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MINERALOGICAL AND STRUCTURAL CHARACTERISTICS OF RARE EARTH ELEMENTS IN INDUSTRIAL WASTE FROM HIGH-TECHNOLOGY PRODUCTION

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Abstract

This article examines the distribution, chemical form, and phase state of rare earth elements in industrial waste from high-tech production. The specifics of the presence of neodymium, dysprosium and samarium in electronic waste, permanent magnet waste and battery systems are investigated, taking into account the influence of technological and operational factors. The relationship between their mineralogical and structural characteristics and the choice of rational technological routes for recycling is analyzed. The role of structural features of man-made materials as an important factor in the formation of effective schemes of secondary involvement in the framework of a closed-loop economy is studied.

Keywords: *rare earth elements, technogenic waste, neodymium, dysprosium, samarium, secondary processing, circular economy*

Introduction

Rare earth elements (REE) remain particularly important raw materials for high-technology industries, as they determine the functional properties of permanent magnets, electronic components, and a range of electrochemical systems. At the same time, the growth of production and the rapid renewal of equipment lead to increasing flows of industrial waste and electronic scrap, in which secondary concentrations of REE are formed that may be comparable in significance to natural sources. The relevance of this study is обусловлена the fact that access to these elements is increasingly limited not so much by geological reserves as by technological barriers to their extraction. Processing efficiency depends on the chemical form and phase state in which the elements occur in specific types of waste.

From a practical point of view, neodymium, dysprosium, and samarium are of particular interest as important components of high-energy magnetic materials and functional blocks of modern electronics, as well as elements that may be present in battery waste and related technological chains. However, their industrial processing is complicated by heterogeneity, the presence of multicomponent matrices, and the formation of stable phases and surface passivating layers. The aim of this study is to investigate the mineralogical and structural characteristics of REE in industrial waste from high-technology production and their significance for selecting technological routes for secondary processing.

Main Part

Distribution, Chemical Form, and Phase State of REE in Industrial Waste from High-Technology Production

In technogenic waste from high-technology production, REE are characterized by pronounced phase and spatial heterogeneity, which fundamentally distinguishes them from natural raw materials. Whereas in ores these components are typically concentrated in relatively stable mineral phases, in waste they are incorporated into functional materials and fixed in the form of intermetallic, oxide, phosphate, or glassy phases formed during manufacturing processes and subsequent product operation.

In electronic waste, the main share of **neodymium and dysprosium** is localized in permanent magnets used in loudspeakers, electric drives, fans, data storage devices, and vibration modules. This results in a low average content of REE in mixed electronic scrap while simultaneously producing high local concentrations in separated magnetic components (Khandekar P. P. et al., 2025). Within such fragments, these elements are predominantly present in intermetallic phases structurally bound to an iron-based metallic matrix, with the dominant carrier phase typically represented by $Nd_2Fe_{14}B$. This determines high potential recoverability upon matrix destruction but reduces selectivity due to the simultaneous involvement of accompanying metals. Outside magnetic assemblies, the target elements occur in significantly smaller amounts and are usually represented by secondary products. These include oxide and hydroxide forms arising from corrosion and degradation of surface coatings, such as Nd_2O_3, Dy_2O_3, Fe_2O_3, and Fe_2O_4, as well as fine particles generated during mechanical crushing and concentrated in fine fractions.

Samarium in electronic waste streams is distributed less uniformly and is mainly associated with specialized magnetic and ceramic components. In such materials, it is usually present in a trivalent state and is isomorphically incorporated into a crystalline or amorphous oxide matrix, which increases chemical stability and limits its availability for selective extraction without intensifying processing conditions (Al-Dossari M. et al., 2024).

The most concentrated and technologically attractive source of REE is **waste from permanent magnetic materials**. In neodymium–iron–boron alloys, the main component forms the crystalline phase that determines the magnetic properties, most commonly $Nd_2Fe_{14}B$. **Dysprosium**, in turn, is introduced in smaller amounts and is distributed predominantly in near-surface regions of grains and along their boundaries, where it performs a function of structural stabilization at elevated temperatures.

In the initial materials, the chemical form of these elements corresponds to intermetallic phases; however, after products are taken out of service and during the storage of magnetic waste, partial oxidation occurs with the formation of oxides and mixed oxide–iron compounds, including Nd_2O_3, Dy_2O_3, and Fe-oxide phases such as Fe_2O_3 and Fe_2O_3. These secondary products are characterized by increased porosity and reactivity, which may accelerate the initial stages of dissolution but simultaneously alter process selectivity due to the formation of passivating shells and the redistribution of components across microstructural regions. **Samarium** in this group of streams is mainly associated with materials based on the samarium–cobalt system, where it is also present in an intermetallic state, most commonly as $SmCo_5$ and *Sm2Co17*, and exhibits higher thermal and chemical stability (Cherkezova-Zheleva Z. et al., 2024).

In battery and accumulator waste, REE are generally present at significantly lower concentrations and are more often fixed in an oxidized state, while their localization depends on the composition of specific batches and the degree of stream mixing. Within the technogenic systems considered, they may occur as impurities and local inclusions, as well as components of stable oxygen-containing compounds, which brings their chemical behavior closer to the oxide and secondary forms characteristic of certain electronic waste streams. For such flows, technologically significant factors include the stability of compounds in the presence of phosphorus- and fluorine-containing components, which may promote the formation of stable phases such as $REEPO_4$ and $REEF_3$, and a high impurity load, which determines the need for preliminary carrier separation and more stringent requirements for selective purification (Akhmetov N. et al., 2023).

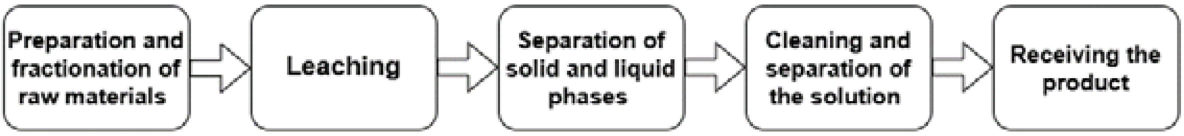
Thus, the distribution and chemical form of neodymium, dysprosium, and samarium in electronic waste, permanent magnets, and battery waste are determined by the type of technogenic material and its operational history. The identified differences define the choice of technological routes and limiting stages of extraction, including dissolution kinetics and requirements for selective separation.

Methods of Secondary Processing of REE

Secondary processing of REE from high-technology production waste requires consideration of their phase state, degree of oxidation, and the nature of their bonding with the material matrix. Neodymium, dysprosium, and samarium exhibit fundamentally different chemical behaviors, which predetermine the choice of processing route. In industrial practice, three basic classes of methods have been established, each possessing specific advantages and limitations.

Hydrometallurgical approaches are based on transferring the target components into an aqueous phase followed by selective separation and upgrading of the product to an industrially relevant quality (Binnemans K. & Jones P. T., 2023). This approach includes several important sequential operations (fig. 1).

Figure 1. *Stages of the Hydrometallurgical Approach*

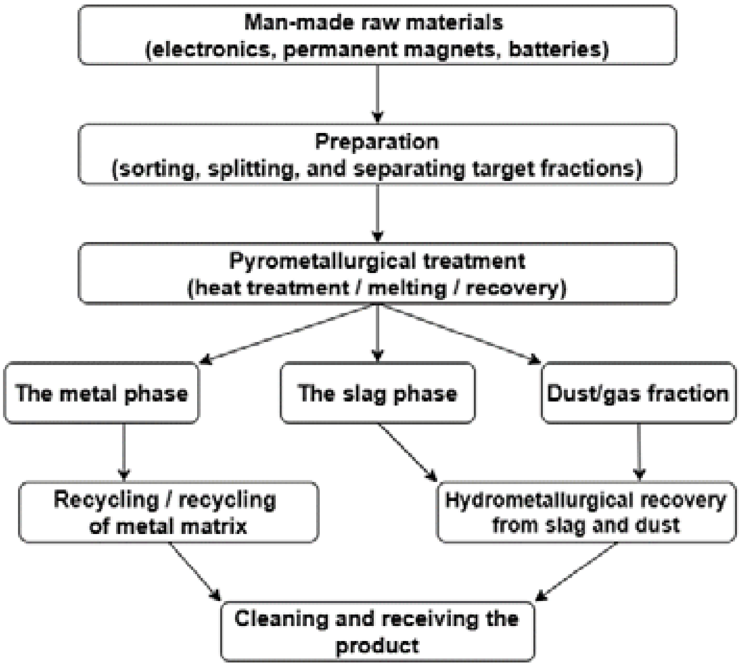


At the **preparation stage**, mechanical disintegration and, if necessary, fractionation of the material is performed, which increases the reactivity of the phases and reduces the effect of heterogeneity in the initial flow. This is followed by **leaching**, during which the target components are transferred into solution. The choice of acidic or alkaline media is determined by the type of matrix and the chemical form of the components, while a technologically significant limitation is the competitive dissolution of accompanying metals, which increases the load on subsequent purification stages. Next, **solid-liquid separation with residue washing is carried out**, which reduces losses of target components and stabilizes the solution composition for subsequent operations. The final part of the route includes **solution purification and separation, as well as the production of the target product**. Fluorine and phosphorus-containing components have a significant influence on all the listed stages. Their presence may stabilize target elements in poorly soluble forms, thereby increasing the requirements for process conditions and the depth of subsequent purification.

Pyrometallurgical methods rely on thermal treatment of the feed material and redistribution of components among phases during smelting, reduction, or high-temperature processing. Their technological advantage lies in high throughput and tolerance to feed heterogeneity (Raabe D., 2023). Mixed fractions can be processed without complete chemical dissolution, and separation is achieved through phase segregation between the metallic phase, slag, and gaseous components (fig. 2).

For REE, the main mechanism is their transition to certain phases during the melting process. Depending on the matrix composition and slag-forming additives, they may concentrate in the slag phase, forming a concentrate suitable for subsequent hydrometallurgical recovery. Thus, pyrometallurgy often serves as a stage of preliminary concentration and stabilization of composition during the processing of structurally complex waste.

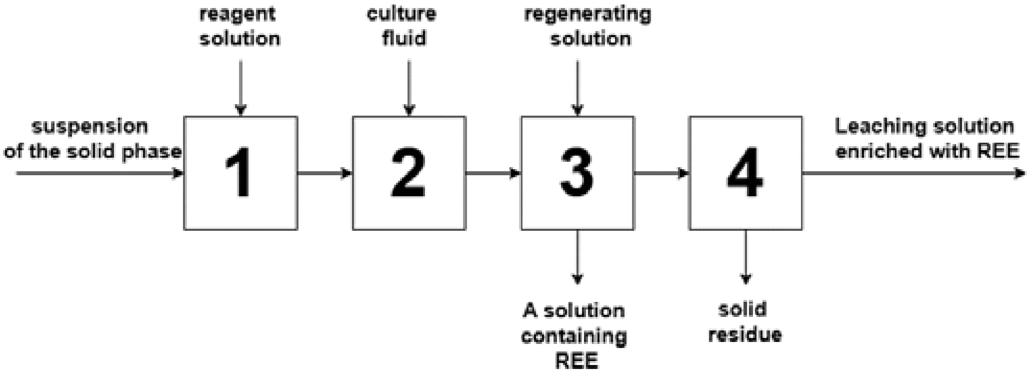
Figure 2. *Scheme of the Pyrometallurgical Approach*



The limitations of this approach are associated with high energy consumption and the need for advanced environmental infrastructure. Industrial feasibility is achieved primarily in the presence of large-scale material flows and access to high-temperature processing facilities.

Biological methods are based on the use of microorganisms or biogenic materials to mobilize REE from the solid phase or to selectively bind them from solutions. In **bioleaching**, the main mechanisms include the formation of organic acids, changes in redox conditions, and the formation of complexing compounds capable of transferring valuable elements into solution without the use of aggressive chemical reagents (fig. 3).

Figure 3. *Bioleaching Scheme*



Biosorption, by contrast, is focused on the recovery of REE from liquid phases through binding to functional groups of biopolymers and cell surfaces. This approach can be used as a stage of concentration or final purification (Shi S. et al., 2023).

A common feature of these approaches is a potentially lower environmental burden when the process is properly organized, as well as reduced requirements for equipment corrosion resistance. At the same time, they are limited by low process rates, high sensitivity to feed composition and environmental parameters, and the inhibiting effects of ionic impurities as well as fluorine and organic-containing compounds.

The technology selection matrix should take into account the type of waste and the predominant forms of occurrence of REE. These parameters determine where losses arise, and which stages become limiting (table 1).

Table 1. *Technological Routes Depending on Waste Type and Forms of Occurrence of REE (Balaram V., 2023; Zhao T. Y. et al., 2025)*

Waste stream	Dominant carrier phases and chemical forms of neodymium, dysprosium and samarium	Recommended recovery approach
Electronic waste	Localization in individual components; more often intermetallides, oxide/sorbed forms in fine fractions.	Increase the concentration of target elements by fractionation; then extract hydrometallurgically with subsequent purification.
Permanent magnet waste	Intermetallides; partially oxide/hydroxide surface forms.	Direct hydrometallurgical extraction is most effective; pyrometallurgy is appropriate as a concentration/stabilization stage in hybrid schemes.
Battery waste	More often trace/local; mainly sorbed/complex and oxide forms; stable phosphate-fluoride compounds are possible.	The soft stages of additional recovery/concentration and work on selected media are advisable; the final quality is achieved by chemical purification.

Overall, industially sustainable solutions are more often formed as **combined schemes**, since none of the method classes simultaneously addresses the tasks of concentration, selectivity, and production of a product with the required purity under high variability of technogenic streams. The most typical logic includes pre-concentration to reduce impurity load and increase the share of REE, followed by the main extraction stage and concluding with purification. Such a hybrid configuration makes it possible to simultaneously increase recovery rates, maintain selectivity with respect to iron, cobalt, and nickel, and reduce environmental risks through controlled handling of solutions, sludges, and gaseous emissions.

Circular Economy and the Effect on Business Sustainability

Secondary processing of REE within the logic of the circular economy allows for simultaneously increasing resource efficiency and reducing the operational risks of companies that use critical materials. For neodymium, dysprosium, and samarium, this is important not only from an environmental perspective, but also because waste recycling creates an additional source of raw materials and helps maintain access to them under conditions of price volatility and potential supply constraints.

A reduction in the cost of access to these components is achieved through **changes in the value creation chain**. In secondary processing, part of the costs is shifted to the collection, sorting, and preparation of waste, after which extraction is carried out from more concentrated technogenic fractions and from a smaller mass of material per unit of product. An additional advantage is associated with procurement controllability. The availability of an in-house or contract-based secondary stream reduces dependence on the spot market, simplifies planning, and makes costs more predictable, thereby reducing losses caused by supply disruptions.

Supply resilience is enhanced through **source diversification**. Secondary raw materials form an alternative supply channel tied to processing infrastructure and the geography of consumption rather than to deposits and primary processing capacities. At the same time, waste recycling reduces the burden on primary extraction, as part of demand is met through the return of materials into circulation. For businesses, this means lower environmental and regulatory risks, as well as more transparent material provenance, which is important for compliance with sustainable development requirements and supply chain management.

The implementation of such loops depends on **practical conditions of deployment**. It is essential to ensure the quality of input materials, specifically a predictable composition and impurity control, which is achieved through sorting and the separation of target fractions. Logistics of collection and the regularity of waste inflows are equally important, since without sufficient volumes it is difficult to ensure economic efficiency and stable capacity utilization. In addition, standardization and traceability are required. Finally, industrial safety is a mandatory condition, including the safe handling of reactive media, sludges, and dust fractions, as well as compliance with emission and disposal requirements.

Thus, secondary processing of REE within a circular economy model provides not only environmental benefits but also measurable business value by reducing raw material risks and increasing cost predictability. The most sustainable results are achieved when technological efficiency of extraction is combined with appropriate organizational conditions for implementation.

Conclusion

In modern high-technology industries, critical materials are increasingly considered not only as resources but also as factors of technological sustainability of production chains. With respect to technogenic waste, it has been shown that such waste forms a heterogeneous yet promising source of REE, primarily neodymium, dysprosium, and samarium. Their distribution and chemical state are determined by the type of technogenic material and operating conditions. Magnetic waste is characterized by high local concentrations and a predominance of intermetallic phases, whereas electronic and battery streams more often contain secondary oxides and stable compounds formed during oxidation and mechanical degradation.

A comparative analysis of processing approaches demonstrates that combined routes integrating feed pre-enrichment and fractionation with hydrometallurgical extraction followed by deep purification exhibit the highest industrial sustainability. The practical implementation of a circular economy in this field requires not only technological optimization but also the assurance of input material quality, stable collection logistics, stream standardization, and compliance with industrial safety requirements, which together reduce raw material risks, increase cost predictability, and decrease the burden on primary extraction.

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