

EXTRACTION OF CRITICAL RARE EARTH METALS (Nd, Pr, Dy) FROM ELECTRONIC WASTE – CURRENT TECHNOLOGIES AND FUTURE PERSPECTIVES

Aleksandar Chanachev, Gospodinka Gicheva

University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: a.chanachev@mgu.bg

ABSTRACT. On a global scale, the generation of waste from electronic and electrical devices is increasing dramatically and creates the need to search for new approaches for their recycling. The inclusion of several valuable materials and elements that are part of their composition creates conditions for systematic and in-depth study of both classical approaches that can be used for their recovery, and new, complex processes that would allow for easier and more environmentally friendly recycling. Among the materials that are particularly important for extraction in the recycling process are rare earth elements. Of these, neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) are widely used in various high-tech industries: the production of hard drives, smartphones, computers, and others. They are found in very small quantities in nature and their primary extraction is also hampered by the geographical location of their deposits, which could pose difficulties in supply chains due to various geopolitical factors. This makes the search for new methods for obtaining such elements from secondary sources, namely e-waste, a particularly interesting and relevant scientific topic, both for the extraction process itself and for creating favourable conditions for sustainability and the development of a circular economy.

Key words: critical rare earth metals, electronic waste, extraction.

ИЗВЛИЧАНЕ НА КРИТИЧНИ РЕДКОЗЕМНИ МЕТАЛИ ОТ ЕЛЕКТРОННИ ОТПАДЪЦИ (Nd, Pr, Dy) – СЪВРЕМЕННИ ТЕХНОЛОГИИ И БЪДЕЩИ НАСОКИ

Александър Чаначев, Господинка Гичева

Минно-геоложки университет „Св. Иван Рилски“, 1700 София

РЕЗЮМЕ. В глобален мащаб генерирането на отпадъци от електронни и електрически устройства нараства драстично и поражда нуждата от търсенето на нови подходи за тяхното рециклиране. Включването на редица ценни за икономиката и индустрията материали и елементи, които влизат в състава им създава условия за систематично и задълбочено изучаване както на класическите подходи, които могат да се използват за оползотворяването им, така и на нови, комплексни процеси, които да позволят по-лесното и по-екологичното протичане на рециклирането. Сред материалите, които са особено важни за извличане в процеса на рециклиране са редкоземните елементи, а от тях неодимът (Nd), празеодимът (Pr) и диспрозий (Dy) намират широко приложение в различни високотехнологични производства – изработването на харддискове, смартфони, компютри и други. Те се намират в много малки количества в природата и първичното им извличане е затруднено и от географското разположение на техните залежи, което би могло да създаде затруднения във веригите на доставка поради различни геополитически фактори. Това прави търсенето на нови методи за получаване на такива елементи от вторични източници, а именно електронни отпадъци, особено интересна и актуална научна тема, както за самия процес на извличане, така и за създаване на благоприятни предпоставки за устойчивост и развитие на кръгова икономика.

Ключови думи: критични редкоземни метали, електронни отпадъци, извличане.

Introduction

Due to the rapid growth in the amount of waste generated by electrical and electronic waste, the depletion of resources from deposits of elements that are essential in modern electronics, as well as environmental protection, modern recycling technologies are being strengthened. The well-known pyrometallurgical and hydrometallurgical processes are still widely used, but in recent years, there has been an increasing trend towards various alternative methods that are more environmentally friendly, such as non-cyanide leaching, bio metallurgy, cryogenic digestion, supercritical extraction, and leaching agents that can be recycled. Such approaches significantly improve the extraction of critical metals and limit the impact on the environment. (Gulliani et al., 2023).

Recycling electrical and electronic equipment is associated with a number of difficulties in its initial preparation before the recycling process. Among these types of waste are various types of batteries, mobile phones, televisions, liquid crystal displays and others, which contain metals, plastics, metal-plastic mixtures, organics, and glass fibers, along with the raw materials that are recycled (Wang & Xu, 2015).

After the initial process of preparing the raw materials for recycling, a series of processes begins, whose aim is to extract from the electronic waste the elements that are of economic importance for various technological industries. In addition to the

extraction of gold, copper, platinum, palladium, and other precious metals, various rare earth elements (REEs) are also extracted, including Nd, Pr and Dy. The group of rare earth elements is included in the category of critical raw materials (CRMs) due to their economic importance and the risks associated with their supply. For this reason, it is important to clarify what exactly we understand by critical raw materials and where we can look for the definition of this concept.

It is important to note that rare earth elements are included in the category of critical raw materials because of their high economic importance and the significant risks associated with their supply. Therefore, a clear understanding of the concept of critical raw materials is essential.

The European Commission defines critical raw materials as raw materials of essential economic importance for the European Union which at the same time are exposed to a high risk of supply chain disruption, due to the concentration of their production in a limited number of countries, various geopolitical factors, or the lack of alternative substitutes. (European Commission, 2023).

The United States Geological Survey (USGS) also provides a definition of critical raw materials, which includes the understanding that a critical mineral is a non-fuel mineral or mineral material that is of significant importance to the economic or national security of the United States, and whose supply chain is vulnerable to disruption and this would have significant

consequences for the economy or national security (USGS, 2022).

The Organisation for Economic Co-operation and Development (OECD) also defines critical raw materials as raw materials that are critical to the green transition because they cannot be replaced in renewable and clean energy technologies and their supply is exposed to significant risks due to the high geographical concentration of production and trade (OECD, 2023).

Therefore, by all the definitions considered, neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) can be classified as critical raw materials. These rare earth elements play a significant role in the production of high-performance permanent magnets used in electric vehicles, wind turbines, robotics, and many modern technologies. On the other hand, their supply chains are highly concentrated geographically and are susceptible to geopolitical and market disruptions, making them strategically important materials.

Rare earth elements and especially neodymium (Nd), praseodymium (Pr), and dysprosium (Dy), play a crucial role in modern technologies and have significant industrial applications, mainly due to their unique magnetic properties and their importance in the production of high-performance NdFeB permanent magnets (Brown, 2025).

Neodymium has a significant industrial importance, with neodymium-iron-boron (NdFeB) magnets possessing the highest energy among commercially available permanent magnets, with their magnetic characteristics approaching the theoretical limit of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase. (Gutfleisch et al., 2011).

Praseodymium (Pr) is of essential importance in technologies related to permanent magnets. Significant amounts of it are found in technological products - computers, cars, and wind turbines. (Du & Graedel, 2011).

Dysprosium (Dy) is a component of Nd-Fe-B permanent magnets, which occurs by partial substitution of Nd atoms, which leads to an increase in the anisotropy field and improvement of coercivity, and allows their application in high-temperature environments, such as traction motors of hybrid electric vehicles and wind generators (Hono & Sepehri-Amin, 2012).

Among the rare earth elements, neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) are important components of a large number of high-tech and industrial productions. Their demand is constantly growing, but their supply chains and sustainability can be threatened by various factors. These factors influence the rapid development of scientific research, which seeks a way to utilise them from various types of secondary sources, including electronic waste.

Sources of Nd, Pr, and Dy in Electronic Waste

The consumption of electrical and electronic equipment is growing, which leads to a continuous increase in the waste generated by them, globally exceeding 50 million tonnes per year, and by 2030 it is expected to reach about 74.7 million tonnes (Pineda-Vásquez et al., 2024). The generated waste is an important secondary source of valuable metals and critical raw materials, and this category also includes rare earth elements, in particular neodymium, praseodymium and dysprosium. Their utilisation can reduce dependence on primary mineral resources and improve the security of supply chains (Gulliani et al., 2023).

The increasing demand for rare earth elements, and in particular neodymium (Nd), praseodymium (Pr) and dysprosium (Dy), is driven by their applications in various types of high-tech products, consumer electronics, vehicles and wind turbines. NdFeB permanent magnets represent one of the richest secondary sources, containing approximately 20–31 wt.% Nd, 4–9 wt.% Pr, and 1–8 wt.% Dy, as determined by their application. The recovery of these elements from e-waste is considered important for improving resource security, reducing dependence on mining, and supporting the transition to a circular economy (Akcil et al., 2021).

The processes related to the production of rare earth elements as primary raw materials, and not as extracted from electronic waste, is mainly concentrated in China. On the other hand, their importance for the industry is extremely great, as an excellent example in this regard are the neodymium magnets - even though they are a very small part of the total weight of hard disk drives, without their presence, their full work would be impossible (Duarte & Rodrigues, 2020; Shanthi Bhavan et al., 2023).

Table 1 shows that the highest concentration of rare earth elements and the considered neodymium, praseodymium, and dysprosium in electronic waste is observed in hard drives, with the main source of neodymium and dysprosium being the permanent magnets in them (Thompson et al., 2018; Pyrgaki et al., 2021; Good et al., 2023; Heim & Vander Wal, 2023; Liang et al., 2024).

Table 1. Content of rare earth elements (REEs) in various electronic waste

E-Waste	Main Components	REEs Present	Concentration (ppm)	Ref.
Hard disk drives	Permanent magnets	Nd, Dy, Pr	2500–15,000	(Heim & Vander Wal, 2023; Thompson et al., 2018)
Smartphones	Screens, speakers, vibration motors	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Y	10–1000	(Good et al., 2023)
Computers	Printed circuit boards, hard disk drives, Speakers	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Y	10–1000	(Pyrgaki et al., 2021)

Note. Adapted from “A Review of the Occurrence and Recovery of Rare Earth Elements from Electronic Waste,” by B. Liang, J. Gu, X. Zeng, W. Yuan, M. Rao, B. Xiao, and H. Hu, 2024, *Molecules*, 29(19), 4624. (<https://doi.org/10.3390/molecules29194624>). Licensed under CC BY 4.0.)

Electronic waste represents a valuable source of secondary rare earth materials, but the recovery of Nd, Pr, and Dy remains limited due to technical challenges, such as small quantities of magnets in electronic products, their integration into components, protective coatings, and difficulties associated with extraction (Lixandru et al., 2017).

Recycling approaches have been investigated, including hydrometallurgical processes; nevertheless, there is still a great need for environmentally sustainable methods. Maât et al. (2016) demonstrated an alternative recovery approach, which is based on hydrothermal treatment with water and sodium chloride, enabling the extraction of rare earth compounds from

Nd-Fe-B permanent magnets recovered from electrical and electronic equipment waste.

Despite their potential as a secondary resource, rare earth recycling from electrical and electronic equipment waste remains limited due to challenges related to collection, separation, and the development of economically feasible recovery processes (Binnemans et al., 2013).

Rare earth elements, and especially neodymium (Nd) praseodymium (Pr) and dysprosium (Dy), have an essential role in industry and high technology and without them many electronic and electrical devices could not function normally. Their concentration in a small number of geographical regions and their relatively small quantities make their primary extraction highly limited and supply chains unsustainable. Due to these factors, their secondary extraction from e-waste is the subject of increased scientific interest and overcoming the technical difficulties associated with this process is of essential importance.

Chemical Recovery Technologies

The chemical recovery processes of electronic and electrical waste must go through a series of steps of preliminary mechanical and physical treatment, thus separating the materials and elements that need to be extracted from the complex matrix of the waste. Because electronic waste has a complex heterogeneous composition, which includes metals, polymers, ceramics, glass, and other components, their effective separation and concentration of the target fractions are important for increasing the efficiency of their recovery at a later stage of the process itself. Pre-treatment includes both dismantling and desoldering, as well as subsequent size reduction, which is achieved by crushing and milling, as well as by sieving and physical separation of metallic from non-metallic fractions. The procedures performed in this way lead to improved access to valuable metals and compounds, which also contain rare earth elements, by increasing the release of the material and significantly reducing interference from non-metallic components. Physical separation techniques, including magnetic, are based on their density and electrostatic separation. They are widely applied due to their low operating costs and the ability to concentrate valuable fractions before hydrometallurgical or pyrometallurgical treatment begins. (Gulliani et al., 2023).

Metallurgy processes

Metallurgical processes involve the extraction, processing, and transformation of metals using chemical and physical processes. Recycling of electronic waste uses metallurgical methods that enable the extraction of valuable metals from complex waste materials. The use of pyrometallurgical processes, such as melting and smelting, performed at high temperatures are widely used industrial techniques that allow the separation of metals based on their thermophysical properties. These processes remove organic components and allow the metals to be concentrated, which is the basis for their subsequent further purification. (Gulliani et al., 2023).

Combined pyrometallurgical-hydrometallurgical approaches are a promising strategy to recover critical metals, including rare earth elements, particularly neodymium, praseodymium, and dysprosium (Gulliani et al., 2023).

Pyrometallurgy Pyrometallurgical processes are among the most established techniques for the recovery of metals from waste electrical and electronic equipment. These methods are based on the use of high-temperature operations such as melting, sintering, remelting, plasma arc furnaces, and blast furnaces. In them, the separation of metals is achieved through differences in their thermophysical properties. Rare earth elements can be extracted using pyrometallurgical approaches. It is important to note that pyrometallurgy is mainly applied as a primary treatment step. In this, organic components are removed and the metal phases are concentrated. The subsequent selective separation and purification of the individual elements require the use of processes that are hydrometallurgical.

Hydrometallurgy (leaching and metal recovery). Among the most promising approaches for extracting critical metals from electronic waste are undoubtedly hydrometallurgical processes. They have a sequence of controlled chemical reactions accompanied by high selectivity, and their impact on the environment is lower than that of pyrometallurgical methods. Two main stages usually make up hydrometallurgical processes, namely: the extraction of metals from materials that have undergone pre-treatment, and the extraction of dissolved metal ions from the leachate. Various techniques are used in the extraction - precipitation, solvent extraction, ion exchange, cementation, and electrolytic extraction (Gulliani et al., 2023).

Due to the similar chemical properties of Nd, Pr and Dy, selective separation of the rare earth elements involved must be carried out after leaching. Solvent extraction and ion exchange techniques have been the subject of much research and interest due to their ability to achieve high selectivity under controlled conditions. Precipitation methods can be used to extract metals from infiltrates, and electrowinning is one of the established techniques for the deposition of metals from acids and ammonia solutions. It is mainly applied to base metals and the question of combining it with other hydrometallurgical steps is the subject of a number of studies aimed at finding more efficient extraction routes (Gulliani et al., 2023).

Electrochemically assisted leaching, as a new approach, is a potential alternative to conventional chemical treatment. It can generate oxidising substances *in situ* and significantly limit the use of reagents that can have a negative impact on health and the environment. Adsorption and biosorption are increasingly important due to their low operating costs and potential for regeneration. They also have excellent ability to selectively precipitate metal ions from aqueous solutions.

Combined hydrometallurgical strategies such as selective separation, leaching, etc. are the basis for future development of concepts for the extraction of Nd, Pr and Dy from secondary resources (Gulliani et al., 2023).

Biometallurgy. The search for ecological alternatives places biometallurgical processes, such as bioleaching, among the most interesting and increasingly actively studied methods for extracting metals from secondary sources. Biometallurgy uses various types of microorganisms that help dissolve metals and significantly reduce the need for the use of energy resources, as well as the consumption of chemical reagents. This allows these processes to have a relatively small impact on the environment. Despite their many advantages, their application on an industrial scale is still significantly limited due to the relatively slow reaction kinetics, as well as the long processing time and the

high sensitivity of microorganisms to environmental conditions (Gulliani et al., 2023).

The basis of microbial metal extraction is the ability of microorganisms to interact with metal-containing materials through direct and indirect mechanisms. In indirect bioleaching, microorganisms, such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*, oxidise Fe^{2+} to Fe^{3+} and elemental sulphur to sulphuric acid, generating ferric ions and acidic conditions that promote metal dissolution. In addition, heterotrophic fungi such as *Aspergillus niger* produce organic acids, including citric, oxalic, and malic acids, which enhance metal dissolution through acidification and complex formation (Gulliani et al., 2023).

Microbial metabolites and organic acids can promote dissolution by forming soluble metal-ligand complexes, enhancing the availability of rare earth ions in solution. Bioleaching systems based on microorganisms such as *Acidithiobacillus* species can achieve significant recovery of rare metals, including reported recoveries of more than 95% of Ce, Eu, and Nd after appropriate pretreatment and sequential bioleaching processes (Gulliani et al., 2023).

The creation of a multi-stage procedure for such a type of bioleaching significantly improves the selectivity of extraction, as well as the efficiency of the entire process. The initial stages are associated with the dissolution of base metals, which favours the subsequent extraction of precious metals and rare earth elements. The oxidation-reduction potential, pH, microbial activity, and the chemical characteristics of the target metals are important in these processes. After bioleaching, subsequent steps in the process are possible (extraction with a solvent, precipitation, or ion exchange) in order to isolate individual rare earth elements due to their similar chemical properties (Gulliani et al., 2023).

Bioleaching is undoubtedly an ecological method for the secondary extraction of rare earth elements, but it has its limitations: slow dissolution rate, microbial inhibition, which is due to toxic components present in electronic waste, the formation of secondary sediments, which can passivate the surface of the materials and thus significantly reduce the extraction efficiency. Research in this area focuses on hybrid approaches that combine bioleaching with catalysts, hydrometallurgical extraction additives, or chemical additives, aiming to improve and make these methods economically viable. These developments and the prior incorporation of suitable separation technologies make biometallurgical approaches a sustainable method for extracting rare earth elements, such as Nd, Pr and Dy (Gulliani et al., 2023).

Critical Comparison and Future Perspectives

Biometallurgy finds a place in the processing of electronic waste as a promising alternative route for its recycling by using microorganisms to facilitate the dissolution of metals. Biometallurgical approaches have environmental advantages - lower energy demand, reduced consumption of hazardous chemical reagents, lower operating costs, and minimal generation of toxic emissions. This gives a significant advantage over conventional pyrometallurgical and hydrometallurgical approaches. Pyrometallurgy requires high temperatures and can result in the loss of volatile metals, and hydrometallurgy often relies on strong acids, oxidising agents, or complexing agents. Bioleaching works under milder conditions and uses

naturally occurring microbial activities to extract metals (Gulliani et al., 2023).

Although with obvious environmental benefits, biometallurgy faces a number of limitations, mainly to applications on a laboratory scale, which can hardly be transferred to real, sufficiently large industrial processes due to the slow progress of the individual processes and the difficulties associated with process control. In contrast, hydrometallurgical methods can achieve high recovery efficiencies within hours or days, and bioleaching often requires several weeks to reach similar extraction levels. Thus, the extended processing time represents a major obstacle for the industrial implementation of this type of technology (Gulliani et al., 2023).

It can be easily summarised that the efficiency of biometallurgical processes is highly dependent on the microbial species, environmental conditions, and composition of the waste matrix. Acidophilic microorganisms, such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*, demonstrate excellent ability to recover base metals, such as Cu, Zn, Ni, and Co, through iron and sulphur oxidation mechanisms. Multi-stage bioleaching strategies, in which base metals are first removed, followed by selective recovery of noble metals, are emerging as an effective approach in e-waste treatment (Gulliani et al., 2023).

Recent developments indicate that catalytic enhancement could represent an important pathway toward improving the industrial feasibility of biometallurgy. The addition of metal catalysts, such as Cu^{2+} and Ag^+ ions, as well as non-metallic catalysts, including graphene, nitrogen-doped carbon nanotubes, and organic acids, has demonstrated significant improvements in dissolution kinetics and metal recovery. These approaches reduce the main limitation of conventional bioleaching by accelerating microbial oxidation reactions while maintaining relatively low environmental impact (Gulliani et al., 2023).

Future research should focus on developing integrated recycling systems combining mechanical pre-treatment, hydrometallurgical enrichment, and biological recovery steps. Such hybrid approaches could overcome the individual limitations of each technology by using physical methods to increase surface accessibility, chemical methods for rapid dissolution, and microbial processes for selective recovery under environmentally benign conditions (Gulliani et al., 2023).

Advances in synthetic biology, microbial engineering, and process automation can increase the efficiency of these processes and greatly improve the scalability of biometallurgical technologies. This is linked to the development of more resistant microbial strains capable of tolerating high metal concentrations and complex composite structures from e-waste processing. These are specific guidelines that have the potential to improve recovery efficiency and significantly reduce processing time. Continuous bioreactor systems, improved microbial immobilisation techniques, and real-time monitoring of redox and pH conditions are among the most essential prerequisites that can facilitate the transition from laboratory experiments to industrial applications (Gulliani et al., 2023).

Biometallurgy is one of the most sustainable approaches for future electronic waste recycling. Its successful commercialisation requires a balance between environmental performance, metal recovery efficiency, processing time, and economic feasibility. It does not aim to completely replace conventional technologies, but seeks approaches that are expected to become an additional component within integrated

circular economy strategies for sustainable metals recovery (Gulliani et al., 2023).

Conclusions

The growing generation of waste from electrical and electronic equipment is an environmental challenge that implies the recovery of spent resources from them, which is the basis of the circular economy. Electronic waste has a complex composition, which includes valuable and critical metals, polymers, and composite structures. A large part of the substances that make them up create potential risks and damages to health and the environment. This means that conventional disposal practices are risky and do not give the possibility of extracting the valuable materials contained in them. This demand calls for effective recycling strategies that will reduce the dependence on primary mineral resources (Gulliani et al., 2023).

A detailed review of existing recycling approaches clearly shows that no single technology can provide a comprehensive solution for recovering all the valuable components that make up e-waste. Pyrometallurgical processes offer high throughput and robust operation, but are associated with high energy requirements and potential emissions. Hydrometallurgical methods provide high efficiency and selectivity of metal recovery, but typically rely on corrosive reagents and generate secondary waste streams that require additional treatment. Biometallurgical approaches represent a more environmentally friendly alternative due to their lower chemical consumption and reduced environmental impact; however, their wider application is limited by slow kinetics, microbial sensitivity, and process scalability challenges (Gulliani et al., 2023).

A sustainable WEEE management strategy should be based on maximising resource recovery while minimising environmental impacts and energy demand. The development of hybrid recycling processes, supported by advances in biotechnology, material science, and process engineering, represents a promising direction toward achieving efficient recovery of valuable metals and critical materials. The implementation of circular economy principles through reduction, reuse, and recycling strategies is essential for improving resource efficiency and reducing the environmental burden associated with electronic waste generation.

Sustainable management requires not only improvements in recycling technologies, but also a series of changes in the design and production stages of electrical and electronic equipment. Extended producer responsibility, the development of products with longer lifespans, modular structures, easier disassembly, and improved reparability, can significantly improve future recovery pathways. The transition to a circular economy of electronic waste depends on the successful integration of technological innovation, environmental considerations, and responsible industrial practices.

Acknowledgements. This work is funded by the National Science Program “Critical and strategic raw materials for a green transition and sustainable development”, approved by the Resolution of the Council of Ministers No. 508/18.07.2024 and funded by the Ministry of Education and Science (MES) of Bulgaria.

References

- Akcil, A., Ibrahim, Y. A., Meshram, P., Panda, S., & Abhilash. (2021). Hydrometallurgical recycling strategies for recovery of rare earth elements from consumer electronic scraps: A review. *Journal of Chemical Technology & Biotechnology*, 96(7), 1785–1797. <https://doi.org/10.1002/jctb.6739>
- Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: A critical review. *Journal of Cleaner Production*, 51, 1–22. <https://doi.org/10.1016/j.jclepro.2012.12.037>
- Brown, A. M. (2025). Reclaiming rare earths. *Nature Reviews Chemistry*, 9, 123–124. <https://doi.org/10.1038/s41570-025-00759-7>
- Duarte, A. C. O., & Rodrigues, R. de S. (2020). Rare earth elements: What are they, what are they for and what are their environmental effects? *Sustentare*, 4(1). <https://doi.org/10.5892/st.v4i1.6154>
- Du, X., & Graedel, T. E. (2011). Global in-use stocks of the rare earth elements: A first estimate. *Environmental Science & Technology*, 45(9), 4096–4101. <https://doi.org/10.1021/es102836s>
- European Commission. (2023). https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en?utm_source=chatgpt.com
- Good, N. M., Kang-Yun, C. S., Su, M. Z., Zytneck, A. M., Vu, H. N., Grace, J. M., Nguyen, H. H., Park, D. M., Skovran, E., & Fan, M. (2023). Scalable bio-platform to recover critical metals from complex waste sources. *bioRxiv*. <https://doi.org/10.1101/2023.09.02.556034>
- Gutfleisch, O., Willard, M. A., Brück, E., Chen, C. H., Sankar, S. G., & Liu, J. P. (2011). Magnetic materials and devices for the 21st century: Stronger, lighter, and more energy efficient. *Advanced Materials*, 23(7), 821–842. <https://doi.org/10.1002/adma.201002180>
- Gulliani, S., Volpe, M., Messineo, A., Volpe, R. (2023). Recovery of metals and valuable chemicals from waste electric and electronic materials: a critical review of existing technologies. *RSC Sustainability*, 1, 1085, DOI: 10.1039/d3su00034f
- Hono, K., & Sepehri-Amin, H. (2012). Strategy for high coercivity in soft and hard magnetic materials. *Scripta Materialia*, 67(6), 530–535. <https://doi.org/10.1016/j.scriptamat.2012.06.038>
- Liang, B., Gu, J., Zeng, X., Yuan, W., Rao, M., Xiao, B., & Hu, H. (2024). A review of the occurrence and recovery of rare earth elements from electronic waste. *Molecules*, 29(19), 4624. <https://doi.org/10.3390/molecules29194624>
- Lixandru, A., Venkatesan, M., Jonsson, C., Poenaru, I., Hall, B., Yang, Y., Walton, A., Güth, K., Gauß, R., & Gutfleisch, O. (2017). Identification and recovery of rare-earth permanent magnets from waste electrical and electronic equipment. *Waste Management*, 68, 482–489. <https://doi.org/10.1016/j.wasman.2017.07.028>
- Maât, N., Nachbaur, V., Lardé, R., Juraszek, J., & Le Breton, J. M. (2016). An Innovative Process Using Only Water and Sodium Chloride for Recovering Rare Earth Elements from Nd–Fe–B Permanent Magnets Found in the Waste of Electrical and Electronic Equipment. *ACS Sustainable Chemistry & Engineering*, 4(9), 5006–5013. <https://doi.org/10.1021/acssuschemeng.6b01226>
- OECD, Raw Materials Critical for the Green Transition: Production, International Trade and Export Restrictions,

- OECD Trade Policy Papers No. 269, OECD Publishing, Paris, 2023, DOI: 10.1787/c6bb598b-en.
- Pineda-Vásquez, T., Rendón-Castrillón, L., Ramírez-Carmona, M., & Ocampo-López, C. (2024). From E-waste to high-value materials: Sustainable synthesis of metal, metal oxide, and MOF nanoparticles from waste printed circuit boards. *Nanomaterials*, 14(1), 69. <https://doi.org/10.3390/nano14010069>
- Pyrgaki, K., Gemeni, V., Karkalis, C., Koukouzas, N., Koutsovitis, P., & Petrounias, P. (2021). Geochemical occurrence of rare earth elements in mining waste and mine water. A review. *Minerals*, 11(8), Article 860. <https://doi.org/10.3390/min11080860>
- Shanthi Bhavan, J., Joy, J., & Pazhani, A. (2023). Identification and recovery of rare earth elements from electronic waste: Material characterization and recovery strategies. *Materials Today Communications*, 36, 106921. <https://doi.org/10.1016/j.mtcomm.2023.106921>
- Thompson, V. S., Gupta, M., Jin, H., Vahidi, E., Yim, M., Jindra, M. A., Nguyen, V., Fujita, Y., Sutherland, J. W., Jiao, Y., & Reed, D. W. (2018). Techno-economic and life cycle analysis for bioleaching rare-earth elements from waste materials. *ACS Sustainable Chemistry & Engineering*, 6(2), 1602–1609. <https://doi.org/10.1021/acssuschemeng.7b02771>
- USGS (U.S. Geological Survey). (2025). https://www.usgs.gov/faqs/what-a-critical-mineral?field_pub_type_target_id=All&field_release_date_value=&items_per_page=6&page=1&utm_source=chatgpt.com
- Wang, J., & Xu, Z. (2015). Disposing and recycling waste printed circuit boards: Disconnecting, resource recovery, and pollution control. *Environmental Science & Technology*, 49(2), 721–733. <https://doi.org/10.1021/es504833y>