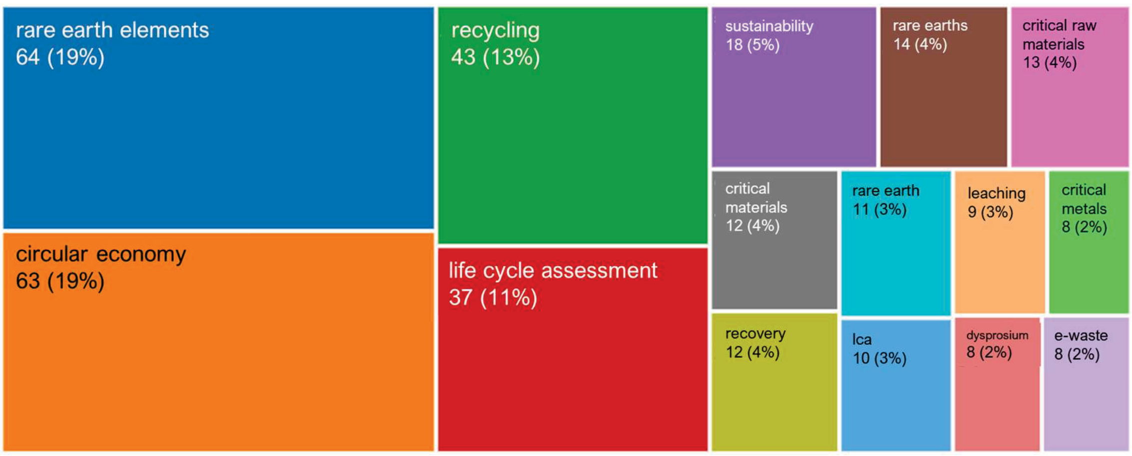
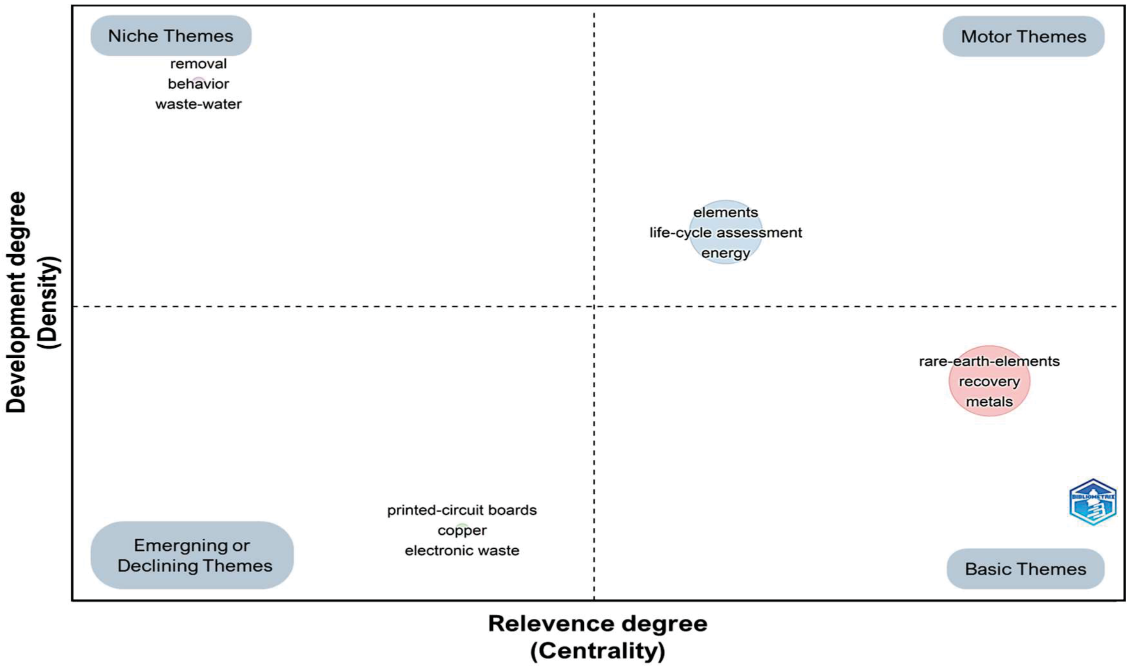


FIGURE 6: THEMATIC MAP ILLUSTRATING THE MOST COMMONLY UTILIZED KEYWORDS



4.2 INVESTIGATIVE ANALYSIS OF BIBLIOMETRIC METRICS RELATED TO SUBJECT AREAS

4.2.1 Institutional afliations, countries, journals, and authors

The list of key research areas, afliations, countries, and journals is presented in Table 4. Concerning the research feld in which the works are being published, “Environmental Sciences Ecology” dominates, representing more than half of the publications at 51.36%. Following closely is “Engineering,” at 44.90%, and in third place is “Science Technology Other Topics,” at 30.27%. It is important to note that the percentages do not add up to 100%, as depending on the publication journal, works may encompass more than one area of concentration. The institution with the largest research hub on the subject is the Helmholtz Association, located in Germany, leading with 7.48% of publications in the feld. However, the country with the highest number of publications is the USA, at 20.75% of the records. Germany and China share the second position at 15.31%, followed by England at 10.20%. Regarding the journals where the works are published, “Resources Conservation and Recycling” accounts for 8.84% of the publications, closely followed by the “Journal of Cleaner Production,” with only a one-publication diference. In sequence, the journal “ACS Sustainable Chemistry

Engineering" represents 5.12% of the publications. From a general perspective, the journals that concentrate on these publications focus on environmental themes, sustainability, recycling, and the conservation of natural resources. Furthermore, many of them emphasize environmental chemistry and sustainable engineering topics.

TABLE 4: SUMMARY TABLE OF THE MAIN INFORMATION FROM THE BIBLIOMETRIC STUDY OF RARE EARTHS FOCUSED ON LIFE CYCLE AND CIRCULAR ECONOMY

Development of Publications	There was a notable increase in publications, particularly in 2013 and 2018.
Analysis of Key Terms	The most frequently used keywords are life cycle assessment, mining, and recycling. The increase in interest in environmental issues is noticeable.
Key Research Areas	Environmental Sciences Ecology (51.36%), Engineering (44.90%), Science Technology Other Topics (30.27%).
Leading Institution	Helmholtz Association (7.48% of publications).
Top Countries	USA (20.75%), Germany and China (15.31% each), England (10.20%).
Dominant Journals	Resources Conservation and Recycling, Journal of Cleaner Production, and ACS Sustainable Chemistry Engineering.
High Centrality, Low Density Themes	Rare-earth elements, recovery, metals.
High Centrality, High Density Themes	Elements, life-cycle assessment, energy.
High Density, Low Centrality Themes	Removal, behavior, waste-water.

Low Centrality, Low Density Themes	Printed-circuit boards, copper, electronic waste.

5 CONCLUSION

The study addressed the critical role of mining and production of rare earth elements in the propulsion of various emerging technologies, along with their corresponding environmental and socioeconomic impacts. Among these impacts, we highlight the emission of greenhouse gases, waste generation, high energy consumption, and the social risks inherent to this industry. It was found that implementing strategies to mitigate these impacts, including optimizing extraction and processing processes, exploring alternative production methods, and applying life cycle assessment and circular economy techniques, is imperative. These practices can provide a more integrated approach to the production and use of REE magnets, ensuring sustainability. The potential of recycling and recovering metals from electronic waste to mitigate environmental impacts and ensure a sustainable supply of REE magnets has also been recognized. The Science Citation Index Expanded (SCI-E) platform (Clarivate Analytics' ISI and Web of Science) showed that the words “rare earth elements” are closely associated with “mining,” “leaching,” and “solvente extraction.” These associations indicate a pronounced interest in studies related to life cycle assessments, considering aspects of mining, leaching processes, and the solvents used in extraction. The areas “rare earth elements,” “recovery,” and “metals” are situated within the basic themes but also are motor themes, distinguished by both high centrality and density, including “elements,” “life cycle assessment,” and “energy.” In summary, bibliometric analysis provided valuable insights into the current state of research, technological developments, environmental impacts, supply chains, and barriers related to rare earth magnet production. By leveraging this information, stakeholders can make informed decisions and implement strategies to improve LCA and circular economy practices in this critical industry. However, it becomes necessary to investigate along this line of research, which will be advantageous to ofer more elaborate suggestions for future research, including potential methodologies, specifc areas within rare earth element production necessitating additional exploration, or emerging technologies pertinent to this feld. Given the abundance of research in this realm yielding diverse conclusions, it is imperative that conclusions be better structured and substantiated with coherent logic and evidence. This study provided a basis for future research and development of CE and LCA studies in the rare earth magnet production chain.

Acknowledgements This study was funded by the Brazilian Science and Research Foundation (CNPq) (productivity Grant 302451/2021- 8); São Paulo Research Foundation (FAPESP, Brazil) (grant numbers 2018/14938-4). The authors would like to thank Fundaçao Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Finance code 001) for its fnancial support during this study.

Author contributions Thamires Martinho Prados involved in conceptualization; methodology; investigation; formal analysis; writing—original draft; fgure design. Tiago Linhares Cruz Tabosa Barroso took part in writing—review and editing. Tania Forster-Carneiro involved in writing—review and editing. Giancarlo Alfonso Lovón-Canchumani took part in conceptualization, project administration, supervision, writing—review and editing. Leda Maria Saragiotto Colpini involved in conceptualization, project administration, supervision, writing—review and editin

Funding The authors have not disclosed any funding.
Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors have not disclosed any competing interests

REFERENCES

Adibi N, Lafhaj Z, Gemechu E, Sonnemann G, Payet J (2014) Introducing a multi criteria indicator to better evaluate impacts of rare earth materials production and consumption in life cycle assessment. J Rare Earths 23(3):288–292

Adibi N, Lafhaj Z, Payet J (2019) New resource assessment characterization factors for rare earth elements: applied in NdFeB permanent magnet case study. Int J Life Cycle Assess 24:712–724

Alecu G, Kappel W (2021) Elements of the circular economy in the manufacture of NdFeB permanent magnets EM ICPE-CA. J Eng Sci Innov 6:175–188

Ali S (2014) Social and environmental impact of the rare earth industries. Resources 3(1):123–134

Alonso E, Sherman AM, Wallington TJ, Everson MP, Field FR, Roth R, Kirchain RE (2012) Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol 46(6):3406–3414

Althaus H-J, Hischier R, Osses M, Chudacof M, Hellweg S, Jungbluth N, Primas A (2007) Life cycle inventories of chemicals (Ecoinvent report No. 8), 8th edn, vol. 2. va

Amaral J (2014) Diagnosis of trends for accessing alternative sources of rare earths from fnished products: recycling of permanent magnets. UFRJ.

Amato A, Beolchini F (2018) End-of-life CIGS photovoltaic panel: a source of secondary indium and gallium. Photovoltaics 27(3):229–236

Amato A, Rocchetti L, Fonti V, Ruello ML, Beolchini F (2016) Secondary indium production from end-of-life liquid crystal displays. Phys Status Solidi 13:979

Amato A, Rocchetti L, Beolchini F (2017) Environmental impact assessment of diferent end-of-life LCD management strategies. Waste Manage 59:432–441. https://doi.org/10.1016/j.wasman.2016.09.024

Amato A, Becci A, Birloaga I, De Michelis I, Ferella F, Innocenzi V, Ippolito NM, Pillar Jimenez Gomez C, Vegliò F, Beolchini F (2019) Sustainability analysis of innovative technologies for the rare earth elements recovery. Renew Sustain Energy Rev 106:41–53. https://doi.org/10.1016/j.rser.2019.02.029

Arshi PS, Vahidi E, Zhao F (2018) Behind the scenes of clean energy: the environmental footprint of rare earth products. ACS Sustain Chem Eng 6(3):3311–3320

Bailey G, Mancheri NM, van Acker K (2017) Sustainability of permanent rare earth magnet motors in (H)EV industry. J Sustain Metall 3(3):611–626

Bailey G, Joyce PJ, Schrijvers D, Schulze R, Sylvestre AM, Sprecher B, Vahidi E, Dewulf W, Van Acker K (2020) Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. Resour Conserv Recycl 155:104675. https://doi.org/10.1016/J.RESCONREC. 2019.104675

Bailey G (2016) Life cycle assessment of the pyrometallurgical and hydrometallurgical recycling routes used in rare earth recycling: a case study of NdFeB magnets. Recycling 6(3)

Balanay R, Halog A (2019) Tools for circular economy: review and some potential applications for the Philippine textile industry. Circ Econ Text Appar Process Manuf Des. https://doi.org/10.1016/B978-0-08-102630-4.00003-0

Balaram V (2019) Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geosci Front 10(4):1285–1303. https://doi.org/10.1016/J. GSF.2018.12.005

Bastianoni S, Gofetti G, Neri E, Patrizi N, Ruini A, Sporchia F, Pulselli F (2023) LCA based circularity índices of systems at diferent scales: a holistic approach. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2023.165245

Bauer D, Diamond D, Li J, Sandalow D, Telleen P, Wanner B (2010) U.S. Department of Energy Critical Materials Strategy

Baxter J (2019) Systematic environmental assessment of end-of-life pathways for domestic refrigerators. J Clean Prod 208:612–620. https://doi.org/10.1016/j.jclepro.2018.10.173

Bemrose CR, Bridgwater J (1987) A review of attrition and attrition test methods. Powder Technol 49(2):97–126. https://doi.org/10.1016/0032-5910(87)80054-2

Binnemans K, Jones PT (2015) Rare Earths and the balance problem. J Sustain Metall 1(1):29–38. https://doi.org/10.1007/s40831-014-0005-1

Binnemans K, Jones PT, Blanpain B, Gerven TV, Yang Y, Walton A, Buchert M (2013a) Recycling of rare earths: a critical review. J Clean Prod 51:1–22

Binnemans K, Jones PT, Blanpain B, Van Gerven T, Yang Y, Walton A, Buchert M (2013b) Recycling of rare earths: a critical review. J Clean Prod 51:1–22. https://doi.org/10.1016/J.JCLEPRO.2012.12.037

Binnemans K, Jones PT, Müller T, Yurramendi L (2018) Rare Earths and the balance problem: How to deal with changing markets? J Sustain Metall 4:126–146

Blomsma F (2018) Collective ‘action recipes’ in a circular economy—on waste and resource management frameworks and their role in collective change. J Clean Prod 199:969–982. https://doi.org/10.1016/J.JCLEPRO.2018.07.145

Bodenheimer M (2014) Certifying improvement, improving certifcation: an analysis based on the artisanal and small-scale mining sector. Research papers in economics

Bonfante MC, Raspini JP, Fernandes IB, Fernandes S, Campos LMS, Alarcon OE (2021) Achieving sustainable development goals in rare earth magnets production: a review on state of the art and SWOT analysis. Renew and Sustain Energy Rev. https://doi.org/10.1016/j.rser.2020.110616

Bontron C (2012) Rare-earth mining in China comes at a heavy cost for local villages. Guardian

Bradsher K (2009) China: earth-friendly elements, mined destructively. New York Times

Brandstrom J, Saidani M (2022) Comparison between circularity metrics and LCA: a case study on circular economy strategies. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.133537

Brocke JV, Simões A, Niehaves B, Niehaves B, Ribeiro A, Ribeiro R, e Cleven A (2009). Reconstruindo o gigante: sobre a importância do rigor na documentação do processo de busca na literature, Anais do ECIS 2009. 161. https://aisel.aisnet.org/ecis2009/161

Carrillo García A, Latif M, Samih S, Chaouki J (2020) Production of rare earth oxides from raw ore in fuidized bed reactor. J Ind Eng Chem 85:141–151. https://doi.org/10.1016/J.JIEC.2020.01.034

Chakhmouradian A, Wall F (2012) Rare earth elements: minerals, mines, magnets (and more). Elements 8(5):333–340

Chancerel P, Rotter S (2009) Recycling-oriented characterization of small waste electrical and electronic equipment. Waste Manage 29(8):2336–2352. https://doi.org/10.1016/j.wasman.2009.04.003

Chancerel P, Marwede M, Nissen NF, Lang KD (2015) Estimating the quantities of critical metals embedded in ICT and consumer equipment. Resour Conserv Recycl 98:9–18. https://doi.org/10.1016/J.RESCONREC.2015.03.003

Chung H, Stopic S, Emil-Kaya E, Gürmen S, Friedrich B (2022) Recovery of rare earth elements from spent NdFeB-magnets: separation of iron through reductive smelting of the oxidized material (second part). Metals. https://doi.org/10.3390/met12101615

Criado JM, Ortega A (1992) A study of the infuence of particle size on the thermal decomposition of CaCO3 by means of constant rate thermal analysis. Thermochim Acta. https://doi.org/10.1016/0040-6031(92)80059-6

Cucchiella F, D'Adamo I, Lenny Koh SC, Rosa P (2016) A proftability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. In: Renewable and sustainable energy reviews, vol 64. Elsevier, pp 749–760. https://doi.org/10.1016/j.rser.2016.06.057

Curran M, de Baan L, De Schryver AM, van Zelm R, Hellweg S, Koellner T, Sonnemann G, Huijbregts MA (2010) Toward meaningful end points of biodiversity in life cycle assessment. Environ Sci Technol 45(1):70–79. https://doi.org/10.1021/es101444k

Dang DH, Thompson KA, Ma L, Nguyen HQ, Luu ST, Duong MTN, Kernaghan A (2021) Toward the circular economy of rare earth elements: a review of abundance, extraction, applications, and environmental impacts. Arch Environ Contam Toxicol 81:521–530

De Meester S, Nachtergaele P, Debaveye S, Vos P, Dewulf J (2019) Using material fow analysis and life cycle assessment in decision support: a case study on WEEE valorization in Belgium. Resour Conserv Recycl 142:1–9. https://doi.org/10.1016/j.resconrec.2018.10.015

Deetman S, Pauliuk S, Van Vuuren DP, Van Der Voet E, Tukker A (2018) Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ Sci Technol 52:4950–4959

Deng H, Kendall A (2019) Life cycle assessment with primary data on heavy rare earth oxides from ion-adsorption clays. Int J Life Cycle Assess 24(9):1643–1652. https://doi.org/10.1007/s11367-019-01582-1

Diehl O, Schönfeldt M, Brouwer E, Dirks A, Rachut K, Gassmann J, Güth K, Buckow A, Gauß R, Stauber R, Gutfeisch O (2018) Towards an alloy recycling of Nd–Fe–B permanent magnets in a circular economy. J Sustain Metall 4(2):163–175. https://doi.org/10.1007/s40831-018-0171-7

Doronin VP, Potapenko OV, Sorokina TP, Lipin PV, Dmitriev KI, Plekhova KS, Kondrashev DO, Kleimenov AV (2021) Features of petrochemical cracking catalysts produced by aluminosilicate technology. Catal Today 378:75–82. https://doi.org/10.1016/J.CATTOD.2021.02.017

Drost D, Wang R (2016) Rare earth element criticality and sustainable management. Atlantis Press

Du X, Graedel TE (2011) Global rare earth in-use stocks in NdFeB permanent magnets. J Ind Ecol

Du X, Graedel TE (2013) Uncovering the end uses of the rare earth elements. Sci Total Env 781–784:461–462

Dudley B (2018) BP statistical review of world energy

Duncan R, Hellman PL, Duncan RK (2017) Evaluation of rare earth element deposits. https://www.researchgate.net/publication/318981361

Dutta T, Kim KH, Uchimiya M, Kwon EE, Jeon BH, Deep A, Yun ST (2016) Global demand for rare earth resources and strategies for green mining. Environ Res 150:182–190. https://doi.org/10.1016/J.ENVRES.2016.05.052

Eggert RG, Carpenter AS, Freiman SW, Graedel TE, Meyer DA, McNulty TP, Moudgil BM, Poulton MM, Surges LJ, Eide EA, Rogers ND (2008) Minerals, critical minerals, and the U.S. Economy

Elwer t T, Goldmann D (2014) Entwicklung eines hydrometallurgischen recyclingverfahrens für NdFeB-Magnete

Emil-Kaya E, Stopic S, Gürmen S, Friedrich B (2022) Production of rare earth element oxide powders by solution combustion: a new approach for recycling of NdFeB magnets. RSC Adv 12(48):31478–31488. https://doi.org/10.1039/d2ra05876f

Eriksson T, Olsson D (2011) The product chains of rare earth elements used in permanent magnets and NiMH batteries for electric vehicles. 1–66

Evans A, Strezov V, Evans TJ (2009) Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 13(5):1082–1088. https://doi.org/10.1016/J.RSER.2008.03.008

Fiore S, Ibanescu D, Teodosiu C, Ronco A (2019) Improving waste electric and electronic equipment management at full-scale by using material fow analysis and life cycle assessment. Sci Total Environ 659:928–939. https://doi.org/10.1016/j.scitotenv.2018.12.417

Firdaus M, Rhamdhani MA, Durandet Y, Rankin WJ, McGregor K (2016) Review of high-temperature recovery of rare earth (Nd/Dy) from magnet waste. J Sustain Metall 2(4):276–295. https://doi.org/10.1007/s40831-016-0045-9

Fouquet Y, Martel-Jantin B (2014) Rare and strategic metals. In: Deep marine mineral resources, pp 55–64

Frost K, Jin H, Olson W, Schafer M, Spencer G, Handwerker C (2020) The use of decision support tools to accelerate the development of circular economic business models for hard disk drives and rare-earth magnets. MRS Energy Sustain. https://doi.org/10.1557/mre.2020.21

Gambogi J (2016) Rare earths 2016

Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy—a new sustainability paradigm? In: Journal of cleaner production, vol 143. Elsevier, pp 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

U.S. Geological Survey (2021) Mineral commodity summaries 2021 Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 114:11–32. https://doi.org/10.1016/J.JCLEPRO.2015.09.007

Golev A, Scott M, Erskine PD, Ali SH, Ballantyne GR (2014) Rare earths supply chains: current status, constraints and opportunities. Resour Policy 41(1):52–59. https://doi.org/10.1016/J.RESOURPOL.2014.03.004

Golroudbary SR, Makarava I, Kraslawski A, Repo E (2022) Global environmental cost of using rare earth elements in green energy technologies. Sci Total Environ 832:155022. https://doi.org/10.1016/J.SCITOTENV.2022.155022

Goodenough KM, Wall F, Merriman D (2018) The rare earth elements: demand, global resources, and challenges for resourcing future generations. Nat Resour Res 27(2):201–216. https://doi.org/10.1007/s11053-017-9336-5

Goonan TG (2011) Rare earth elements: end use and recyclability

Gosen, B. S. Van, Verplanck, P. L., Long, K. R., Gambogi, J., & Seal II, R. R. (2014). The rare-earth elements: Vital to modern technologies and lifestyles.

Gosen BS Van, Verplanck PL, Seal II RR, Long KR, Gambogi J (2017) Critical mineral resources of the United States—economic and environmental geology and prospects for future supply. U.S. Geological Survey, pp 1–44

Gue IHV, Promentilla MAB, Tan RR, Ubando AT (2020) Sector perception of circular economy driver interrelationships. J Clean Prod 276:123204. https://doi.org/10.1016/J.JCLEPRO.2020.123204

Gupta CK, Krishnamurthy N (1992) Extractive metallurgy of rare earths. Int Mater Rev 37(1):197–248

Gusmerotti NM, Testa F, Corsini F, Pretner G, Iraldo F (2019) Drivers and approaches to the circular economy in manufacturing frms. J Clean Prod 230:314–327. https://doi.org/10.1016/J.JCLEPRO.2019.05.044

Gutfeisch O (2000) Controlling the properties of high energy density permanent magnetic materials by diferent processing routes. J Phys D Appl Phys 33(17)

Habib K (2019) A product classification approach to optimize circularity of critical resources—the case of NdFeB magnets. J Clean Prod 230:90–97. https://doi.org/10.1016/J.JCLEPRO.2019.05.048

Habib K, Wenzel H (2014) Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. J Clean Prod 84(1):348–359. https://doi.org/10.1016/J.JCLEPRO.2014.04.035

Habib K, Wenzel H (2016) Reviewing resource criticality assessment from a dynamic and technology specifc perspective—using the case of direct-drive wind turbines. J Clean Prod 112:3852–3863. https://doi.org/10.1016/J.JCLEPRO.2015.07.064

Habib K, Klausen Schibye P, Peter Vestbø A, Dall O, Wenzel H (2014) Material fow analysis of NdFeB magnets for Denmark: a comprehensive waste fow sampling and analysis approach. Environ Sci Technol 48(20):12229–12237. https://doi.org/10.1021/es501975y

Habib K, Parajuly K, Wenzel H (2015) Tracking the fow of resources in electronic waste—the case of end-of-life computer hard disk drives. Environ Sci Technol 49(20):12441–12449. https://doi.org/10.1021/acs.est.5b02264

Habib K, Hamelin L, Wenzel H (2016) A dynamic perspective of the geopolitical supply risk of metals. J Clean Prod 133:850–858. https://doi.org/10.1016/J.JCLEPRO.2016.05.118

Habib K (2015) Critical resources in clean energy technologies and waste fows [PhD]. University of Southern Denmark

Hao Z, Li Y, Li H, Wei B, Liao X, Liang T, Yu J (2015) Levels of rare earth elements, heavy metals and uranium in a population living in Baiyun Obo, Inner Mongolia, China: a pilot study. Chemosphere 128:161–170. https://doi.org/10.1016/J.CHEMOSPHERE.2015.01.057

Haque N, Hughes A, Lim S, Vernon C (2014) Rare earth elements: overview of mining, mineralogy, uses, sustainability and environmental impact. In: Resources, vol 3. pp 614–635. MDPI AG. https://doi.org/10.3390/resources3040614

Hernandez M, Messagie M, Hegazy O, Marengo L, Winter O, Van Mierlo J (2017) Environmental impact of traction electric motors for electric vehicles applications. Int J Life Cycle Assess 22(1):54–65. https://doi.org/10.1007/s11367-015-0973-9

Herrington R (2021) Mining our green future. In: nature reviews materials, vol 6, pp 456–458. Nature Research. https://doi.org/10.1038/s41578-021-00325-9

Holger S, Petra Z, Josephine M, Andrea S, Sandra V, Jürgen-Friedrich H (2017) The social footprint of permanent magnet production based on rare earth elements—a social life cycle assessment scenario. Energy Procedia 142:984–990. https://doi.org/10.1016/J.EGYPRO.2017.12.157

Honshima M, Ohashi K (1994) High-energy NdFeB magnets and their applications. In: JMEPEG, vol 3

Huang XW, Long ZQ, Wang LS, Feng ZY (2015) Technology development for rare earth cleaner hydrometallurgy in China. In: Rare metals, vol 34, pp 215–222. University of Science and Technology Beijing. https://doi.org/10.1007/s12598-015-0473-x

Huang X, Zhang G, Pan A, Chen F, Zheng C (2016) Protecting the environment and public health from rare earth mining. In: Earth's future, vol 4. John Wiley and Sons, pp 532–535. https://doi.org/10.1002/2016EF000424

Hurst C (2010) China's rare earth elements industry: What can the west learn? Institute for the analysis of global security (IAGS)

Imholte DD, Nguyen R, Vedantam A, Brown M, Iyer A, Smith B, Collins J, Anderson C, O'kelley B (2017) An assessment of U.S. rare earth availability for supporting U.S. WIND ENERGY GROWTH TARGETS. https://www.sciencedirect.com/science/article/pii/S0301421517307383

Işıldar A, Rene ER, van Hullebusch ED, Lens PNL (2018) Electronic waste as a secondary source of critical metals: management and recovery technologies. Resour Conserv Recycl 135:296–312. https://doi.org/10.1016/J.RESCONREC.2017.07.031

Işıldar A, van Hullebusch ED, Lenz M, Du Laing G, Marra A, Cesaro A, Panda S, Akcil A, Kucuker MA, Kuchta K (2019) Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE)—a review. In: Journal of hazardous materials, vol 362. Elsevier B.V. pp 467–481 https://doi.org/10.1016/j.jhazmat.2018.08.050

ISO 14040 (2006) Environmental management: life cycle assessment—principles and framework

ISO 14044 (2006) Environmental management: life cycle assessment—requirements and guidelines

Jally B, Laubie B, Chour Z, Muhr L, Qiu R, Morel JL, Tang Y, Simonnot MO (2021) A new method for recovering rare earth elements from the hyperaccumulating fern Dicranopteris linearis from China. Miner Eng 166:106879. https://doi.org/10.1016/J.MINENG.2021.106879

Jawahir IS, Bradley R (2016) Technological elements of circular economy and the principles of 6R-based closed-loop material fow in sustainable manufacturing. Procedia CIRP 40:103–108. https://doi.org/10.1016/J.PROCIR.2016.01.067

Jin H, Afuny P, McIntyre T, Yih Y, Sutherland JW (2016) Comparative life cycle assessment of NdFeB magnets: virgin production versus magnet-to-magnet recycling. Procedia CIRP 45–50

Jin H, Duk Song B, Yih Y, Sutherland W, J. (2018a) Sustainable value recovery of NdFeB magnets: a multi-objective network design and genetic algorithm. ACS Sustain Chem Engi 6(4):4767–4775. https://doi.org/10.1021/acssuschemeng.7b03933

Jin H, Song BD, Yih Y, Sutherland JW (2018b) Sustainable value recovery of NdFeB magnets: a multi-objective network design and genetic algorithm. Sustain Chemi Eng 6(4):4767–4775

John B, Möller A, Weiser A (2016) Sustainable development and material fows. Sustainability Science, pp 219–230

Jordens A, Cheng YP, Waters KE (2013) A review of the benefciation of rare earth element bearing minerals. Miner Eng 41:97–114. https://doi.org/10.1016/J.MINENG.2012.10.017

Jowitt SM, Werner TT, Weng Z, Mudd GM (2018) Recycling of the rare earth elements. Current Opinion Green Sustainble Chem 13:1–7. https://doi.org/10.1016/J.COGSC.2018.02.008

Kanazawa Y, Kamitani M (2006) Rare earth minerals and resources in the world. J Alloy Compd 408–412:1339–1343. https://doi.org/10.1016/J.JALLCOM.2005.04.033

Karal E, Kucuker MA, Demirel B, Copty NK, Kuchta K (2021) Hydrometallurgical recovery of neodymium from spent hard disk magnets: a life cycle perspective. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.125087

Kaya M (2016) Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manage 57:64–90. https://doi.org/10.1016/J.WASMAN.2016.08.004

Kaya EE, Kaya O, Stopic S, Gürmen S, Friedrich B (2021) Ndfeb magnets recycling process: an alternative method to produce mixed rare earth oxide from scrap ndfeb magnets. Metals. https://doi.org/10.3390/met11050716

Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005

Koltun P, Tharumarajah A (2014) Life cycle impact of rare earth elements. ISRN Metall 2014:1–10. https://doi.org/10.1155/2014/907536

Krishnamurthy N, Gupta CK (2004). Extractive metallurgy of rare earths (1st ed.)

Kruse S, Raulf K, Pretz T, Friedrich B (2017) Infuencing factors on the melting characteristics of NdFeB-based production wastes for the recovery of rare earth compounds. J Sustain Metall 3(1):168–178. https://doi.org/10.1007/s40831-016-0093-1

Kruse S, Raulf K, Trentmann A, Pretz T, Friedrich B (2015) In: Processing of Grinding slurries arising from NdFeB magnet production. Chemie Ingenieur Technik.

Kul M, Topkaya Y, Karakaya İ (2008) Rare earth double sulfates from pre-concentrated bastnasite. Hydrometallurgy 93(3–4):129–135

Kumar A, Holuszko M, Espinosa DCR (2017) E-waste: an overview on generation, collection, legislation and recycling practices. Resour Conserv Recycl 122:32–42. https://doi.org/10.1016/J.RESCONREC.2017.01.018

Kumari A, Panda R, Jha MK, Kumar JR, Lee JY (2015) Process development to recover rare earth metals from monazite mineral: a review. Miner Eng 79:102–115. https://doi.org/10.1016/J.MINENG.2015.05.003

Langkau S, Erdmann M (2021) Environmental impacts of the future supply of rare earths for magnet applications. J Ind Ecol 25(4):1034–1050. https://doi.org/10.1111/jiec.13090

Latunussa CEL, Ardente F, Blengini GA, Mancini L (2016) Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol Energy Mater Sol Cells 156:101–111. https://doi.org/10.1016/j.solmat.2016.03.020

Lee JCK, Wen Z (2017) Rare earths from mines to metals: comparing environmental impacts from China’s main production pathways. J Ind Ecol 21(5):1277–1290

Li Z, Diaz LA, Yang Z, Jin H, Lister TE, Vahidi E, Zhao F (2019) Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. Resour Conserv Recycl 149:20–30

Liu Z, Li M, Hu Y, Wang M, Shi Z (2008) Preparation of large particle rare earth oxides by precipitation with oxalic acid. J Rare Earths 26(2):158–162. https://doi.org/10.1016/S1002-0721(08)60057-5

Liu Q, Cao J, Li KQ, Miao XH (2009) Chromosomal aberrations and DNA damage in human populations exposed to the processing of electronics waste. Environ Sci Pollut Res 16(3):329–338

Lusty P, Walters AS (2010) Rare earth elements. PS: Environ Sci

Lyman JW, Palmer GR (1993) Recycling of neodymium iron boron magnet scrap, Report of investigations

Machacek E, Richter JL, Habib K, Klossek P (2015) Recycling of rare earths from fuorescent lamps: value analysis of closing-the-loop under demand and supply uncertainties. Resour Conserv Recycl 104:76–93. https://doi.org/10.1016/J.RESCONREC.2015.09.005

Magrini C, Jagodzińska K (2022) Can bioleaching of NIB magnets be an answer to the criticality of rare earths? An ex-ante life cycle assessment and material fow cost accounting. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.132672

Maqbool A, Khan S, Haleem A, Khan MI (2020) Investigation of drivers towards adoption of circular economy: a DEMATEL approach. Recent advances in mechanical engineering, pp 147–160

Marscheider-Weidemann F, Langkau S, Hummen T, Erdmann L, Tercero ELA, Angerer G, Marwede M, Benecke S, FraunhoferInstitut für Zuverlässigkeit und Mikrointegration. (2016). Rohstofe für Zukunftstechnologien 2016: Auftragsstudie

Marx J, Schreiber A, Zapp P, Walachowicz F (2018) Comparative life cycle assessment of NdFeB permanent magnet production from diferent rare earth deposits. ACS Sustain Chem Eng 6(5):5858–5867

Masmoudi-Soussi A, Hammas-Nasri I, Horchani-Naifer K, Férid M (2020) Rare earths recovery by fractional precipitation from a sulfuric leach liquor obtained after phosphogypsum processing. Hydrometallurgy 191:105253. https://doi.org/10.1016/J.HYDROMET.2020.105253

McLellan BC, Corder GD, Golev A, Ali SH (2014) Sustainability of the rare earths industry. Procedia Environ Sci 20:280–287. https://doi.org/10.1016/J.PROENV.2014.03.035

Mejame M, King D, Banhalmi-zakar Z, He Y (2022) Circular economy: a sustainable management strategy for rare earth elements consumption in Australia. Current Res Environ Sustain 4:100157. https://doi.org/10.1016/J.CRSUST.2022.100157

Meng D, Zhao Q, Pan X, Zhang T, an. (2020) Clean production of rare earth oxide from rare earth chloride solution by electrical transformation. Hydrometallurgy. https://doi.org/10.1016/j.hydromet.2020.105372

Menikpura SNM, Santo A, Hotta Y (2014) Assessing the climate co-benefts from Waste Electrical and Electronic Equipment (WEEE) recycling in Japan. J Clean Prod 74:183–190

Moldoveanu GA, Papangelakis VG (2012) Recovery of rare earth elements adsorbed on clay minerals: I. Desorption Mech Hydrometall 117–118:71–78. https://doi.org/10.1016/J.HYDROMET.2012.02.007

Mudd GM (2010a) Global trends and environmental issues in nickel mining: sulfdes versus laterites. Ore Geol Rev 38(1–2):9–26. https://doi.org/10.1016/J.OREGEOREV.2010.05.003

Mudd GM (2010b) The environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resour Policy 35(2):98–115. https://doi.org/10.1016/J.RESOURPOL.2009.12.001

Nakamoto M, Kubo K, Katayama Y, Tanaka T, Yamamoto T (2012) Extraction of rare earth elements as oxides from a neodymium magnetic sludge. Metall Mater Trans B 43(3):468–476. https://doi.org/10.1007/s11663-011-9618-y

Nakamura H (2018) The current and future status of rare earth permanent magnets. Scr Mater 154:273–276

Navarro J, Zhao F (2014). Life-cycle assessment of the production of rare-earth elements for energy applications: a review. In: Frontiers in energy research, vol 2. Frontiers media S.A. https://doi.org/10.3389/fenrg.2014.00045

Nie W, Zhang R, He Z, Zhou J, Wu M, Xu Z, Chi R, Yang H (2020) Research progress on leaching technology and theory of weathered crust elution-deposited rare earth ore. Hydrometallurgy 193:105295. https://doi.org/10.1016/J.HYDROMET.2020.105295

Nlebedim IC, King AH (2018) Addressing criticality in rare earth elements via permanent magnets recycling. JOM 70(2):115–123. https://doi.org/10.1007/s11837-017-2698-7

Nordelöf A, Grunditz EA, Lundmark ST, Tillman A, Alatalo M, Thiringer T (2019) Life cycle assessment of permanent magnet electric traction motors. Transportation research part D: transport and environment

Norgate T, Haque N (2010) Energy and greenhouse gas impacts of mining and mineral processing operations. J Clean Prod 18(3):266–274. https://doi.org/10.1016/J.JCLEPRO.2009.09.020

Oguri T, Suzuki G, Matsukami H, Uchida N, Tue NM, Tuyen LH, Viet PH, Takahashi S, Tanabe S, Takigami H (2018) Exposure assessment of heavy metals in an e-waste processing area in northern Vietnam. Sci Total Environ 621:1115–1123. https://doi.org/10.1016/J.SCITOTENV.2017.10.115

Önal MAR, Aktan E, Borra CR, Blanpain B, Van Gerven T, Guo M (2017) Recycling of NdFeB magnets using nitration, calcination and water leaching for REE recovery. Hydrometallurgy 167:115–123. https://doi.org/10.1016/j.hydromet.2016.11.006

Padeste C, Oswald HR, Reller A (1991) The thermal behaviour of pure and nickel-doped hydromagnesite in diferent atmospheres. Mater Res Bull 26(12):1263–1268. https://doi.org/10.1016/0025-5408(91)90140-H

Pell R, Wall F, Yan X, Li J, Zeng X (2019) Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development. Miner Eng 135:64–73. https://doi.org/10.1016/J.MINENG.2019.02.043

Polyakov EG, Sibilev AS (2015) Recycling rare-earth-metal wastes by pyrometallurgical methods. Metallurgist 59(5–6):368–373. https://doi.org/10.1007/s11015-015-0111-8

PwC (2015) Make it your business

Qiu Y, Suh S (2019) Economic feasibility of recycling rare earth oxides from end-of-life lighting Technologies. Resour Conserv Recycl 150

Rabatho JP, Tongamp W, Takasaki Y, Haga K, Shibayama A (2013) Recovery of Nd and Dy from rare earth magnetic waste sludge by hydrometallurgical process. J Mater Cycles Waste Manage 15(2):171–178. https://doi.org/10.1007/s10163-012-0105-6

Rademaker JH, Kleijn R, Yang Y (2013) Recycling as a strategy against rare earth element criticality: a systemic evaluation of the potential yield of NdFeB magnet recycling. Environ Sci Technol 47(18):10129–10136

Raspini JP, Bonfante MC, Cúnico FR, Alarcon OE, Campos LMS (2022) Drivers and barriers to a circular economy adoption: a sector perspective on rare earth magnets. J Mater Cycles Waste Manage 24(5):1747–1759. https://doi.org/10.1007/s10163022-01424-7

Raspini J (2021) Barreiras e facilitadores à implementação da economia circular: fortalecimento das cadeias de valor e suprimento de ímãs de terras raras [Dissertação]. Universidade Federal de Santa Catarina.

Raulf K (2016) Recycling von Schleifschlämmen aus der neodym–eisen–bor–magnetproduktion - vorkonditionierung für die metallurgische verwertung

Reisman D, Weber R, Mckernan J, Northeim C (2013) Rare earth elements: a review of production, processing, recycling, and associated environmental issues. U.S. Environmental Protection Agency

Ritzén S, Sandström GÖ (2017) Barriers to the circular economy—integration of perspectives and domains. Procedia CIRP 64:7–12. https://doi.org/10.1016/J.PROCIR.2017.03.005

Rizos V, Behrens A, van der Gaast W, Hofman E, Ioannou A, Kafyeke T, Flamos A, Rinaldi R, Papadelis S, Hirschnitz-Garbers M, Topi C (2016) Implementation of circular economy business models by small and medium-sized enterprises (SMEs): barriers and enablers. Sustainability. https://doi.org/10.3390/su8111212

Rocchetti V, Vegliò F, Kopacek B, Beolchini F (2013) Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ Sci Technol 47:1581–1588

Rotter VS, Chancerel P, Ueberschaar M (2013) Recycling-oriented product characterization for electric and electronic equipment as a tool to enable recycling of critical metals. Rewas, 192–201

Ruello ML, Amato A, Beolchini F, Monosi S (2016) Valorizing endof-life LCD scraps after indium recovery. Phys Status Solidi

Savari S, Sachdeva S, Kumar A (2008) Electrolysis of sodium chloride using composite poly (styrene-co-divinylbenzene) cation exchange membranes. J Membr Sci 310(1–2):246–261. https://doi.org/10.1016/J.MEMSCI.2007.10.049

van Schaik A, Reuter MA (2014) Material-centric (aluminum and copper) and product-centric (cars, WEEE, TV, lamps, batteries, catalysts) recycling and DfR rules. In: Handbook of recycling: state-of-the-art for practitioners, analysts, and scientists, pp 307–378. https://doi.org/10.1016/B978-0-12-396459-5.00022-2

Schlör H, Venghaus S, Zapp P, Marx J, Schreiber A, Hake JF (2018) The energy-mineral-society nexus—a social LCA model. Appl Energy 228:999–1008. https://doi.org/10.1016/j.apenergy.2018.06.048

Schreiber A, Marx J, Zapp P, Hake JF, Voßenkaul D, Friedrich B (2016) Environmental impacts of rare earth mining and separation based on eudialyte: a new European way. Resources. https://doi.org/10.3390/resources5040032

Schreiber A, Marx J, Zapp P (2019) Comparative life cycle assessment of electricity generation by diferent wind turbine types. J Clean Prod 233:561–572. https://doi.org/10.1016/j.jclepro.2019.06.058

Schreiber A, Marx J, Zapp P (2021) Life Cycle Assessment studies of rare earths production—fndings from a systematic review. Sci Total Environ 791:148257. https://doi.org/10.1016/J.SCITOTENV.2021.148257

Schüler D, Buchert M, Liu Dipl-IR, Dittrich Dipl-GS (2011) Final report for the Greens/EFA Group in the European parliament. www.resourcefever.org

SCIO (2012) Situation and policies for China's rare earths industry

Sharma SK, Panda BN, Mahapatra SS, Sahu S (2011) Analysis of barriers for reverse logistics—an Indian

Silvestri L, Forcina A, Silvestri C, Traverso M (2021) Circularity potential of rare earths for sustainable mobility: recent developments, challenges and future prospects. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.126089

Spreafico C (2022) An analysis of design strategies for circular economy through life cycle assessment. Environ Monit Assess 194

Sprecher B, Xiao Y, Walton A, Speight J, Harris R, Kleijn R, Visser G, Kramer GJ (2014a) Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. Environ Sci Technol 48(7):3951–3958

Sprecher B, Xiao Y, Walton A, Speight J, Harris R, Kleijn R, Visser G, Kramer GJ (2014b) Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. Environ Sci Technol 48(7):3951–3958. https://doi.org/10.1021/es404596q

Sun Z, Xiao Y, Agterhuis H, Sietsma J, Yang Y (2016) Recycling of metals from urban mines—a strategic evaluation. J Clean Prod 112:2977–2987. https://doi.org/10.1016/J.JCLEPRO.2015.10.116

Takeda O, Okabe TH (2014) Current status on resource and recycling technology for rare earths. Metall Mater Trans E 1(2):160–173. https://doi.org/10.1007/s40553-014-0016-7

Talens Peiró L, Villalba Méndez G (2013) Material and energy requirement for rare earth production. J Miner Metals Mater Soc 65(10):1327–1340. https://doi.org/10.1007/s11837-013-0719-8

Talens Peiró L, Castro Girón A, Gabarrell i Durany X (2020) Examining the feasibility of the urban mining of hard disk drives. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.119216

Tan Q, Deng C, Li J (2016) Innovative application of mechanical activation for rare earth elements recovering: process optimization and mechanism exploration. Sci Rep 6

Tanaka M, Oki T, Koyama K, Narita H, Oishi T (2013) Chapter 255—Recycling of rare earths from scrap. In: Handbook on the physics and chemistry of rare earth, vol 43. pp 159–211

Tharumarajah R, Koltun P (2011) Cradle to gate assessment of environmental impact of rare earth metals. Aust Life Cycle Assess Soc 1–5

Thompson MT (2009) Practical issues in the use of NdFeB permanent magnets in maglev, motors, bearings, and eddy current brakes. Proc IEEE 97(11):1758–1767. https://doi.org/10.1109/JPROC.2009.2030231

Tkaczyk AH, Bartl A, Amato A, Lapkovskis V, Petranikova M (2018) Sustainability evaluation of essential critical raw materials: cobalt, niobium, tungsten and rare earth elements. J Phys D Appl Phys. https://doi.org/10.1088/1361-6463/aaba99

Tse P-K (2011) China's rare-earth industry

Ueberschaar M, Rotter VS (2015) Enabling the recycling of rare earth elements through product design and trend analyses of hard disk drives. J Mater Cycles Waste Manage 17(2):266–281. https://doi.org/10.1007/s10163-014-0347-6

USGS (1976) Principles of the mineral resource classifcation system

Vahidi E, Zhao F (2017) Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction. J Environ Manage 203:255–263. https://doi.org/10.1016/j.jenvman.2017.07.076

Vahidi E, Zhao F (2018) Assessing the environmental footprint of the production of rare earth metals and alloys via molten salt electrolysis. Resour Conserv Recycl 139:178–187. https://doi.org/10.1016/j.resconrec.2018.08.010

Vahidi E, Navarro J, Zhao F (2016) An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. Resour Conserv Recycl 113:1–11. https://doi.org/10.1016/J.RESCONREC.2016.05.006

Vahidi E, Zhao F (2016) Life cycle analysis for solvent extraction of rare earth elements from aqueous solutions. Springer, Cham, pp 113–120

Vander Hoogerstraete T, Blanpain B, Van Gerven T, Binnemans K (2014) From NdFeB magnets towards the rareearth oxides: a recycling process consuming only oxalic acid. RSC Adv 4:64099–64111

Van der Voet E, Van Oers L, Verboon M, Kuipers K (2019) Environmental implications of future demand scenarios for metals: methodology and application to the case of seven major metals. J Ind Ecol 23(1):141–155. https://doi.org/10.1111/jiec.12722

Viczián I (2013) Földvári, Mária: handbook of the thermogravimetric system of minerals and its use in geological practice. Central Eur Geol 56(4):397–400. https://doi.org/10.1556/ceugeol.56.2013.4.6

Voncken JHL (2015) The ore minerals and major ore deposits of the rare earths. In: The rare earth elements an introduction. pp 15–52

Waisman H, Coninck H de, Rogelj J (2019) Key technological enablers for ambitious climate goals. Insights from the IPCC special report on global warming of 1.5 °C. Environmental RESEARCH Letters, p 14

Walz R, Gandenberger C (2016) Kritikalität und positionalität: Was ist kritisch für wen—und weshalb? Kritische Metalle in Der Großen Transformation, pp 19–38

Wang P, Kara S (2019) Material criticality and circular economy: necessity of manufacturing oriented strategies. Procedia CIRP 80:667–672. https://doi.org/10.1016/J.PROCIR.2019.01.056

Wang X, Yao M, Li J, Zhang K, Zhu H, Zheng M (2017) China's rare earths production forecasting and sustainable development policy Implications. Sustainability. https://doi.org/10.3390/su9061003

Wang L, Wang P, Chen WQ, Wang QQ, Lu HS (2020) Environmental impacts of scandium oxide production from rare earths tailings of Bayan Obo Mine. J Clean Prod 270

Wang Y, Sun B, Gao F, Chen W, Nie Z (2022) Life cycle assessment of regeneration technology routes for sintered NdFeB magnets. Int J Life Cycle Assess 27(8):1044–1057. https://doi.org/10.1007/s11367-022-02081-6

Weber RJ, Reisman DJ (2012) Rare earth elements: a review of production, processing, recycling, and associated environmental issues

Weng ZH, Jowitt SM, Mudd GM, Haque N (2013) Assessing rare earth element mineral deposit types and links to environmental impacts. Appl Earth Sci 122(2):83–96

Weng Z, Jowitt SM, Mudd GM, Haque N (2015) A detailed assessment of global rare earth element resources: opportunities and challenges. Econ Geol 110(8):1925–1952

Weng Z, Haque N, Mudd GM, Jowitt SM (2016) Assessing the energy requirements and global warming potential of the production of rare earth elements. J Clean Prod 139:1282–1297. https://doi.org/10.1016/J.JCLEPRO.2016.08.132

Winterstetter A, Laner D, Rechberger H, Fellner J (2016) Evaluation and classifcation of diferent types of anthropogenic resources: the cases of old landflls, obsolete computers and in-use wind turbines. J Clean Prod 133:599–615. https://doi.org/10.1016/J.JCLEPRO.2016.05.083

Wübbeke J (2013) Rare earth elements in China: policies and narratives of reinventing an industry. Resour Policy 38(3):384–394. https://doi.org/10.1016/J.RESOURPOL.2013.05.005

Wulf C, Zapp P, Schreiber A, Marx J, Schlör H (2017) Lessons learned from a life cycle sustainability assessment of rare earth permanent magnets. J Ind Ecol 21(6):1578–1590. https://doi.org/10.1111/jiec.12575

Xie F, Zhang TA, Dreisinger D, Doyle F (2014) A critical review on solvent extraction of rare earths from aqueous solutions. Miner Eng 56:10–28. https://doi.org/10.1016/J.MINENG.2013.10.021

Xing P, Li F, Guo J, Tu G (2010) High temperature dephosphorus behavior of Baotou mixed rare earth concentrate with carbon. J Rare Earths 28(SUPPL. 1):194–197. https://doi.org/10.1016/S1002-0721(10)60364-X

Xu X, Sturm S, Samardzija Z, Vidmar J, Scancar J, Rozman KZ (2019) Direct recycling of Nd–Fe–B magnets based on the recovery of $Nd_2Fe_{14}B$ grains by acid-free electrochemical etching. Chemsuschem 12(21):4754–4758. https://doi.org/10.1002/cssc.201902342

Xue PZ, Lin JF (2011) Discussion on the rare earth resources and its development potential of Inner Mongolia of China. In: International conference on materials for renewable energy & environment, pp 9–12

Yan X, Tan DKY, Inderwildi OR, Smith JAC, King DA (2011) Life cycle energy and greenhouse gas analysis for agave-derived bioethanol. Energy Env Sci 4:3110–3121

Yang XJ, Lin A, Li XL, Wu Y, Zhou W, Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environ Develop 8(1):131–136. https://doi.org/10.1016/J.ENVDEV.2013.03.006

Yang Y, Walton A, Sheridan R, Güth K, Gauß R, Gutfleisch O, Buchert M, Steenari B-M, Van Gerven T, Jones PT, Binnemans K (2017b) REE recovery from end-of-life NdFeB permanent magnet scrap: a critical review. J Sustain Metall 3(1):122–149

Yang Y, Walton A, Sheridan R, Güth K, Gauß R, Gutfleisch O, Buchert M, Steenari BM, Van Gerven T, Jones PT, Binnemans K (2017a) REE recovery from end-of-life NdFeB permanent magnet scrap: a critical review. In: Journal of sustainable metallurgy, vol 3. Springer, pp 122–149. https://doi.org/10.1007/s40831-016-0090-4

Yoon HS, Kim CJ, Chung KW, Kim SD, Lee JY, Kumar JR (2016) Solvent extraction, separation and recovery of dysprosium (Dy) and neodymium (Nd) from aqueous solutions: waste recycling strategies for permanent magnet processing. Hydrometallurgy 165:27–43. https://doi.org/10.1016/j.hydromet.2016.01.028

Yoshizuka K, Nishihama S, Sato H (2010) Analytical survey of arsenic in geothermal waters from sites in Kyushu, Japan, and a method for removing arsenic using magnetite. Environ Geochem Health 32(4):297–302. https://doi.org/10.1007/s10653-010-9300-3

Yuksekdag A, Kose-Mutlu B, Siddiqui AF, Wiesner MR, Koyuncu I (2022) A holistic approach for the recovery of rare earth elements and scandium from secondary sources under a circular economy framework—a review. Chemosphere 293:133620. https://doi.org/10.1016/J.CHEMOSPHERE.2022.133620

Yurtaeva AS, Sorokina TP, Plekhova KS, Potapenko OV, Gulyaeva TI, Talsi VP, Doronin VP (2021) Effect of modification conditions on the physicochemical characteristics of Y zeolite as a component of a petrochemical cracking catalyst. Pet Chem 61(3):325–331. https://doi.org/10.1134/S0965544121030038

Zaimes GG, Hubler BJ, Wang S, Khanna V (2014) Environmental life cycle perspective on rare earth oxide production. ACS Sustain Chem Eng 3(2):237–244

Zapp P, Marx J, Schreiber A, Friedrich B, Voßenkaul D (2018) Comparison of dysprosium production from diferent resources by life cycle assessment. Resour Conserv Recycl 130:248–259. https://doi.org/10.1016/j.resconrec.2017.12.006

Zapp P, Schreiber A, Marx J, Kuckshinrichs W (2022) Environmental impacts of rare earth production. In: MRS bulletin, vol 47. Springer, pp 267–275. https://doi.org/10.1557/s43577-022-00286-6

Zhang L, Wang J, Feng Y (2018) Life cycle assessment of opencast coal mine production: a case study in Yimin mining area in China. Environ Sci Pollut Res 25(9):8475–8486. https://doi.org/10.1007/s11356-017-1169-6

CHAPTER II

Life cycle assessment of Nd-Fe-B rare earth magnet production

ABSTRACT

Rare earth elements (REE) are strategic for Brazilian industry, particularly in renewable energy, electronics, and electric mobility. Growing demand drives the need for a sustainable and efficient supply, considering their environmental and economic impacts. These materials are widely used in the production of neodymium-iron-boron (Nd-Fe-B) permanent magnets, whose production chain has significant environmental impacts, from mining to final manufacturing. This study assesses the life cycle (LCA) of Nd-Fe-B magnets in the Brazilian context, following ISO 14040 and ISO 14044 guidelines. The modeling was conducted using Sankey software, and environmental impacts were quantified in SimaPro 9.1, incorporating data from the EcoInvent database and literature sources to ensure a robust methodological approach aligned with international best practices. The results indicate that mining has a high environmental impact, especially compared to secondary sources such as recycling. The exploitation of lower-grade deposits increases energy and water consumption, highlighting the need for more efficient technologies. The roasting stage stands out due to high energy consumption and emissions of particulate matter and greenhouse gases. In oxide production, leaching and pre-separation are the most critical stages, with intensive use of chemical reagents like hydrochloric acid, contributing to marine eutrophication and ionizing radiation. In magnet manufacturing, machining is the most impactful stage, significantly contributing to global warming, ozone layer depletion, and high water consumption. Given these impacts, the study reinforces the need for mitigation measures, including environmental regulations for REE mining, incentives for the circular economy, and the adoption of emerging technologies, such as more efficient hydrometallurgical processes and advanced magnet recycling techniques. Additionally, using renewable energy sources can significantly reduce the carbon footprint of these materials, promoting more sustainable resource consumption.

Keywords: Sustainability. Environmental impact. Rare earth elements. Mining. SimaPro.

Manuscript elaborated and formatted according to the guidelines of scientific publication, submitted to the journal *Environmental Chemical Engineering*. Available at: < www.sciencedirect.com/journal/journal-of-environmental-chemical-engineering>

1 INTRODUCTION

Rare earth elements (REE) are mainly composed of lanthanides and have similar physical and chemical properties, which make them essential for various technological and industrial applications. These elements play a key role in the transition to clean energy and are widely used in the manufacture of wind turbines, solar panels and electric vehicle engines [1-4]. REE are classified into two categories: light rare earths (cerium, lanthanum, praseodymium, neodymium, promethium, europium, gadolinium and samarium) and heavy rare earths (dysprosium, yttrium, terbium, holmium, erbium, thulium, ytterbium and lutetium) [5].

The growing demand for REE is directly related to its use in advanced technology products, mainly in the production of neodymium-iron-boron (Nd-Fe-B) permanent magnets [6,7]. These magnets are significantly stronger than traditional magnets, making it possible to reduce the size of devices without compromising performance. Currently, the demand for Nd-Fe-B represents around 20% of the total REE consumed globally [8]. However, worldwide dependence on these elements is a critical factor, since the European Union classifies them as strategic raw materials due to their high economic importance and the risk of supply [9,10]. Although global production of REE is concentrated in China, the lack of production capacity in other countries results in a strong dependence on imports, limiting the progress of various renewable energy technologies [7]. In view of this restriction, it is essential to explore new sources of REE and develop innovative methods for its extraction from unconventional materials [11].

The global dependence on China for the supply of REE represents a strategic and economic challenge for several countries, especially those seeking to expand their clean technology industries. Despite holding less than 40% of global reserves, China meets more than 60% of international demand for these elements, consolidating its dominance in the production chain [12].

The growing scarcity of rare earths on the international market has encouraged countries such as Uganda, Australia, Brazil and Chile to intensify their prospecting and exploration activities for these ores, also driving scientific and technological advances aimed at making more efficient use of these resources [13].

In addition, diversification of the supply chain is essential to reduce dependence on China, either by exploring new deposits or by developing recycling technologies.

The growth of the global rare earths market, driven by the energy transition and digital transformation, reinforces the need for more responsible and sustainable mining practices, with the implementation of technologies that increase process efficiency and minimize environmental impacts [14].

The production chain for rare earth magnets (REM) involves multiple stages, from ore extraction to final manufacture, and is characterized by significant environmental impacts. Although REE are available in greater quantities than other industrial metals, their uneven geological distribution and low concentration in economically viable deposits make their utilization an environmental and technological challenge [11]. Furthermore, the increase in demand for Nd and dysprosium (Dy), which are essential for the production of Nd-Fe-B permanent magnets, reinforces the need for sustainable strategies for their extraction and reuse [15,16]. It is estimated that by 2050 the demand for these elements will increase by 9 to 35 times in relation to the volumes currently extracted, making it essential to adopt a circular economy model to ensure the sustainability of the supply of these strategic elements for the energy transition [17-19].

REE extraction presents considerable environmental and social challenges. Conventional mining techniques, such as open-pit and underground mining, demand large amounts of energy, water and chemicals, contributing to soil degradation, water pollution and significant atmospheric emissions [20-22]. The environmental impacts associated with mining include climate change, eutrophication of water bodies, freshwater ecotoxicity, depletion of fossil resources, ionizing radiation, soil acidification, formation of photochemical oxidants, ozone layer degradation, human toxicity and terrestrial ecotoxicity [23,24]. During the ore processing, extraction and separation phase, radionuclides such as uranium and thorium are released, increasing the environmental risk and the challenges of waste management [21,22,25;26].

Mining and refining operations require high energy consumption and generate greenhouse gas (GHG) emissions [27-29]. In some operations, the uranium and thorium present in these tailings can be used as by-products for nuclear power generation, reducing the need for primary mining of these elements and contributing to a low-carbon energy model [30-32].

Given this scenario, life cycle assessment (LCA) has emerged as an essential tool for quantifying the environmental impacts of ETRs and proposing mitigation strategies. Standardized by ISO 14040 and ISO 14044, LCA allows the identification of the main critical points in the production cycle, from the extraction of raw materials to final disposal, providing subsidies for the adoption of more sustainable practices [33,34]. The recycling of rare earth permanent magnets has been considered a viable alternative for minimizing environmental impacts and reducing dependence on primary extraction [35]. In addition, the circular economy has gained prominence as a production model that seeks to reduce material waste and encourage the reuse and recycling of these elements [19].

The LCA of rare earth mining indicates that energy consumption varies between 0.2 and 1 GJ/t of rare earth oxides (REO), while water use can reach between 0.3 and 1.8 ML/t REO [36]. In addition, the environmental impact in terms of GHG emissions is significant, with the process resulting in 1.4 kg CO_2-eq/kg REO produced. The main source of emissions is the use of hydrochloric acid, responsible for around 38% of total emissions, followed by steam consumption (32%) and electricity (12%). Studies indicate that 51% of GHG are due to the use of energy in various forms, such as diesel, steam, fuel oil and electricity. These figures demonstrate the need to reduce dependence on high-emitting inputs in order to make r eproduction more sustainable [36].

The use of alternative techniques, such as in situ leaching, has been studied as an option for reducing environmental damage [21,22,37-39]. Studies indicate that environmental impacts vary according to the reagent used, with ammonium sulphate being one of the main contributors to the impacts of the process. Although in situ leaching has less influence on acidification, it contributes significantly to eutrophication. However, this technique, applied to the extraction of clays rich in heavy rare earth elements (HREE), reduces environmental impacts and accounts for approximately 35% of the production of these elements in China [39].

Converting the extracted ore into REO involves physical and chemical processes with a high environmental impact. Minerals such as bastnasite, monazite and xenotime are the main sources of these oxides, and their processing includes stages of milling, physical beneficiation, chemical separation and hydrometallurgy [36,38,40,41]. The hydrometallurgy part of oxides requires large volumes of strong acids, resulting in potentially toxic liquid and solid waste [40,38]. Depending on the method used, the environmental impacts vary considerably. The production of REO from bastnasite/monazite represents around 35% of the total environmental impacts of the production chain, while extraction based on ion adsorption clays can reach up to 55% of these impacts [42].

Studies indicate that the production of one ton of REO can result in the emission of 60,000 m³ of exhaust gases, which is nothing more than the burning of fuel, as well as 200 m³ of acidic wastewater and 1.4 tons of radioactive waste [43]. Among the most significant environmental impacts associated with the production of REE is the global warming potential (GWP). The GWP of neodymium (Nd) and dysprosium (Dy) is significantly high, reaching values of 17.6 and 59.6 kg CO_2-eq/kg, respectively, compared to just 1.5 kg CO_2-eq/kg for iron [44].

Nd-Fe-B magnets are essential for various technologies, made up of approximately 29-32% Nd, 1-2% B and 64-68.5% Fe, standing out for their superior magnetic properties and high efficiency in applications such as electric motors and wind turbines [45]. However, their production involves significant environmental challenges, since the extraction and magnetization stages consume large amounts of energy and result in the emission of atmospheric pollutants [46-48]. The durability of magnets varies depending on the application, and can be as little as 2 to 3 years in consumer electronics, while in wind turbines it can reach 20 to 30 years [49-51].

As demand grows, the generation of waste in the production and disposal of magnets has become a critical problem. During manufacture, around 20-30% of the metal alloy is converted into scrap, which reinforces the need for effective recycling processes [52,53]. Despite this, global recovery rates for rare earths from end-of-life products are less than 1% [35,51]. The development of new recycling processes is key to minimizing environmental impacts and reducing dependence on primary mining [54,55].

The production chain for rare earth magnets (REM) presents significant environmental challenges, from mining to final manufacture. The high demand for Nd and Dy drives the need for a sustainable production model that minimizes environmental impacts and guarantees the supply of these essential elements for the global energy transition. LCA is an essential tool for identifying and mitigating impacts throughout the life cycle of REE, providing support for the implementation of more sustainable strategies, such as recycling and the adoption of the circular economy.

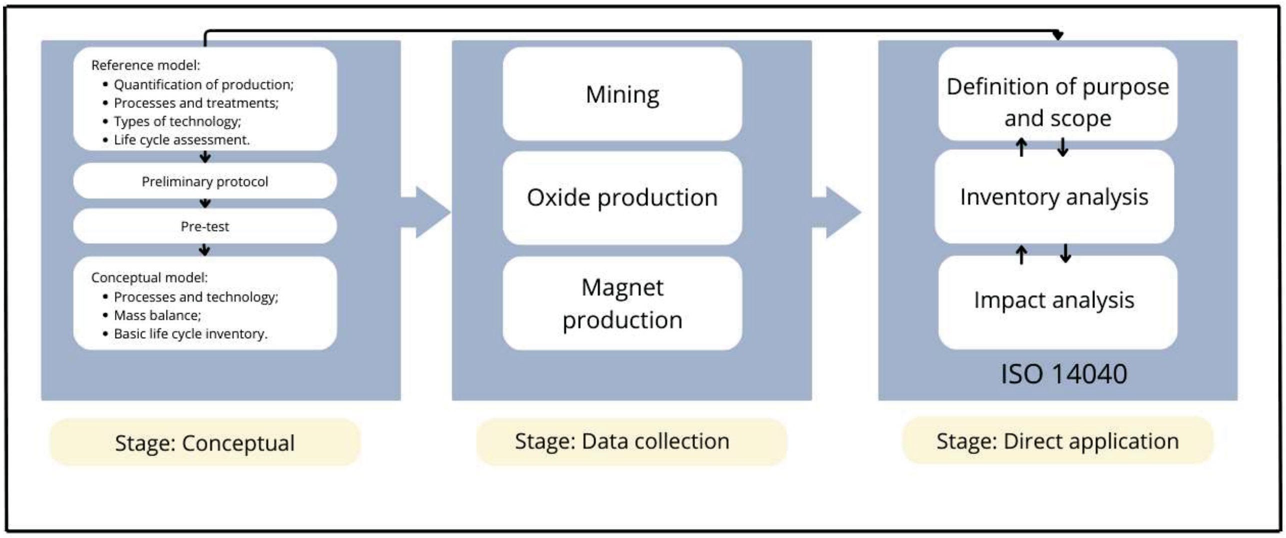
The aim of this study is to evaluate the life cycle of Nd-Fe-B magnet production in Brazil, taking into account the specificities of the country's energy and transportation sectors. Based on this analysis, mitigating measures will be proposed to reduce the environmental impacts associated with its production, contributing to a more sustainable development model in the rare earths sector.

2 METHODOLOGY

The methodology of this research is structured in three stages, as illustrated in Figure 1. The first stage, of a conceptual nature, involves a bibliographical survey, drawing up the research protocol (form) and pre-testing it, resulting in the definition of the research model. The second stage, of practical application, involves technical visits and data collection at different stages of the production process. Finally, the third stage, of direct application, involves modeling the system and carrying out the LCA stages [33,34].

Among the methodologies used, LCA stands out for its systemic and comprehensive approach. It is a methodology that is widely used to assess the environmental performance of systems, processes or products, considering all the stages of the life cycle and the respective consumption of resources and associated emissions [56]. Its systemic approach makes it possible to avoid transferring impacts between different life cycle stages, geographical regions or environmental impact categories, providing a more comprehensive and accurate analysis of environmental effects [57].

FIGURE 1- STRUCTURE OF THE STUDY METHODOLOGY



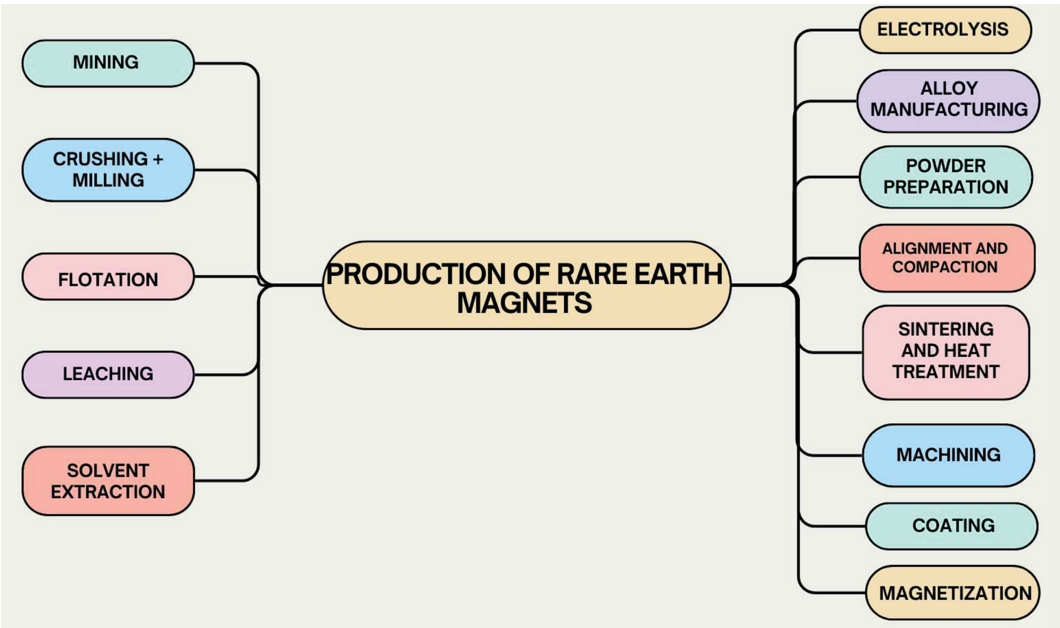
SOURCE: [14].

The third stage of this research will be structured on the basis of [58] and the ISO 14040 and ISO 14044 guidelines [33,34]. To carry out the LCA, four sub-steps will be considered: defining the objective and scope, analyzing the inventory, assessing the impacts and interpreting the results. The first sub-stage will establish the purpose of the study and the delimitation of the production chain, defining the limits of the system and its application in the context analyzed. Next, the life cycle inventory (LCI) analysis will quantify the inputs and outputs of materials and energy throughout the different phases of the production process, from mining to REM production. This modeling will be carried out with SimaPro software, using data from the literature and the EcoInvent database, adapted to the Brazilian reality. The structure of the material flows will be represented graphically in the E! Sankey software.

2.1 DEFINING THE SCOPE AND OBJECTIVE

The aim of this study is to evaluate the life cycle of REM production, composed of Nd, Fe and B, considering the Brazilian reality. The main focus is on analyzing the LCI, quantifying the environmental impacts at each stage of the production process. To this end, a production system flow was structured, highlighting the identification of resource inputs and outputs, as well as the associated environmental impacts, from mining to the manufacture of rare earth magnets, as illustrated in Figure 2.

FIGURE 2- SYSTEM FLOW



SOURCE: [59].

The analysis considers aspects such as climate change, toxicity and energy consumption to assess the environmental impacts of magnet manufacturing in Brazil. Defining system boundaries is essential in LCA, as it determines the processes and flows of materials and energy that will be included in the analysis. In the Brazilian context, these boundaries cover everything from the extraction of raw materials to the manufacture of magnets, including the mining phase, the oxide production phase and the magnet production phase and, optionally, the distribution or disposal of final products. The inventories that precede them were adjusted to reflect the national reality, taking into account energy sources and fuels. This delimitation made it possible to quantify the flows at each stage, enabling a detailed assessment of environmental impacts and opportunities for improvement throughout the life cycle.

2.1.1 Functional unit

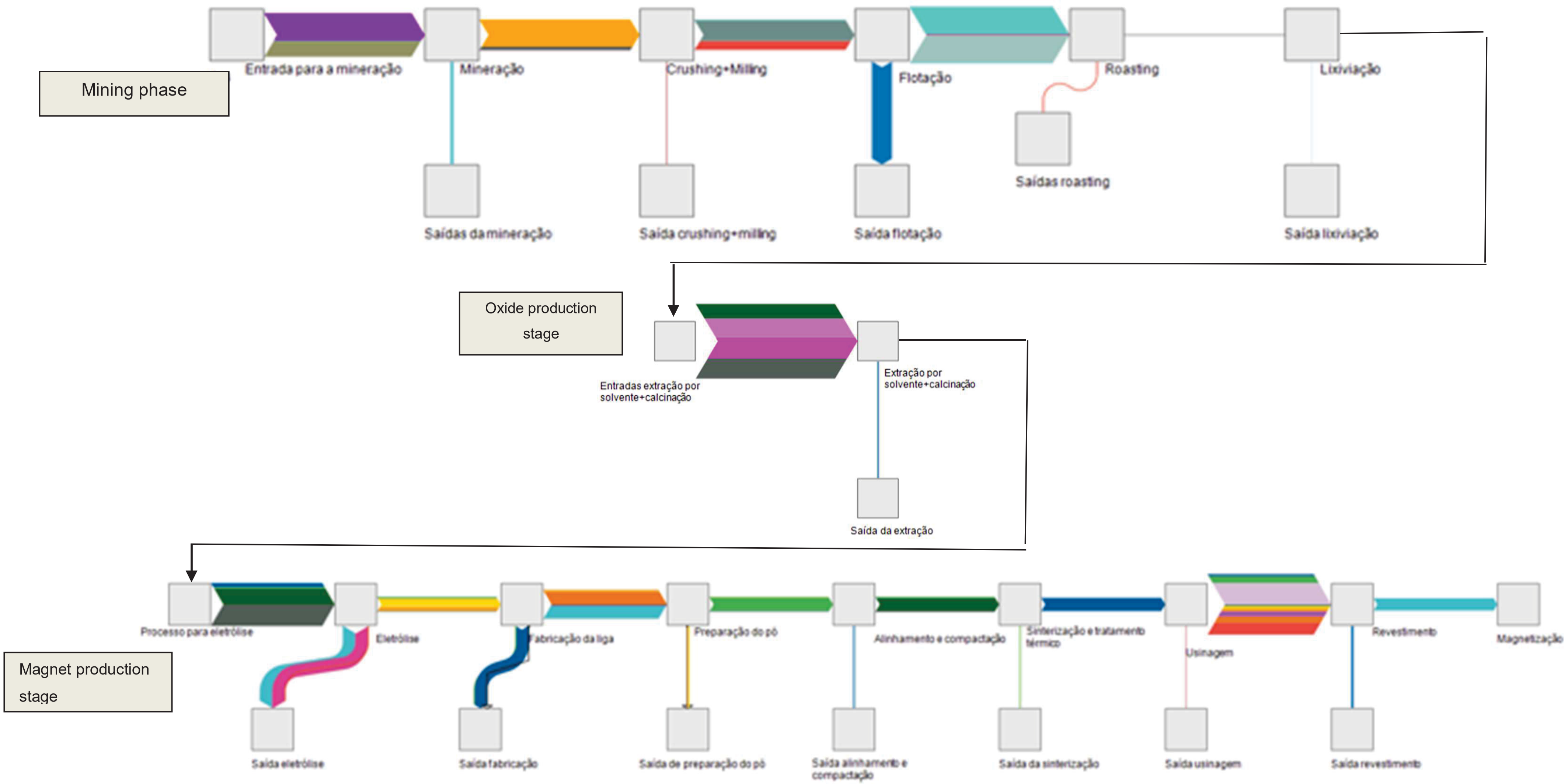
The functional unit adopted for the evaluation corresponds to the production of 1 kg of rare earth magnets. In order to better represent the Brazilian reality, the analysis was adjusted based on a production plant design of 100 tons, considering the inputs and outputs of the system in a laboratory-factory located in the Southeast region of Brazil.

2.1.2 System modeling

The system was modeled on the basis of a blueprint, allowing data to be entered into the E! Sankey software. This process made it possible to build process flow diagrams that represent all the production stages, from mining to magnet production, reflecting the particularities of national production. Based on this, the modeling uses arrows with dimensions proportional to the amount of flow, making it easier to see the transfer of materials, energy consumption and costs between processes.

Figure 3 represents the modeling of the system covering all the phases of the production process, including mining and each stage within this phase, followed by the production of rare earth oxides and their stage and, consequently, the production of rare earth magnets and all their comprehensive stages. The modeling of the mining system presents a detailed flow of the main stages of the process, from the input of inputs, such as energy, explosive materials and transport, to the final leaching. The resources used include water, electricity, chemicals and metals, while the outputs reflect the generation of solid waste, dust, gases and tailings. The connections between the stages - mining, crushing and milling, flotation, roasting and leaching - show the continuous flow of material, in which each stage receives inputs and generates by-products that can be reused or discarded. In addition, the modeling highlights significant environmental concerns, such as emissions of radioactive dust, sulfur dioxide and carbon dioxide, reinforcing the need for mitigation strategies. In the mining process, land use represented in purple has a significant impact, followed by water consumption in orange. In addition, the high demand for primary energy in gray and transportation in blue highlight the intensity of energy consumption in this phase.

FIGURA 3- MODELAGEM DO SISTEMA PRODUÇÃO DOS ÍMÃS DE TERRAS RARAS



The extraction and calcination of REO involves various inputs, such as electricity, hydrochloric acid (HCl), ammonium hydroxide and rare earth fractions classified as medium, heavy, lanthanum and cerium. The separation of these elements occurs through chemical and physical characteristics, allowing important products to be obtained for use in green technologies. The modeling of the system highlights the importance of energy and chemical reagents as essential inputs in this process. The environmental impact is mainly influenced by the use of HCl in pink, followed by ammonium hydroxide in light purple and electricity in gray, which are critical inputs for the production of rare earth oxides.

In the modeling of the REM (rare earth magnets) production system, the phases from material preparation to final magnetization are detailed. The process begins with electrolysis, where oxides of didymium, fluorides and lime are used to produce Nd-Pr-Fe-B alloys, generating outputs such as gases and liquid waste. Next, the manufacture of the alloy involves melting and mixing the metallic materials, followed by the preparation of the powder by grinding and refining, ensuring the proper distribution of the particles. The powder is compacted and aligned to ensure that the particles are oriented correctly, optimizing the magnetic properties of the final magnet. This is followed by sintering and heat treatment, consolidating the powder into a solid block, which is then shaped in the machining stage. The magnet is coated with nickel and copper to protect against corrosion before undergoing the final magnetization process, activating its magnetic properties.

2.2 LIFE CYCLE INVENTORY ANALYSIS

The LCI consists of identifying and quantifying the resources used in the production of a product, including energy, water, raw materials and processed materials, as well as the emissions and waste released into the environment, including atmospheric pollutants, discharges into soil and water, and the losses incurred during the production process [60]. Data for this study was collected from primary and secondary sources. The primary sources included direct measurements and information obtained from the stakeholders of the system analyzed, while the secondary sources consisted of existing databases and scientific literature.

After validation, the data was entered into the SimaPro 9.1 software, where mass and energy balancing was carried out. Inventory modeling enabled the integration of input and output flows for each unit process, providing a detailed view of the system's environmental profile. In addition, a critical analysis of the LCI was conducted to identify possible sources of uncertainty and data limitations.

In the context of this research, the LCI for Nd-Fe-B magnets took into account factors such as the energy matrix and transportation logistics. This approach will make it possible to propose strategies to mitigate environmental impacts throughout the production chain. In order to validate the system's data, meetings and technical visits were made to the factory laboratory, allowing for a detailed description of the processes and verification of the mass balances. The modeling of the system was improved based on the inventory data, using the EcoInvent database and complementing the information with references from the literature, ensuring an inventory in line with the Brazilian reality.

The research is part of the project “Sustainability in the production chain and technologies for manufacturing magnets based on rare earth elements”, managed by Regina I (Rare Earth Global Industry and New Applications) and the Laboratory for Waste Management and Sustainable Technologies - LabGerts at UFPR - Jandaia do Sul Advanced Campus, and some of the information in the Life Cycle Inventory - LCI is confidential.

2.3 LIFE CYCLE IMPACT ASSESSMENT

To assess environmental impacts, the SimaPro software was used in conjunction with the Ecoinvent data library and the ReCiPe method, developed by RIVM, Radboud University, CML and Pré Consultants [61].

The methodology adopted sought to harmonize the environmental impacts in the models, considering both the midpoint categories, which analyse factors such as global warming, acidification and eutrophication, and the endpoint categories, which assess the final impacts on human health, ecosystems and natural resources. The ReCiPe method quantifies environmental impacts throughout the life cycle of a product or process, covering 17 categories, including global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, form of particulate matter, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic, human non-carcinogenic, land use, scarcity of mineral resources, scarcity of fossil resources, water consumption, allowing a comprehensive assessment of environmental effects, human health and resource consumption.

In addition to ReCiPe, a second impact assessment was carried out using the method of the Intergovernmental Panel on Climate Change (IPCC), which complements the analysis by considering specific indicators, such as the GWP for a 100-year horizon, the consumption of non-renewable fossil energy and the full set of ReCiPe endpoint indicators (Hierarchist). This approach provides a more detailed view of climate change, identifying its causes, effects and risks for humanity and the environment, contributing to a broader understanding of the environmental impacts of the system assessed.

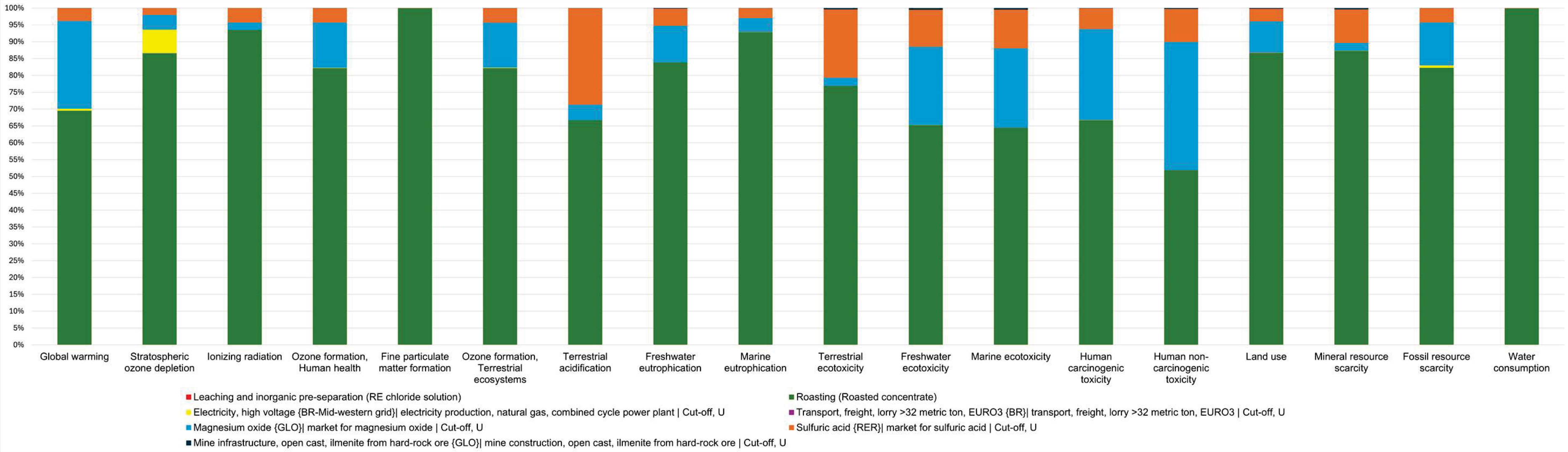
3 PRESENTATION OF RESULTS AND DISCUSSION

This study addresses the characterization and normalization of environmental impacts using the ReCiPe and IPCC methods, highlighting the main environmental indicators identified in the results.

3.1 CHARACTERIZATION IN THE MINING PHASE

The LCA provides a detailed understanding of the environmental impacts associated with mining up to the production of rare earth magnets, identifying the most critical stages of the production system. As shown in Figure 4 for the characterization part of the mining of 1 kg of Nd-Fe-B magnets using the ReCiPe methodology.

FIGURE 4- CHARACTERIZATION OF THE MINING PHASE FOR THE PRODUCTION OF 1 KG OF ND-FE-B MAGNETS - RECIPE METHOD



As illustrated in the figure, the roasting stage, represented by the green color, stood out as the most impactful in several environmental categories, contributing 99.94% of the impact in the fine particulate matter category and 99.86% in water consumption. In addition, magnesium oxide, represented by the color navy blue, had significant impacts on human toxicity, accounting for 37.99% of non-carcinogenic toxicity and 26.95% of carcinogenic toxicity, showing environmental and health risks associated with this compound.

In the particulate matter category, the mining phase exhibited an emission equivalent to 0.368 kg PM 2.5 eq., indicating a significant potential for fine particle emissions into the atmosphere. These emissions can directly impact air quality and pose health risks, particularly in regions near extraction sites. Water consumption was quantified at 1.53 m^3, highlighting the mining process's dependence on water resources. The high demand for water can lead to reduced availability for other uses and contribute to alterations in the local aquatic ecosystem. Regarding global warming potential, the mining phase contributed 0.172 kg CO_2 eq., reflecting greenhouse gas emissions associated with extraction activities and energy consumption. Although relatively low compared to other life cycle stages, this impact underscores the need to assess alternatives for reducing carbon emissions in the mining sector.

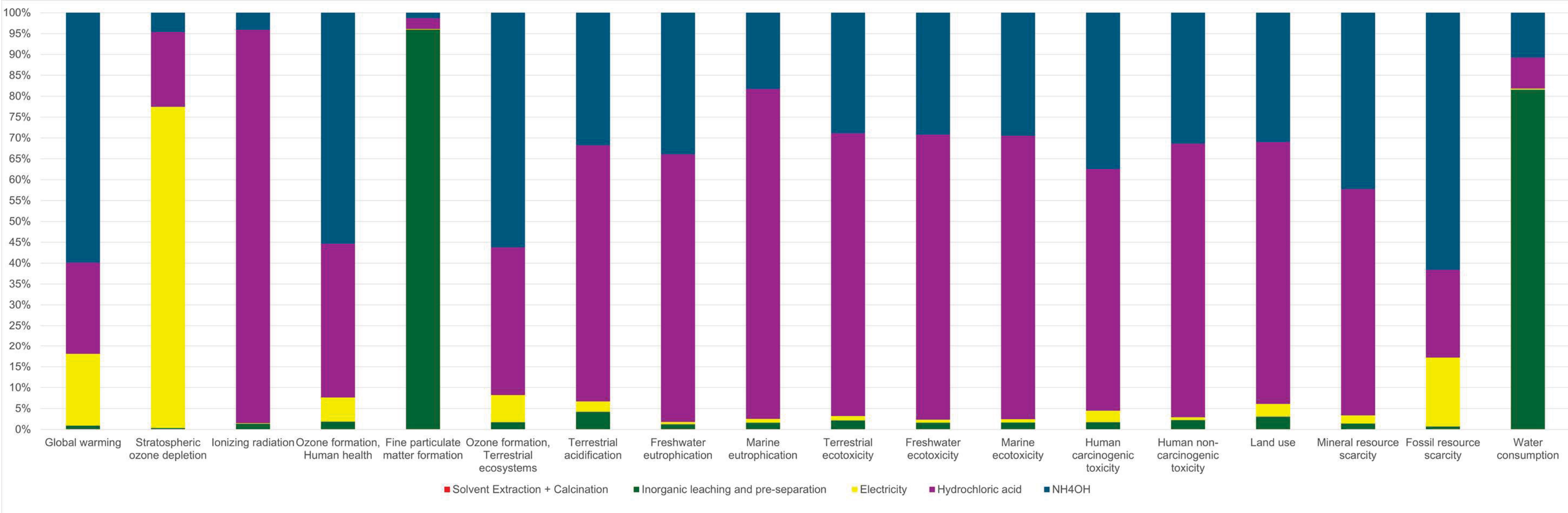
The results obtained in this study align with the findings of [62], which indicate that rare earth mining can generate significant environmental impacts due to high energy consumption, particulate matter emissions, and the need for large volumes of chemical reagents. According to the authors, rare earth extraction primarily occurs in carbonatite deposits, ion-adsorption clays, and alkaline rocks, involving energy-intensive processes and generating radioactive waste. In Brazil, REE mining predominantly takes place through open-pit operations, which, while reducing operational costs compared to underground mining, present environmental challenges related to deforestation and intensive water and electricity consumption. Furthermore, the literature highlights that the carbon footprint of rare earth mining can vary significantly, with projects in shale deposit formations reaching a GWP of up to 229 t CO_2eq/t-TREO.

Another relevant aspect of the analysis is the comparison with the studies by [64], which evaluated the extraction of REO from ion-adsorption clays. The authors highlight that the production of 1 kg of HREOs can result in emissions ranging from 258 to 408 kg CO_2-eq., in addition to requiring between 270 and 443 MJ of primary energy. The mining and extraction phase is the primary contributor to environmental impacts due to the intensive use of ammonium sulfate for leaching and the high electricity demand. Ammonium sulfate stands out as one of the major contributors to impact categories such as terrestrial acidification and eutrophication, reinforcing the need for strategies to minimize its use in the process. Furthermore, the reliance on China's coal-based energy matrix increases emissions associated with electricity consumption, highlighting the importance of developing more efficient and sustainable methods for rare earth mining.

3.2 CHARACTERIZATION OF THE RARE EARTH OXIDE PRODUCTION PHASE

For the characterization of the oxide production phase, Figure 5 was developed to illustrate the impact categories and identify the stages that contribute the most to environmental impacts.

FIGURE 5- CHARACTERIZATION OF THE RARE EARTH OXIDE PRODUCTION PHASE FOR THE PRODUCTION OF 1 KG OF ND-FE-B MAGNETS – RECIPE METHOD



The production of REO involves energy- and chemical-intensive processes, resulting in significant environmental impacts. The leaching and pre-separation stage, highlighted in the analysis with light green, showed the highest impacts in the fine particulate matter formation category (95.96%) and water consumption (81.57%), represented by dark blue, indicating a high demand for water resources. Additionally, the chemical compound hydrochloric acid exhibited a substantial influence across various environmental categories, represented in yellow, contributing 94.39% to the ionizing radiation category and 79.21% to marine eutrophication.

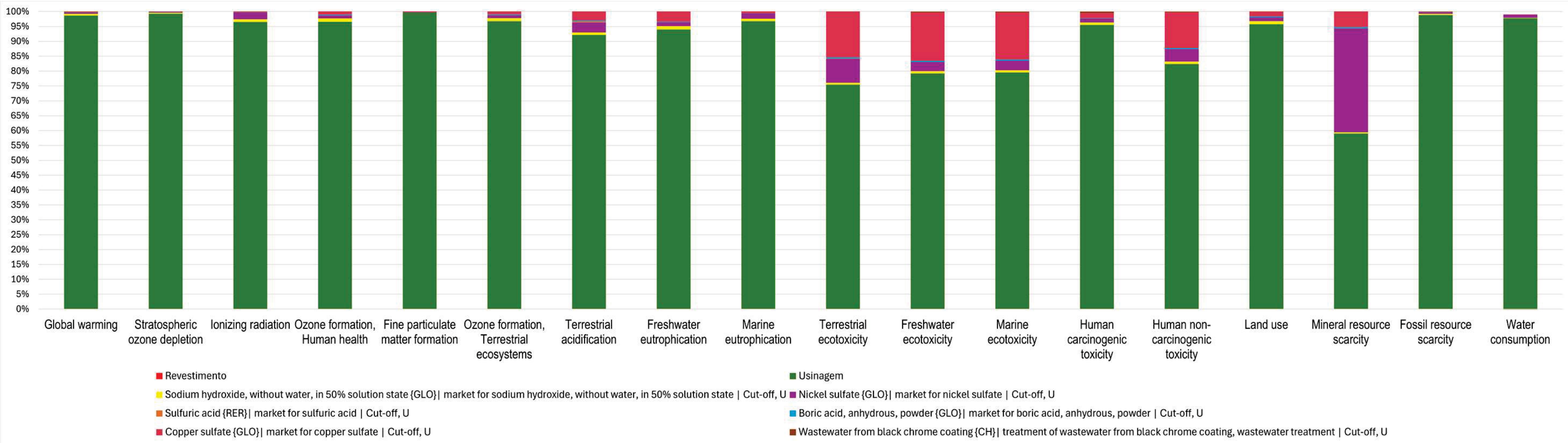
These results align with the findings of [62], which emphasize that oxide refining is the most impactful phase of the production chain, primarily due to the intensive use of electricity and chemical reagents.

Similarly, [64] analyzed CO_2-eq emissions throughout the REE production chain, from mining to electrolytic refining. The study revealed that, in the solvent extraction and electrolytic refining stages, chemical reagents such as neodymium fluoride, lithium fluoride, and electricity become the main contributors to environmental impact. These observations highlight the need to optimize input usage and adopt lower-impact technologies in REO production. The solvent extraction method, widely used for rare earth element separation, presents challenges due to its high demand for solvents and strong acids, which can contaminate water resources and generate large volumes of chemical waste.

3.3 CHARACTERIZATION OF THE RARE EARTH MAGNET PRODUCTION PHASE

For the Nd-Fe-B magnet manufacturing phase, graphical representations were created to show the categories and environmental impacts associated with the process. Figure 6 illustrates the characterization of environmental impacts throughout the different production phases, from the mining of rare earth magnets to the magnet production stage.

FIGURE 6- CHARACTERIZATION OF THE ND-Fe-B MAGNET PRODUCTION PHASE FOR 1 KG - RECIPE METHOD



As observed, machining, highlighted in green, had a significant influence on all the categories analyzed, accounting for 98.68% of the emissions associated with global warming, 99.32% of the stratospheric ozone depletion, and 98.69% of water consumption. Additionally, nickel sulfate, represented in yellow, had a significant impact on the mineral resource scarcity category, contributing 34.92%.

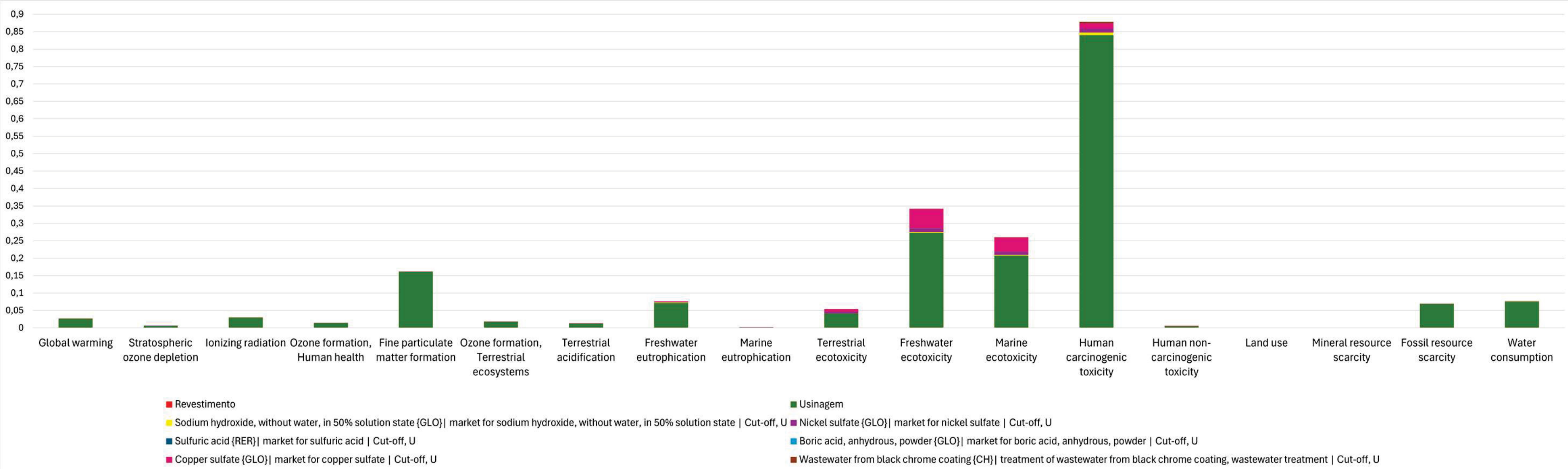
The results of this research are in line with the findings of [64], who analyzed the CO_2-eq emission network throughout the manufacturing and recycling of Nd-Fe-B permanent magnets. The study identified that Nd-Fe-B magnets, steel, and ferroboron showed the highest dependence on CO_2-eq emission flows, while recycled REE and glucose had less influence on the propagation of these emissions. Additionally, the Nd-Pr alloy, electricity, and steel were identified as critical in magnet manufacturing, while glucose, diesel, and electricity were more central in the recycling of these materials.

Regarding the global warming potential, magnet manufacturing resulted in 212 kg CO_2 eq. This result highlights the significance of greenhouse gas emissions associated with rare earth processing, reinforcing the need to evaluate alternatives for carbon emission reduction in the sector. In the aquatic ecotoxicity category, copper sulfate contributed 16.3% to freshwater ecotoxicity and 15.8% to marine ecotoxicity. Nickel sulfate, in turn, contributed 34.9% to the mineral resource scarcity category, highlighting its influence on the availability of essential metals. Furthermore, rare earth magnet manufacturing resulted in an emission of 11.3 kg 1,4-DCB (Brazilian common name) in the marine ecotoxicity category, illustrating the environmental impact associated with the release of toxic substances during the industrial process.

The literature emphasizes that Nd-Fe-B magnet production is a process highly intensive in energy and chemical inputs. According to [62], the energy consumption in REE metallurgy surpasses that of conventional metals such as copper and aluminum due to the complexity of the purification processes. In addition to atmospheric emissions associated with fossil fuel combustion, there are additional environmental risks related to chemical contamination from solvents used in metal separation.

3.4 NORMALIZATION OF THE PRODUCTION OF 1 KG OF ND-FE-B MAGNETS

FIGURE 7- NORMALIZATION OF RARE EARTH MAGNET PRODUCTION - RECIPE METHOD



The normalization of the results showed that the machining stage contributed to the human toxicity category, to the freshwater ecotoxicity category, and to the marine ecotoxicity category. Copper sulfate was identified as one of the main contributors in these categories, being the second most relevant element in terms of environmental impact.

These data highlight the need for control and optimization measures in machining to minimize its influence on the life cycle of REM. The results indicate the significance of the mining, oxide production, and rare earth magnet manufacturing stages in generating environmental impacts and emphasize the importance of mitigation strategies, such as the adoption of cleaner technologies, water reuse, and process optimization. Future studies could explore measures to reduce the environmental footprint through alternative sustainable production scenarios.

3.5 ND-FE-B MAGNET PRODUCTION USING THE IPCC METHOD

	Fossil	Biogenic	Land transformation
GWP	207 kg CO_2 eq.	0,211 kg CO_2 eq.	0,134 kg CO_2 eq.

Regarding the results considering the IPCC, rare earth magnet production showed an impact of 207 kg CO_2 eq. in the fossil GWP category, 0.211 kg CO_2 eq. in the biogenic GWP category, and 0.133 kg CO_2 eq. in the land transformation category. These data reinforce the need for strategies to mitigate the environmental impact in magnet manufacturing, aiming to reduce carbon emissions and minimize land occupation impact.

3.6 TOXICITY OF ELEMENTS IN RARE EARTH MAGNET PRODUCTION AND THEIR IMPACTS ON HUMAN HEALTH

Rare earth magnet production involves several stages, from mining to final manufacturing, requiring the extraction and processing of a wide range of minerals and heavy metals. Many of these elements have adverse effects on human health, depending on the form of exposure, concentration, and duration of contact. Workers involved in this production cycle are particularly susceptible to occupational hazards, while the release of these metals into the environment can pose a long-term public health problem.

This section will present a table outlining the presence of inputs throughout the rare earth magnet production cycle, from ore extraction to final manufacturing. Additionally, inventory data will be compared with three recent studies analyzing the toxicity of these elements and their impacts on the human body. This approach will allow a detailed assessment of the risks associated with each stage of the production process, reinforcing the need for environmental and occupational mitigation strategies.

TABLE 2- CHEMICAL ELEMENTS

Minerals	Air emissions	Water emissions	Soil emissions	Raw materials
Arsenic	96,4 mg	439 mg	787µg	
Tin	81 µg	1,56 mg	4,38 µg	354 mg
Scandium	916 µg	630 µg	135 µg	263 µg
Lanthanium-140	464 µBq	17,3 mBq		592 g
Cerium-141		6,44 mBq	1,32 mBq	
Copper				220g
Nickel				99,8 g
Dysprosium				25,7 g
Neodymium				437 g
Praseodymium				116 g
Samarium				77,2 g

Recent studies highlight the relevance of metal and REE toxicity to human health. The study [65] investigated the presence of metals and REE in healthy and tumor tissues from the mammary glands of dogs, used as a model for human impacts. The results indicated that metals such as copper (Cu) and molybdenum (Mo) showed high concentrations in tumor tissues, being associated with oxidative stress and inflammatory processes related to cancer development. Furthermore, lead (Pb), thallium (Tl), arsenic (As), and mercury (Hg) were identified as neurotoxic and carcinogenic, in addition to being linked to kidney and cardiovascular diseases. REE, on the other hand, were found more frequently in healthy tissues than in tumor tissues, suggesting a possible protective relationship or influence on tumor progression.

In the study [66], the environmental and human health impacts of mining and processing critical minerals in Indonesia were analyzed, including nickel (Ni), gold (Au), copper (Cu), tin (Sn), and bauxite (Al_2O_3). Ni was associated with respiratory diseases such as asthma and bronchitis, as well as potential carcinogenic effects. Au, Sn, and Cu were identified as metals with hepatic and neurological toxicity, while aluminum (Al) was linked to respiratory and neurological diseases. Furthermore, elements such as Pb, Hg, As, and chromium (Cr) were associated with elevated risks of cancer, kidney damage, and neurotoxicity.

On the other hand, the study [67] reviewed toxicological studies on the impacts of rare earth elements on occupational health, covering workers exposed to mining, transportation, and manufacturing of materials containing these elements. The results indicate that scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), and Nd tend to cause pulmonary and hepatic toxicity. In contrast, praseodymium (Pr), samarium (Sm), europium (Eu), and gadolinium (Gd) may have toxic effects on the kidneys. Elements such as terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) show potential for metabolic and respiratory impacts, although they are still poorly studied.

The data analysis highlights the significant presence of heavy metals and rare earth elements in various industrial and environmental contexts, with adverse impacts on human health, including lung diseases, cancer, and neurological and kidney disorders. Occupational exposure to these elements requires stringent safety measures to reduce health risks for workers, while the release of these compounds into the environment remains a critical challenge for public health and environmental sustainability.

3.7 LIMITATIONS OF THE PRESENT STUDY

This study has some limitations inherent to the methodology used and the availability of data, which may influence the accuracy of the results. One of the main restrictions is related to the scarcity of detailed primary data on rare earth magnet production in Brazil. As a result, it was necessary to rely on secondary data sources and information from international studies, which may limit the representativeness of the environmental impacts specific to the national context.

Furthermore, the adaptation of LCA inventories to reflect the Brazilian reality required the use of estimates and approximations, particularly regarding energy consumption and chemical inputs. The lack of a robust national LCA database limits the accuracy of process modeling, as impact coefficients may not fully reflect local conditions.

Another limitation concerns the scope of the study, which considered stages from mining to magnet manufacturing but did not include aspects such as distribution, use, and final disposal. While the focus was on production, the life cycle analysis could be expanded to assess impacts over a broader horizon, considering the circular economy and the recycling potential of Nd-Fe-B magnets.

Finally, the uncertainties associated with environmental impact assessment methodologies should also be highlighted. The choice of the ReCiPe method and the EcoInvent database provides a detailed analysis but may not fully capture all regional variables and specific dynamics of the rare earth magnet production sector in Brazil. Therefore, future research could aim to enhance national databases, integrate new impact assessment methodologies, and include additional stages of the production chain for a more comprehensive view of the sustainability of these materials.

4 FINAL CONSIDERATIONS

This study analyzed the life cycle of Nd-Fe-B magnet production, covering the stages of mining, oxide production, and magnet manufacturing, with a focus on the Brazilian reality. The results obtained highlight that each phase of the production process generates significant environmental impacts, requiring mitigation measures to enable more sustainable production.

Mining proved to be a highly impactful stage, particularly due to the high consumption of energy and water, in addition to fine particulate emissions and toxic waste. The roasting process, essential for rare earth element extraction, contributed significantly to the global environmental impact, standing out in the categories of particulate emissions and water resource consumption.

In the oxide production stage, leaching and pre-separation were the most impactful phases, with high water consumption and intensive use of chemical reagents such as hydrochloric acid. This process resulted in significant contributions to marine eutrophication and ionizing radiation, emphasizing the need for strategies to reduce the use of aggressive chemicals and minimize the waste generated.

The magnet manufacturing phase presented considerable impacts, with machining standing out as a major contributor to global warming, ozone layer depletion, and high water consumption. Machining and coating applications also pointed to the need for more sustainable solutions, such as material reuse and the use of recycling technologies.

5 FUTURE PERSPECTIVES

Based on the findings, several recommendations are suggested for future research:

- Optimization of water and energy consumption: Develop more efficient techniques for the mining and refining of rare earth elements, minimizing the use of natural resources and reducing associated environmental impacts;
- Recycling and material reuse: Investigate innovative processes for recovering rare earths from industrial scrap and end-of-life products, promoting the circular economy;
- Environmental impact assessment of renewable energy use: Analyze the feasibility of using solar, wind, and other sustainable energy sources to reduce the carbon footprint of the Nd-Fe-B magnet production chain;
- Comparison between different LCA methodologies: Investigate the robustness of the results obtained through different approaches and databases, ensuring greater reliability in environmental analyses;
- Public policies for a sustainable rare earth sector: Evaluate the role of government incentives and environmental regulations in the transition to cleaner and more efficient production.

The production of REM is a strategic sector for energy transition and technological advancements, but it requires an increasing commitment to sustainability. The results of this study highlight the importance of proper environmental planning, promoting solutions that balance the demand for these essential materials with the minimization of environmental impacts associated with their production.

REFERENCES

[1] K. Binnemans, P.T. Jones, B. Blanpain, T. Van Gerven, Y. Yang, A. Walton, M. Buchert. Recycling of rare earths: a critical review. J. Clean. Prod. 51 (2013) 1-22. https://doi.org/10.1016/j.jclepro.2012.12.037

[2] V. Gonzalez, DAL. Vignati, C. Leyval, L. Giamberini, Environmental fate and ecotoxicity of lanthanides: Are they a uniform group beyond chemistry? Environ. Int. 71 (2014) 148–157.https://doi.org/10.1016/j.envint.2014.06.019

[3] Adamas Intelligence, Rare earth magnet market outlook for 2035. Advanced Propulsion Center, 2023. Automotive industry demand forecast for the fourth quarter of 2022.

[4] D. Gielen, M. Lyons, Critical Materials for the Energy Transition: Rare Earth Elements. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 2022.

[5] L. Depraiter, S. Goutte, The role and challenges of rare earths in the energy transition. Resources Policy 86 (2023). https://doi.org/10.1016/j.resourpol.2023.104137

[6] H. Jin, K. Geada, I. Sousa, H. Ghaderi, A. Bevan, M. Zakotnik, C Handwerker, Life Cycle Assessment of Emerging Technologies in the Recovery of Hard Disk Drive Value. Resource. Conserve. Recycle 157 (2020). https://doi.org/10.1016/j.resconrec.2020.104781

[7] R. Eggert, C. Wadia, C. Anderson, D. Bauer, F. Campos, L. Meinert, P. Taylor, Rare Earths: Market Disruption, Innovation and Global Supply Chains. Anu. Environ. Rev. Resource. 41 (2016) 199-222. https://doi.org/10.1146/annurev-environ-110615-085700

[8] K. Habib, P. Schibye, A. Vestb, V. Dall, H. Wenzel, Material Flow Analysis of NdFeB Magnets to Denmark: A Comprehensive Sampling and Waste Stream Analysis Approach. Environ. Sci. Technol. 48 (2014) 12229–12237 https://doi.org/10.1021/es501975y

[9] Study on critical raw materials for the EU; European Commission, 2023.

[10] R. Gauß, C. Burkhardt, F. Carencotte, M. Gasparón, O. Gutfleisch, I. Higgins, M. Karajic,´ A. Klossek, M. Makinen, B. Schäfer, R. Schindler, B. Veluri, Rare earth magnets and motors: A European Call for Action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, 2021.

[11] United States Geological Survey (USGS). Mineral Commodity Summaries, U.S Departtment of the Interior. U.S Geological Survey (2020), https://doi.org/10.3133/mcs2020

[12] M. Ezrati. How much control does China have over rare earth elements? https://www.forbes.com/sites/miltonezrati/2023/12/11/how-much-control-does-china-have-over-rare-earth-elements/?sh=62033e0f5b21 Forbes (2023).

[13] D.J. Packey, D. Kingsnorth, The impact of unregulated ionic clay rare earth mining in China. Res. Policy 48 (2016) 112-116 10.1016/j.resourpol.2016.03.003

[14] Lovón-Canchumani, g.; Lima, f. M. R. S. (org.); Oliveira, p. P. (org.). Avaliação do Ciclo de Vida na Mineração: Estudos da produção de minério de ferro. Serie CETEM. 78. ed. Rio de Janeiro: CETEM/MCTI, 2015. v. 1.

[15] R.K. Jyothi, T. Thenepalli, J.W. Ahn, P.K. Parhi, K.W. Chung, J.Y. Lee, Review of rare earth elements recovery from secondary resources for clean energy technologies: grand opportunities to create wealth from waste. J. Clean. Prod. (2020) https://doi.org/10.1016/j.jclepro.2020.122048

[16] A. Schreiber, J. Marx, P. Zapp, Life Cycle Assessment studies of rare earths production—fndings from a systematic review. Sci Total Environ 791(2021) https://doi.org/10.1016/J.SCITOTENV.2021.148257

[17] T. Junne, N. Wulff, C. Breyer, T. Naegler, Critical materials in global low-carbon energy scenarios: the case for neodymium, dysprosium, lithium, and cobalt. Energy, 211 (2020) https://doi.org/10.1016/j.energy.2020.118532

[18] D.H. Dang, K.A. Thompson, L. Ma, H.Q. Nguyen, S.T. Luu, M.T.N. Duong, A. Kernaghan, Toward the circular economy of rare earth elements: a review of abundance, extraction, applications, and environmental impacts. Arch. Environ. Contam. Toxicol. (2021) https://doi.org/10.1007/s00244-021-00867-7

[19] J. Korhonen, A. Honkasalo, J. Seppälä. Circular economy: the concept and its limitations. Ecol. Econ.143 (2018) 37-46. 10.1016/j.ecolecon.2017.06.041

[20] L. Wang, T. Liang, Geochemical fractions of rare earth elements in soil around a mine tailing in Baotou, China. Sci. Rep. 5 (2015)12483 https://doi.org/10.1038/srep12483

[21] GM. Mudd, The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resources Policy 35, (2010) 98-115 https://doi.org/10.1016/j.resourpol.2009.12.001

[22] GM. Mudd, Global trends and environmental issues in nickel mining: Sulfides versus laterites. Ore Geology Reviews 38 (2010) 9-26 https://doi.org/10.1016/j.oregeorev.2010.05.003.

[23] J. Marx, A. Schreiber, P. Zapp, F. Walachowicz, Comparative life cycle assessment of NdFeB permanent magnet production from different rare earth deposits. ACS Sustain Chem Eng, 6 (2018) 5858-5867 https://doi.org/10.1021/acssuschemeng.7b04165

[24] J. Navarro, F. Zhao, Life-cycle assessment of the production of rare-earth elements for energy applications: a review. Front. Energy Res., 2 (2014) 1-17, https://doi.org/10.3389/fenrg.2014.00045

[25] T. Norgate, N. Haque, Energy and greenhouse gas impacts of mining and mineral processing operations. J. Clean. Prod. 18 (2010) 266-274 https://doi.org/10.1016/j.jclepro.2009.09.020.

[26] USEPA, Rare Earth Elements: a Review of Production, Processing, Pecycling, e Questões Ambientais Associadas. United States Environmental Protection Agency (2012) 135.

[27] S.H. Ali, D. Giurco, N. Arndt, E. Nickless, G. Brown, A. Demetriades, R. Durrheim, M.A. Enriquez, J. Kinnaird, A. Littleboy, L.D. Meinert, Mineral supply for sustainable development requires resource governance. Nature, 543 (2017) 367-372 https://doi.org/10.1038/nature21359

[28] V. Balaram, Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geosci. Front. 10 (2019) 1285-1303 https://doi.org/10.1016/j.gsf.2018.12.005

[29] Y. Fujita, S.K. McCall, D. Ginosar, Recycling rare earths: perspectives and recent advances. MRS Bull., 47 (2022) 283-288 https://doi.org/10.1557/s43577-022-00301-w

[30] D. Talan, Q. Huang, A review of environmental aspect of rare earth element extraction processes and solution purification techniques Miner. Eng., 179 (2022) 107430 https://doi.org/10.1016/j.mineng.2022.107430

[31] IEA, Nuclear Power in a Clean Energy System. International Energy Agency (2019).

[32] S. Sadekin, S. Zaman, M. Mahfuz, R. Sarkar, Nuclear power as foundation of a clean energy future: a review. Energy Procedia, 160 (2019) 513-518 https://doi.org/10.1016/j.egypro.2019.02.200

[33] ISO 14040 (2006) Environmental management: life cycle assessment—principles and framework.

[34] ISO 14044 (2006) Environmental management: life cycle assessment—requirements and guidelines.

[35] K. Binnemans, PT. Jones, Rare Earths and the Balance Problem. J. Sustentar Metal 1 (2015) 29−38. https://doi.org/10.1007/s40831-014-0005-1

[36] CK. Gupta, N. Krishnamurthy, Extractive Metallurgy of Rare Earths, CRC Press, 2004.

[37]] A. Jordens, YP. Cheng, KE. Waters, A review of the beneficiation of rare earth element bearing minerals. Mineiro. Eng. 41 (2013) 97-114 https://doi.org/10.1016/j.mineng.2012.10.017

[38] GJ. Simandl, Geology and market-dependent significance of rare earth element resources. Mineralium Deposita 49 (2014) 889-904 https://doi.org/10.1007/s00126-014-0546-z

[39] Kanazawa Y, Kamitani M (2006) Rare earth minerals and resources in the world. J Alloy Compd 408–412:1339–1343. https://doi.org/10.1016/J.JALLCOM.2005.04.033

[40] CK. Gupta, N. Krishnamurthy, Global Production Estimation of Rare Earth Elements and Their Environmental Impacts on Soils. Metallurgy of Rare Earths. International Materials Review, 37 (1992).

[41] F. Habashi, Extractive Metallurgy of Rare Earth. Canadian Metallurgical Quarterly, 52 (2013) 224-233 https://doi.org/10.1179/1879139513Y.0000000081

[42] E. Vahidi, F. Zhao, Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction. J. Environ. Manage., 203 (2017), 255-263 http://dx.doi.org/10.1016/j.jenvman.2017.07.076 0301-4797.

[43] T. Xu, X. Zheng, B. Ji, Z. Xu, S. Bao, X. Zhang, G. Li, J. Mei, Z. Li, Green recovery of rare earth elements under sustainability and low carbon: a review of current challenges and opportunities. Sep. Purif. Technol. 330 (2024) https://doi.org/10.1016/j.seppur.2023.125501

[44] P. Nuss, MJ. Eckelman, Life Cycle Assessment of Metals: A Scientific Synthesis. PLoS ONE 9 (2014) 101298 https://doi.org/10.1371/journal.pone.0101298

[45] J.W. Heim II, R.L. Vander Wal, NdFeB permanent magnet uses, projected growth rates and Nd plus Dy demands across end-use sectors through 2050: a review. Minerals, 13 (2023) 1274 https://doi.org/10.3390/min13101274

[46] J. Mohapatra, J.P. Liu, Rare-earth-free permanent magnets: the past and future. E. Brück (Ed.), Handbook of Magnetic Materials, Elsevier (2018) 1-57 https://doi.org/10.1016/bs.hmm.2018.08.001

[47] J. Cui, M. Kramer, L. Zhou, F. Liu, A. Gabay, G. Hadjipanayis, B. Balasubramanian, D. Sellmyer, Current progress and future challenges in rare-earth-free permanent magnets. Acta Mater, 158 (2018) 118-137 https://doi.org/10.1016/j.actamat.2018.07.049

[48] J.D. Widmer, R. Martin, M. Kimiabeigi, Electric vehicle traction motors without rare earth magnets. SM&T, 3 (2015) 7-13 https://doi.org/10.1016/j.susmat.2015.02.001

[49] A. Amato, A. Becci, I. Birloaga, I. De Michelis, F. Ferella, V. Innocenzi, NM. Ippolito, P.J. Gomez, F. Veglio̖, F. Beolchini, F, Sustainability analysis of innovative

technologies for the rare earth elements recovery. Renewable Sustainable Energy Rev. 106 (2019) 41-53 https://doi.org/10.1016/j.rser.2019.02.029

[50] X.Y. Du, T.E. Graedel, Global in-use stocks of the rare earth elements: a first estimate. Environ. Sci. Technol., 45 (2011) 4096-4101 https://doi.org/10.1021/es102836s

[51] Y.X. Yang, A. Walton, A. Sheridan, K. Guth, R. Gauß, O. Gutfleisch, M. Buchert, B.M. Steenari, T.V. Gerven, P.T. Jones, K. Binnemans, REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review J. Sustain. Metall., 3 (2017), pp. 122-149 https://doi.org/10.1007/s40831-016-0090-4

[52] C. Tunsu, Hydrometallurgy in the recycling of spent NdFeB permanent magnets. Waste Electrical and Electronic Equipment Recycling, 8 (2018) 175-211 https://doi.org/10.1016/B978-0-08-102057-9.00008-1

[53] T. Horikawa, K. Miura, M. Itoh, K.I. Machida. Effective recycling for Nd–Fe–B sintered magnet scraps. J. Alloys Compd., 408 (2006) 1386-1390 https://doi.org/10.1016/j.jallcom.2005.04.091

[54] A. Kumari, M.K. Sinha, S. Pramanik, S.K. Sahu, Recovery of rare earths from spent NdFeB magnets of wind turbine: Leaching and kinetic aspects. Waste Manage 75 (2018) 486-498 https://doi.org/10.1016/j.wasman.2018.01.033

[55] M.A.R. Önal, C.R. Borra, M.X. Guo, B. Blanpain, T.V. Gerven, Hydrometallurgical recycling of NdFeB magnets: complete leaching, iron removal and electrolysis. J. Rare Earths 35 (2017) 574-583 https://doi.org/10.1016/S1002-0721(17)60950-5

[56] D. Easley, J. Kleinberg. Networks, crowds, and markets: Reasoning about a Highly Connected World, 1, Cambridge university press, Cambridge (2010).

[57] G. Finnveden, MZ. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in Life Cycle Assessment. Journal of Environmental Management 91 (2009),1-21 https://doi.org/10.1016/j.jenvman.2009.06.018

[58] E. Vahidi E, J. Navarro, F. Zhao, An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. Resour Conserv Recycl 113 (2016) 1–11. https://doi.org/10.1016/J.RESCONREC.2016.05.006

[59] LabGERTS - Waste Management and Sustainable Technologies Laboratory - UFPR (2022). Technical Report REGINA Project (Rare Earth Global Industry and New Applications).

[60] F. Torabi, P. Ahmadi, Simulation of Battery systems: fundamentals and applications, Academic Press (2019) https://doi.org/10.1016/C2017-0-04172-1

[61] Pre-sustainability (2012). http://www.pre-sustainability.com/simapro-lca-software.

[62] Z. Weng, N. Haque, G.M. Mudd, S.M. Jowitt, Assessing the energy requirements and global warming potential of the production of rare earth elements. Journal of Cleaner Production. 139 (2016) 1282-1297. https://doi.org/10.1016/j.jclepro.2016.08.132.

[63] H. Deng, A. Kendall, Life cycle assessment with primary data on heavy rare earth oxides from ion-adsorption clays. The International Journal of Life Cycle Assessment 24 (2019) 1643–1652. https://doi.org/10.1007/s11367-019-01582-1#Abs1

[64] Á. Fahimi, F. Zhao, S. Singh, E. Vahidi, Mapping complexity: Analyzing rare earth production life cycle inventories with network analysis. Resources, Conservation and Recycling. 211 (2024) https://doi.org/10.1016/j.resconrec.2024.107894.

[65] S.V.P. Defourny, G. Caioni, M. Bellocci, V. Melai, G. Scortichini, R. Salini, M. Mrtino, GD Teodoro, A. Cocco, M.C Cantelmi, C. Merola, A. Petrini, Domestic dogs as environmental sentinel in comparative toxicologic pathology: Assessment of metals and rare earth elements concentrations in healthy and neoplastic mammary glands. One Health 18 (2024) 100749 https://doi.org/10.1016/j.onehlt.2024.100749

[66] Y. Wahyono, NA Sasongko, A. Trench, M. Anda, H. Hadiyanto, N. Aisyah, A. Anisah, N. Ariyanto, I. Kumalasari, V.Z.E. Putri, MC Lestari, LP Panggabean, R. Ridlo, S. Sundari, AD. Suryaningtyas, ED. Novianti, MRF Hakim, AL. Prihatin, HHA. Matin, Evaluating the impacts of environmental and human health of the critical minerals mining and processing industries in Indonesia using life cycle assessment. Case Studies in Chemical and Environmental Engineering 10 (2024) 100944 https://doi.org/10.1016/j.cscee.2024.100944

[67] KT. Rim, KH. Koo, JS. Park, Toxicological Evaluations of Rare Earths and Their Health Impacts to Workers: A Literature Review. Safety and Health at Work 4 (2013) 12-26 https://doi.org/10.5491/SHAW.2013.4.1.12

ANNEX 1 – RESEARCH PROTOCOL (LIFE CYCLE ASSESSMENT PROJECT OF RARE EARTH MAGNETS)

Form for Life Cycle Inventory Analysis			
Filled by:	Date of filling:		
Identification of the elementary process:	Source location of the data:		
Time period: Year	Month of start:	Month of end:	
Description of the elementary process: (attach additional sheets if necessary)			
Atmospheric emissions[a]	Unit	Quantity	Description of sampling procedures (attach additional sheets if necessary)
Releases to water[b]	Unit	Quantity	Description of sampling procedures (attach additional sheets if necessary)
Releases to soil[c]	Unit	Quantity	Description of sampling procedures (attach additional sheets if necessary)
Other releases[d]	Unit	Quantity	Description of sampling procedures (attach additional sheets if necessary)

Describe any specific calculations, data collection, sampling, or variations in the description of the functions of the elementary process (attach additional sheets if necessary)

[a] For example, inorganic: Cl_2, CO, CO_2, dust/particulate, F_2, H_2S, H_2SO_4, HCl, HF, N_2O, NH_3, NOx, SOx; organic: hydrocarbons, PCBs, dioxins, phenols; metals: Hg, Pb, Cr, Fe, Zn, Ni.

[b] For example: BOD, COD, acids, Cl_2, CN^-, detergents/oils, dissolved organic compounds, F-, Fe ions, Hg ions, hydrocarbons, Na^+, NH^{4+}, NO^{3-}, organochlorines, other metals, other nitrogen compounds, phenols, phosphates, $SO_4{}^{2-}$, suspended solids.

[c] For example: mineral waste, mixed industrial waste, municipal solid waste, toxic waste (please list the compounds included in this data category).

[d] For example: noise, radiation, vibration, odor, waste heat.

SOURCE: LABGERTS (2024)