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# Recovery and valorisation of rare earth elements in dust from mechanical pretreatment of waste printed circuit boards

Anđelka Popović [1], Predrag Kojić [1], Igor Antić [1], Borivoj Adnadjević [2], Miljan Šunjević [3*]

[1] Faculty of Technology Novi Sad, University of Novi Sad, Serbia
[2] Faculty of Physical Chemistry, University of Belgrade, Serbia
[3]Faculty of Technical Sciences, University of Novi Sad, Serbia

* Corresponding author E.mail: msunjevic@uns.ac.rs

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**Abstract**
Rare earth elements (REEs) are increasingly recognized as critical raw materials for advanced electronic, digital, energy and communication technologies. At the same time, the rapid growth of waste electronic equipment has created new opportunities for the recovery of critical elements from secondary resources. Waste printed circuit boards (WPCBs) are among the most valuable fractions of electronic waste, but the dust generated during their mechanical pretreatment is commonly regarded as a residual by-product with limited practical value. This study explores the redistribution and valorisation potential of REEs in dust produced during shredding and milling of WPCBs in an industrial recycling process. Two material streams were analysed: WPCBs with electronic components attached and WPCBs after component dismantling. Dust samples collected from the mechanical pretreatment stage were analysed by inductively coupled plasma mass spectrometry (ICP-MS) for 17 REEs and uranium. The results confirmed the presence of REEs in both investigated dust streams, with concentrations ranging from 0.10 to 133.8 mg/kg. The findings indicate that REEs are not completely transferred to conventional recyclable fractions during pretreatment, but partly redistributed into the fine dust fraction. Consequently, WPCB dust should be considered not only as a waste management and occupational exposure issue, but also as a potential secondary source of critical elements. The research provides a circular economy approach in which an unavoidable by-product of recycling is further characterized, separated and potentially valorised.

**Keywords***:* *Rare Earth Elements, Waste Printed Circuit Boards, mechanical pretreatment, and circular economy.*

## Introduction

21st century will be characterized by Rare Earth Elements - REEs (individually and in combination with other REEs). The Japan science society marked REEs as the seeds of technology, while in the USA they are considered as technology metals (Wang, 2026). Rare earth elements are critical raw materials widely used in modern electronic devices due to their unique magnetic, optical, and electrochemical properties (Duchna and Cieślik, 2022). REEs are the components in more than 200 products with a wide range of applications, including batteries, catalysts, ceramics, electronics, glass, lasers, medicine, polishes, and metallic alloys (including permanent magnets) (Ascenzi et al., 2020; Balaram, 2019; Charalampides et al., 2015; Sager and Wiche, 2024). Elements such as neodymium (Nd), dysprosium (Dy), praseodymium (Pr), gadolinium (Gd), and yttrium (Y) are essential components of permanent magnets, electronic circuits, sensors, displays, and communication technologies (Baranovskaya et al., 2021; Hossain et al., 2021; Jannah et al., 2020). A significant use of REEs can be found in array of defence applications, including actuators of guided missiles and other munitions, electronic displays, fibre optics, guidance systems for aircrafts and drones, lasers, and optics (Jannah et al., 2020). All of the mo-

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dern common high-tech consumer products such as smart phones, computer hard drives, electric and hybrid vehicles, and monitors are possible due to REEs. Rare Earth Elements have become irreplaceable part of modern technology and our lives with their unique magnetic, phosphorescent, and catalytic properties. The increasing demand for these materials, combined with supply chain vulnerabilities and limited primary resources, has intensified global interest in secondary recovery routes.

## REEs in eWaste and circular economy

Waste printed circuit boards (WPCBs) represent one of the most valuable fractions of electronic waste due to their complex composition and content of strategic metals. While recycling efforts have traditionally focused on copper and precious metals, increasing attention has recently been directed toward the recovery of critical raw materials, including REEs (Ghosh et al., 2015; Popović et al., 2022; Wang et al., 2017). During mechanical pretreatment operations such as shredding and milling, a fine dust fraction is inevitably generated. This fraction is generally considered a process residue and is commonly disposed of or stored despite containing potentially valuable constituents. From a circular economy perspective, the valorisation of such by-product streams is of particular importance. Unlike primary resources, the dust fraction is already generated within existing recycling systems and therefore does not require additional collection, extraction, or pre-processing operations. Recovery of REEs from this material could contribute to improved resource efficiency, reduction of waste storage requirements, and enhancement of the overall sustainability of WPCB recycling processes. Although several studies have investigated the occurrence of REEs in electronic waste, limited information is available regarding their redistribution into dust fractions generated during mechanical pretreatment (Ghosh et al., 2015; Popović et al., 2022; Wang et al., 2017). Understanding the concentration and distribution behaviour of REEs in these process streams is essential for evaluating their potential as secondary resources and for designing future recovery strategies.

## Management of eWaste

The increasing concern about eWaste (electronic Waste) activities has become serious issue. Management of eWaste has shown some improvement in recent years, with the minimal proportion of recycled in comparison to the total produced eWaste. Good example for eWaste management is Denmark with 12.4 kg/cap/year collected corresponding to 45% of total electrical and electrical equipment produced (Parajuly et al., 2017). The eWaste is commonly disassembled manually (e.g. separation of a battery in a laptop) and sorted before further processing. In Europe, most successful management system has been achieved by Switzerland, Norway, and Sweden with recycling rate of 49%. In 2010 around 9.5Mt eWaste has been produced with 35% coming from Europe (Parajuly et al., 2020; Selin). New circular economy policy of the European Union is expected to enhance recycling of eWaste. The Republic of Serbia is an example of a transitional eWaste recycling situation in Europe. Serbia harmonized and adopted parts of the WEEE Directive 2012/19 requirements, but the eWaste management practices are still quite underdeveloped, partly due to insufficient collection infrastructure, including equipment and collection points. The production rate of eWaste is estimated at 11.1 kg/cap/year, corresponding to around 80,000 tons annually (Berežni et al., 2021; Nišić et al., 2024). The majority of eWaste is still mixed with municipal solid waste at landfill sites, causing significant environmental and health issues. Estimation is that around 20% of eWaste has been formally recycled in Serbia. In the recycling process, valuable and hazardous components are separated manually and extracted using mechanical treatment processes. Some extracted components are used as secondary raw materials, while others are sold to other countries for further recycling, as the typical example of circular economy. Electronic and IT industry are basis for progress of modern society, which requires REEs materials for sustaining technology and development, understanding that REEs materials are scarce by its nature, strategic circular economy approach is essential.

## Materials and Methods

The research was divided in three segments: detection, recovery and valorisation. Detection refers to the analytical confirmation of REEs in the dust generated during mechanical pretreatment of WPCBs. Detection was performed using ICP-MS after microwave-assisted acid digestion of dust samples. Recovery refers to the identification of a technically relevant REE fraction that may be suitable for further treatment. Valorisation refers to the possible transformation of mechanically generated WPCB dust from a residual by-product into a secondary raw material within an integrated recycling chain. In this context, valorisation includes not only the

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potential extraction of REEs, but also improved waste management, separate dust collection, reduced loss of critical elements and increased material efficiency of WPCB recycling.

**WPCB origin**

The examined WPCB material was obtained from an accredited electronic waste recycling company located in Novi Sad, Serbia. The company performs mechanical pretreatment of electronic waste as part of the recycling chain for the recovery of valuable metallic and non-metallic fractions. The input material consisted of mixed WPCBs collected from the local Serbian electronic waste stream. The investigated material was heterogeneous and included printed circuit boards originating from computers, laptop computers and mobile phones. The approximate composition of the input stream was 80% computer printed circuit boards, 10% laptop boards and 10% mobile phone boards. Two experimental WPCB mixtures were prepared for the purpose of comparing the effect of component presence on REE redistribution into dust. Mix I consisted of WPCBs with electronic components attached. This mixture included boards with processsors, memory modules, control circuits, chips and other surface-mounted or attached components. This mixtu-re represents the mechanical pretreatment of complete WPCBs. Mix II consisted of WPCBs after dismantling of major electronic components. In this mixture, detachable components such as processors, memory modules, control circuits, chips and other larger electronic parts were removed before mechanical processing. This mixture represents a pretreatment scenario in which component removal is performed before shredding and milling. The use of a mixed WPCB stream was selected in order to reflect realistic industrial recycling conditions rather than a narrowly controlled laboratory material. The boards were processed as received from the recycling stream and were not washed prior to mechanical treatment, in order to avoid moisture-related changes in milling behaviour and dust generation.

**Mechanical pretreatment, dust generation and sampling**

Mechanical pretreatment was performed under industrial recycling conditions (Fig, 1.). The process included preliminary crushing, milling and particle-size reduction, followed by separation operations. The WPCBs were first reduced to smaller pieces and subsequently milled using a knife mill to obtain particles of approximately 3 mm. During shredding and milling, fine particulate material was released from the WPCB structure. The dust was extracted through the industrial cyclone and filtration system. Dust samples were collected separately from the mechanical pretreatment of Mix I and Mix II. The generated dust originated from fragmentation and abrasion of metallic coatings, soldering residues, glass fibres, ceramic components, polymerric matrix material and electronic components. After collection, the dust samples were transferred into clean, sealed containers to prevent contamination, loss of fine particles and moisture uptake. The samples we-

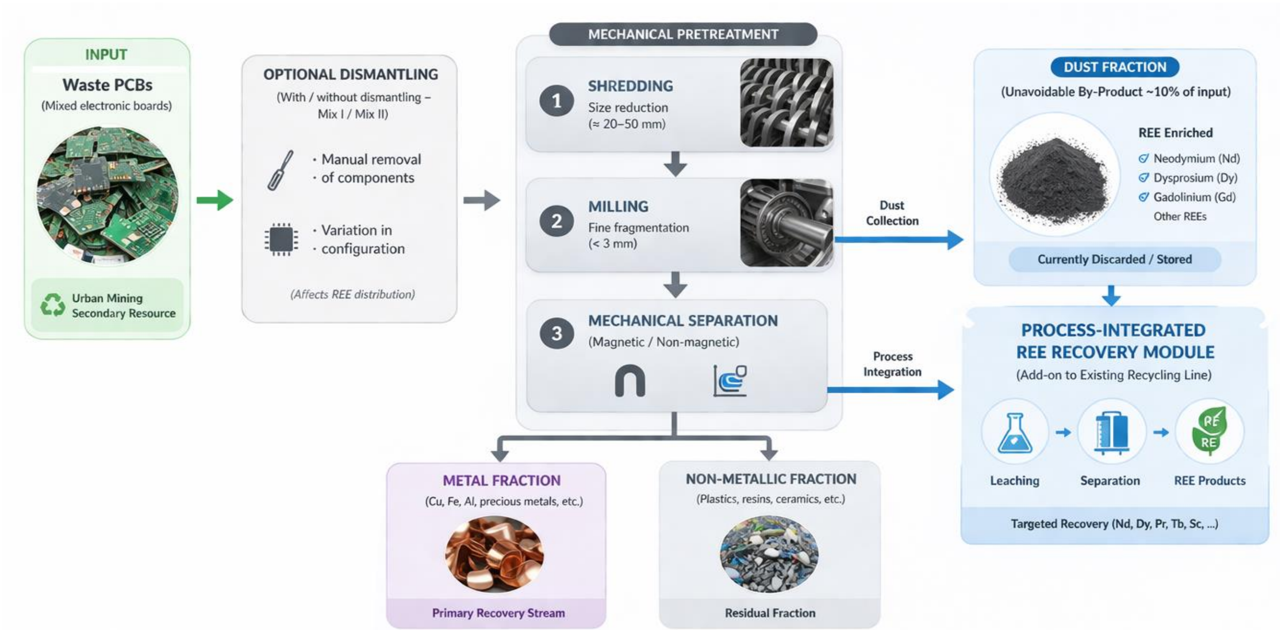


**Figure 1.** *WPCB recycling process*

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re labelled according to the corresponding input mixture and stored under dry conditions until laboratory preparation and chemical analysis. The collected dust represented the fine particulate by-product of WPCB mechanical pretreatment. This fraction was selected because it is usually not the primary target of recycling operations, although it may contain critical elements redistributed from the original WPCB structure during mechanical fragmentation.

### Determination of REEs

The REEs sample testing was performed at the Laboratory for Chemical Examination (HTK) of the Institute for Mining and Metallurgy Bor, Serbia. The analysis followed the laboratory's accredited method J.g.2:2014, adapted to the complex matrix of dust generated during the mechanical pretreatment of waste printed circuit boards (WPCBs). In the present study, J.g.2:2014 refers to a laboratory analytical procedure combining microwave-assisted acid digestion of the solid sample with subsequent elemental determination by Agilent 7500 Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Approximately 0.1 g of each homogenized dust sample was accurately weighed and transferred into a microwave digestion vessel. Initially, 8 mL of an acid mixture containing concentrated hydrochloric and nitric acids in a volumetric ratio of 3:1 was added. The samples were subjected to the first microwave digestion stage at 220 °C for 15 min using an ETHOS microwave digestion system. After cooling, 2 mL of hydrofluoric acid was added to improve the dissolution of silicate, glass-fibre and other refractory mineral phases present in the WPCB dust. A second microwave digestion stage was then performed at 220 °C for 20 min. Following the second digestion stage, the samples were cooled and treated with 20 mL of boric acid ($H_3BO_3$) solution. This treatment was applied to complex residual fluoride ions and minimize fluoride-related interferences or damage to the analytical system. The resulting solutions were cooled and diluted to a final volume of 50 mL using deionized water.The concentrations of REEs were determined using an Agilent 7500 inductively coupled plasma mass spectrometer. ICP-MS was selected because of its high sensitivity, multielement capability and suitability for determining trace and ultra-trace concentrations in complex waste-derived matrices. The investigated analytes included selected lanthanides, scandium and yttrium. Uranium was determined separately because of its environmental relevance and its possible association with mineral and particulate residues in WPCB dust;

**Table 1**. *Sampling results (in mg/kg).*

| Element | Oreas 924 | CRM | Ratio | MIX I | MIX II |
|---|---|---|---|---|---|
| Sc | 13.5 | 13.2 | 1.02 | 3.2 | 3.3 |
| Y | 26.1 | 26.4 | 0.99 | 27.0 | 6.9 |
| La | 42.7 | 42.5 | 1.00 | 18.7 | 14.8 |
| Ce | 85.5 | 85.0 | 1.01 | 26.3 | 29.2 |
| Pr | 9.2 | 9.6 | 0.96 | 9.6 | 3.4 |
| Nd | 34.1 | 36.0 | 0.95 | 133.8 | 24.9 |
| Sm | 6.4 | 6.7 | 0.94 | 14.9 | 2.8 |
| Eu | 1.3 | 1.4 | 0.95 | 5.0 | 2.2 |
| Gd | 5.8 | 5.8 | 1.01 | 10.1 | 2.2 |
| Tb | 0.8 | 0.9 | 0.96 | 0.66 | 0.26 |
| Dy | 4.7 | 5.1 | 0.93 | 12.4 | 2.2 |
| Ho | 0.9 | 1.0 | 0.91 | 10.1 | 1.2 |
| Er | 2.7 | 2.9 | 0.93 | 1.4 | 0.73 |
| Tm | 0.36 | 0.40 | 0.90 | <0.10 | <0.10 |
| Yb | 2.4 | 2.6 | 0.91 | 0.65 | 0.54 |
| Lu | 0.4 | 0.4 | 0.90 | 0.12 | 0.10 |
| Th | 14.8 | 16.6 | 0.89 | 4.8 | 5.8 |
| U | 2.7 | 3.1 | 0.89 | 1.0 | 1.2 |

however, uranium was not classified as an REE. Quality assurance and quality control were conducted using the OREAS 924 Certified Reference Material (CRM). The reference material was analyzed in triplicate under the same analytical conditions as the WPCB dust samples. Analytical accuracy was evaluated by comparing the measured concentrations with the corresponding certified values. Recovery was calculated according to:

$$\text{Recovery (\%)} = C_{measured} \, / \, C_{certified} * 100 \qquad [1]$$

where $C_{measured}$ is the experimentally determined concentration and $C_{certified}$ is the certified concentration of the corresponding element in OREAS 924. These quality-control measurements were used to assess the suitability of the modified J.g.2:2014 procedure for the heterogeneous WPCB dust matrix. The validated analytical results were used to compare the concentrations of individual REEs in dust samples generated from Mix I and Mix II and to assess whether pretreatment dust represents a potentially significant carrier of critical elements. All concentrations are reported in mg/kg on a dry-mass basis (Table 1).

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**Recovery and valorisation assessment**

The recovery and valorisation assessment was performed in order to evaluate whether dust generated during mechanical pretreatment of WPCBs can be considered a potentially recoverable REE-bearing fraction rather than only a residual waste stream. The assessment was based on three methodological elements: distinction between detection, recovery and valorisation; preliminary mass-balance consideration of the dust fraction; and definition of criteria for evaluating recovery and valorisation potential. A preliminary mass-balance approach was used to estimate the relevance of the dust fraction within the WPCB pretreatment process. Based on operational experience from the recycling facility, the dust fraction generated during mechanical pretreatment can represent approximately 10% of the total mass of treated WPCBs, depending on input material composition, moisture content, milling intensity and efficiency of dust collection. The calculation was based on the measured concentration of each REE and the corresponding mass of collected or estimated dust material.

The potential mass of an individual REE was calculated as:

$$mREE_i(mg)=m_{sample}(kg)\times CREE_i(mg/kg) \qquad [2]$$

where $mREE_i$ is the estimated mass of an individual rare earth element, $m_{sample}$ is the mass of the analysed dust fraction, and $CREE_i$ is the measured concentration of the corresponding REE. Selected calculation was used only as a preliminary indicator of REE material potential. It does not represent actual recovery yield, since extraction efficiency, leaching behavior, separation efficiency and process losses were not experimentally determined in the research.

**Recovery priority ranking**

The Recovery Priority Ranking was developed to identify which REEs should be considered the most relevant targets for future recovery studies. The ranking was based on four criteria: measured concentration, technological importance, criticality and consistency of occurrence in the investigated dust samples. The recovery priority score was calculated as:

$$RPS_i=w_1C_i+w_2T_i+w_3K_i+w_4O_i \qquad [3]$$

where $RPS_i$ is the recovery priority score of element i; $C_i$ is the normalized concentration score of element iii; $T_i$ is the technological importance score; $K_i$ is the criticality score; $O_i$ is the occurrence score across the examined samples; and $w_1$, $w_2$, $w_3$ and $w_4$ are weighting factors. For the research purposes, the following weighting factors may be applied:

$$RPS_i=0.40C_i+0.25T_i+0.25K_i+0.10O_i \qquad [4]$$

The selected weighting gives the highest importance to measured concentration, while also considering technological relevance, critical raw material importance and occurrence in both investigated dust samples. The concentration score was normalized as:

$$C_i=CREE_i/CREE_{max}\times 5 \qquad [5]$$

where $CREE_i$ is the measured concentration of element i, and $CREE_{max}$ is the highest measured REE concentration in the dataset. This converts concentration into a score from 0 to 5. The occurrence score was assigned as 5 if the element was detected in both Mix I and Mix II, 3 if the element was detected in one mix only and 0 if the element was below detection limit. The technological importance and criticality scores were assigned on a 1–5 scale, where 1 represents low relevance and 5 represents very high relevance. The final recovery priority was classified as: 4.0-5.0 High priority, 2.5-3.9 Medium priority and <2.5 Low priority. Elements with high $RPS_i$ values were considered the most relevant candidates for future leaching, separation and recovery experiments. The ranking does not indicate immediate economic feasibility, but provides a structured basis for selecting target REEs for further recovery-oriented research.

## Results and Discussion

Mechanical pretreatment of WPCBs resulted in the formation of a fine dust fraction generated during shredding and milling. The fraction is normally collected by the cyclone/filter system and is commonly treated as a residual by-product of recycling. However, because the dust originates from mechanical fragmentation of metallic coatings, soldering materials, glass fibers, ceramics, polymeric matrix and electronic components, it may contain valuable and critical elements. Operational experience from the recycling facility indicates that the dust fraction can account for approximately 10% of the total treated WPCB mass, depending on input material composition, moisture content and milling conditions. Therefore, this fraction should be considered in material flow analysis and not excluded from recovery-oriented assessment.

**REE concentration in WPCB dust**

The ICP-MS analysis confirmed the presence of rare earth elements in both dust samples generated during

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**Table 2.** *Element concentration in the eDust*

| Element | Mix I, mg/kg | Mix II, mg/kg |
|---|---|---|
| Sc | 3.20 | 3.30 |
| Y | 27.00 | 6.90 |
| La | 18.70 | 14.80 |
| Ce | 26.30 | 29.20 |
| Pr | 9.60 | 3.40 |
| Nd | 133.80 | 24.90 |
| Sm | 14.90 | 2.80 |
| Eu | 5.00 | 2.20 |
| Gd | 10.10 | 2.20 |
| Tb | 0.66 | 0.26 |
| Dy | 12.40 | 2.20 |
| Ho | 10.10 | 1.20 |
| Er | 1.40 | 0.73 |
| Tm | <0.10 | <0.10 |
| Yb | 0.65 | 0.54 |
| Lu | 0.12 | 0.10 |
| ΣREE | 274.43 | 94.63 |
| Th | 4.80 | 5.80 |
| U | 1.00 | 1.20 |

the mechanical pretreatment of WPCBs. The results in Table 2. show clear differences between Mix I, representing WPCBs with attached components, and Mix II, representing WPCBs after component dismantling. This indicates that the presence of electronic components has a strong influence on the redistribution of selected REEs into the fine dust fraction. The total REE concentration was substantially higher in Mix I than in Mix II. Mix I contained approximately 274.43 mg/kg of total REEs, while Mix II contained approximately 94.63 mg/kg. Therefore, the REE concentration in dust from Mix I was approximately 2.9 times higher than in Mix II. The dominant REE in Mix I was Nd, with 133.8 mg/kg, representing almost half of the total REE content in this sample. This is particularly important because Nd is one of the most technologically relevant REEs due to its use in permanent magnets, electric motors and advanced electronic applications. Other important elements in Mix I included Y at 27.0 mg/kg, Ce at 26.3 mg/kg, La at 18.7 mg/kg, Sm at 14.9 mg/kg and Dy at 12.4 mg/kg. The presence of Nd, Pr, Sm and Dy indicates that the dust fraction may contain magnet-related REEs of potential recovery interest. In Mix II, the dominant elements were Ce, Nd, La and Y, although at generally lower concentrations than in Mix I. Ce reached 29.2 mg/kg, slightly higher than in Mix I, while Nd decreased sharply from 133.8 mg/kg in Mix I to 24.9 mg/kg in Mix II. This decrease suggests that attached electronic components strongly contribute to Nd redistribution into the dust fraction during mechanical pretreatment. Similar reductions were observed for Y, Pr, Sm, Gd, Dy and Ho. The comparison between the two mixtures indicates that dismantling of electronic components before shredding and milling significantly reduces the total REE concentration in the generated dust. This suggests that a considerable portion of REEs, especially Nd and other magnet-related or component-associated elements, originates from attached electronic components rather than only from the board substrate. However, the continued presence of REEs in Mix II shows that the remaining WPCB structure, including glass-fibre matrix, coatings, ceramic particles, soldering residues and fine non-metallic fractions, may also contribute to REE occurrence in pretreatment dust. Thorium and uranium were not included in the total REE calculation, but their presence is relevant for environmental and waste management interpretation. Th ranged from 4.8 to 5.8 mg/kg, while U ranged from 1.0 to 1.2 mg/kg. Although these values are relatively low, they confirm that pretreatment dust is a chemically complex fraction requiring controlled handling, proper storage and further assessment before recovery or disposal. The combined concentration and mass-balance interpretation shows that WPCB pretreatment dust is not only a residual by-product, but a potentially relevant secondary material. The higher REE content in Mix I suggests that processing complete boards may concentrate more REEs in the dust fraction, while component dismantling reduces but does not eliminate REE presence. The finding is important for designing future recovery strategies, because it shows that dust management should be integrated with decisions on dismantling, separation and downstream treatment.

**Recovery priority ranking**

The recovery priority ranking was applied to identify which REEs detected in WPCB pretreatment dust should be considered the most relevant targets for future recovery studies. The ranking was based on a combination of measured concentration, technological importance, criticality and occurrence in the investigated mixtures. The approach was used because the most abundant REE is not always the most strategically important, while some elements with moderate or low concentrations may still be relevant because of their role in high-value technologies. The

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ranking combines both material availability and technological relevance. The highest recovery priority was assigned to elements that showed high concentrations in the dust and strong industrial importance. In the research, Nd clearly has shown as the most important target element. It had the highest measured concentration, reaching 133.8 mg/kg in Mix I, and it is one of the most important REEs for permanent magnets, electric motors and advanced electronic technologies. For this reason, Nd should be considered the primary candidate for future recovery-oriented experiments. Other elements with relevant recovery potential included Y, Ce, La, Dy, Pr, Sm and Gd. Y, Ce and La were present in relatively high concentrations, while Dy, Pr and Sm are especially important because of their use in magnet-related applications. Although Tb was detected at low concentration, it remains relevant from a strategic perspective due to its high technological importance and criticality. The calculated ranking (Table 3.) shows that the most promising recovery targets from WPCB dust are Nd, Ce, La and Y, followed by Dy, Pr, Sm, Gd and Sc. Elements such as Tb, Eu and Ho may be considered secondary targets, especially if they can be co-recovered together with more abundant REEs during future processing. The calculated ranking confirms that Nd has the strongest recovery potential in the investigated dust, due to its dominant concentration and high technological relevance. Although Ce, La and Y have lower criticality than Nd, their relatively high concentrations and broad industrial applications make them important recovery candidates. Dy and Pr have lower concentrations but remain relevant because of their high importance in permanent magnet technologies. The results show that some low-concentration elements, such as Tb and Sc, should not be automatically excluded from future recovery considerations. Their concentration in the dust is limited, but their technological importance and criticality justify monitoring them in future leaching and separation studies, particularly if they can be recovered together with more abundant REEs. The recovery priority ranking indicates that future experimental work should primarily focus on Nd, followed by Ce, Y, La, Dy and Pr. The ranking does not demonstrate economic feasibility or actual recovery efficiency, but it provides a transparent basis for selecting target REEs for further leaching, separation and valorisation studies.

**Table 3**
*Calculated Recovery Priority Ranking (Mix I and II are given in mg/kg)*

| Element | Mix I | Mix II | C | T | K | O | RPS | Priority |
|---|---|---|---|---|---|---|---|---|
| Nd | 133.80 | 24.90 | 5.00 | 5 | 5 | 5 | 5.00 | High |
| Ce | 26.30 | 29.20 | 1.09 | 4 | 4 | 5 | 3.94 | Medium |
| La | 18.70 | 14.80 | 0.70 | 4 | 4 | 5 | 3.78 | Medium |
| Y | 27.00 | 6.90 | 1.01 | 4 | 4 | 5 | 3.90 | Medium |
| Dy | 12.40 | 2.20 | 0.46 | 5 | 5 | 5 | 3.18 | Medium |
| Pr | 9.60 | 3.40 | 0.36 | 5 | 5 | 5 | 3.14 | Medium |
| Sm | 14.90 | 2.80 | 0.56 | 4 | 4 | 5 | 3.72 | Medium |
| Gd | 10.10 | 2.20 | 0.38 | 4 | 4 | 5 | 3.65 | Medium |
| Sc | 3.20 | 3.30 | 0.12 | 5 | 5 | 5 | 3.05 | Medium |
| Eu | 5.00 | 2.20 | 0.19 | 4 | 4 | 5 | 3.58 | Medium |
| Tb | 0.66 | 0.26 | 0.02 | 5 | 5 | 5 | 3.00 | Medium |
| Ho | 10.10 | 1.20 | 0.38 | 3 | 3 | 5 | 2.65 | Medium |
| Er | 1.40 | 0.73 | 0.05 | 3 | 3 | 5 | 2.52 | Medium |
| Yb | 0.65 | 0.54 | 0.02 | 2 | 2 | 5 | 1.51 | Low |
| Lu | 0.12 | 0.10 | 0.00 | 2 | 2 | 5 | 1.50 | Low |
| Tm | <0.10 | <0.10 | 0.00 | 2 | 2 | 0 | 1.00 | Low |

**Valorisation potential in WPCB recycling**

The obtained results indicate that dust generated during mechanical pretreatment of WPCBs should not be considered only as a residual by-product, but also as a potentially relevant secondary material within the recycling chain. Although the dust fraction is usually treated as a problematic residue, the presence of REEs confirms that part of the critical material content of WPCBs is redistributed into this fraction during shredding and milling. From the perspective of WPCB recycling, valorisation potential is based on three main aspects: the chemical value of the dust, its availability as

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an already generated by-product, and its possible integration into existing recycling processes. The dust does not require additional primary extraction or separate collection from consumers, because it is already formed during industrial pretreatment and can be collected through cyclone and filtration systems. This gives the fraction practical relevance for circular economy-oriented recycling. The higher total REE concentration in Mix I suggests that dust generated from WPCBs with attached components has stronger valorisation potential than dust generated after component dismantling. Mix I contained 274.43 mg/kg of total REEs, while Mix II contained 94.63 mg/kg. The difference indicates that attached components contribute significantly to REE enrichment in the dust fraction. However, the presence of REEs in Mix II also shows that the remaining board substrate, glass-fibre matrix, soldering residues, coatings and fine non-metallic particles may still act as carriers of REEs. The most important valorisation target identified in the research is Nd, which reached 133.8 mg/kg in Mix I. The element has high technological relevance because of its use in permanent magnets, electric motors and advanced electronic devices. Other relevant elements include Ce, Y, La, Pr, Dy, Sm and Gd. Ce, La and Y are important because of their relatively higher occurrence and broad industrial applications, while Pr and Dy are particularly relevant for magnet-related technologies. Therefore, the dust fraction may have value not only because of total REE content, but also because it contains elements with strategic technological importance.

## Conclusions

The research unveiled that dust generated during mechanical pretreatment of WPCBs is not only a residual by-product, but also a relevant REE fraction. The total REE concentration was significantly higher in dust from WPCBs with attached components (Mix I: 274.43 mg/kg) than in dust from dismantled boards (Mix II: 94.63 mg/kg), indicating that attached electronic components strongly influence REE redistribution into the fine dust fraction. From a waste management and circular economy perspective, WPCB pretreatment dust should be considered a potential secondary raw material rather than a waste fraction only. Its separate collection and characterization could reduce the loss of critical elements and improve the overall material efficiency of WPCB recycling. However, the results represent a preliminary valorisation assessment. Further research should include leaching experiments, separation tests, recovery efficiency analysis, environmental risk assessment and techno-economic evaluation. The findings confirm that WPCB pretreatment dust is an overlooked fraction with potential for REE recovery and valorisation within electronic waste recycling systems.

### Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## References

ASCENZI P., BETTINELLI M., BOFFI A., BOTTA M., DE SIMONE G., LUCHINAT C., MARENGO E., MEI H., AIME S. (2020) Rare earth elements (REE) in biology and medicine. Rendiconti Lincei. Scienze Fisiche e Naturali, 31:821-833. https://doi.org/10.1007/s12210-020-00930-w

BALARAM V. (2019) Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geoscience Frontiers, 10:1285-1303. https://doi.org/10.1016/j.gsf.2018.12.005

BARANOVSKAYA V.B., KARPOV YU.A., PETROVA K.V., KOROTKOVA N.A. (2021) Actual trends in the application of rare-earth metals and their compounds in the production of magnetic and luminescent materials: A review. Russ. Journal Non-ferrous Metals, 62:10-31 https://doi.org/10.3103/S1067821221010041

BEREŽNI I., CASTRO F.D., BATINIĆ B., VACCARI M., STANISAVLJEVIC N. (2021) WEEE treatment and system management in Italy and Serbia: A comparison. Waste Management and Research, 39:1302-1316. https://doi.org/10.1177/0734242X211050195

CHARALAMPIDES G., VATALIS K.I., APOSTOPLOS B., PLOUTARCH-NIKOLAS B. (2015) Rare earth elements: Industrial applications and economic dependency of Europe. Procedia Economics and Finance, 24:126-135. https://doi.org/10.1016/S2212-5671(15)00630-9

DUCHNA M., CIEŚLIK I. (2022) Rare earth elements in new advanced engineering applications. In: Aide M.T. (ed.), Rare Earth Elements - Emerging Advances, Technology Utilization, and Resource Procurement. IntechOpen. https://doi.org/10.5772/intechopen.109248

GHOSH B., GHOSH M.K., PARHI P., MUKHERJEE P.S., MISHRA B.K. (2015) Waste printed circuit boards recycling: An extensive assessment of current status. Journal

DOI: 10.60923/issn.2281-4485/25766

of Cleaner Production, 94:5-19.
https://doi.org/10.1016/j.jclepro.2015.02.024

HOSSAIN M.K., AHMED M.H., KHAN M.I., MIAH M.S., HOSSAIN S. (2021) Recent progress of rare earth oxides for sensor, detector, and electronic device applications: A review. ACS Applied Electronic Materials, 3:4255-4283.
https://doi.org/10.1021/acsaelm.1c00703

JANNAH N.F., ARITONANG S., SUNARDI S., ADIPRAYOGA S.N., RAJAK D.D.A. (2020) Rare earth metals utilization opportunities in the development of Indonesia defense industry technology. IOP Conference Series: Materials Science and Engineering, 850:012050.
https://doi.org/10.1088/1757-899X/850/1/012050

NIŠIĆ D., LUKIĆ B., GORDIĆ Z., PANTELIĆ U., VUKIĆEVIĆ A. (2024) E-waste management in Serbia, focusing on the possibility of applying automated separation using robots. Applied Sciences, 14:5685.
https://doi.org/10.3390/app14135685

PARAJULY K., FITZPATRICK C., MULDOON O., KUEHR R. (2020) Behavioral change for the circular economy: A review with focus on electronic waste management in the EU. Resources, Conservation and Recycling: X, 6:100035.
https://doi.org/10.1016/j.rcrx.2020.100035

PARAJULY K., HABIB K., LIU G. (2017) Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management. Resources, Conservation and Recycling, 123:85-92.
https://doi.org/10.1016/j.resconrec.2016.08.004

POPOVIĆ A., MANOJLOVIĆ V., ADNADJEVIĆ B., PETROVIĆ J., KAMBEROVIĆ Ž., RANITOVIĆ M. (2022) Recovery of rare-earth elements from printed circuit boards by vacuum pyrolysis and multiple electrostatic separation. Processes, 10:1152.
https://doi.org/10.3390/pr10061152

SAGER M., WICHE O. (2024) Rare earth elements (REE): Origins, dispersion, and environmental implications - A comprehensive review. Environments, 11:24.
https://doi.org/10.3390/environments11020024

SELIN H., VANDEVEER S.D. (2006) Raising global standards: Hazardous substances and e-waste management in the European Union. Environment: Science and Policy for Sustainable Development, 48:6-18.
https://doi.org/10.3200/ENVT.48.10.6-18

WANG H., ZHANG S., LI B., PAN D., WU Y., ZUO T. (2017) Recovery of waste printed circuit boards through pyrometallurgical processing: A review. Resources, Conservation and Recycling, 126:209-218.
https://doi.org/10.1016/j.resconrec.2017.08.001

WANG Q. (2026) Nature-positive rare earth governance: Japan's strategy in a China-dominated system. Resources Policy, 113:105852.
https://doi.org/10.1016/j.resourpol.2026.105852