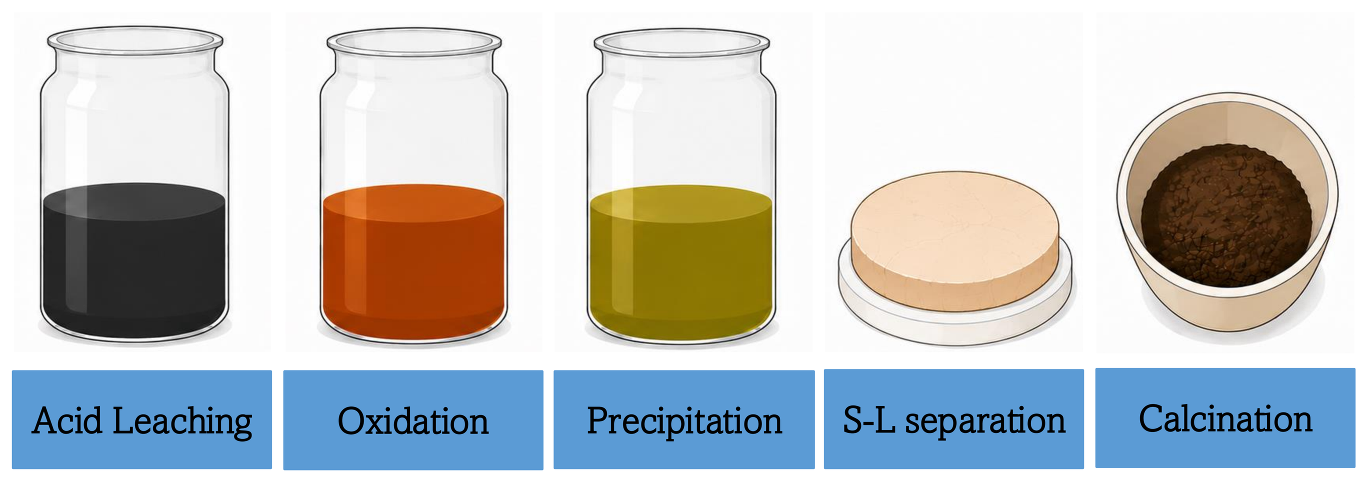
Sustainable Hydrometallurgical Recovery of REE from EoL NdFeB Magnets: Pilot-Scale Validation and Environmental Assessment

Ana Paula Silva[1], Nina Lokar[2], Blaž Likozar[2], Dimitra Skentzou[3], José Pinheiro-Torres[1], Bruna Silva[1]*

[1]N9VE – Nature, Ocean and Value, Lda, Porto, Portugal
[2] National Institute of Chemistry, Department of Catalysis and Chemical Reaction Engineering, Hajdrihova 19, SI-1000, Ljubljana, Slovenia
[3] SE&C IKE, 11528 Athens, Greece
*E-mail: aps@n9ve.pt

Introduction

Rare earth elements (REE), particularly neodymium (Nd), praseodymium (Pr) and dysprosium (Dy), are essential for high-performance permanent magnets (PM) used in electric vehicles, wind turbines and advanced electronics[1]. The European Union (EU) is highly dependent on imported REE, with approximately 98% of its supply originating from China, creating strategic and supply-chain vulnerabilities. At the same time, primary REE extraction is associated with significant environmental impacts, while less than 1% of REE are currently recycled within the EU[2]. Recycling end-of-life (EoL) NdFeB permanent magnets can therefore reduce environmental impacts of primary production, improve resource circularity and recover critical materials from secondary sources. Developing efficient recycling technologies is consequently essential to strengthening the resilience of European REE supply chain and supporting the objectives of the Critical Raw Materials Act (CRMA)[3].



Aims

- Develop a sustainable hydrometallurgical process for REE recovery.
- Validate the process at pilot scale.
- Produce high-purity rare earth oxides (REO).
- Asess and reduce the environmental footprint of the process.

Results

1. High purity REO (99%)

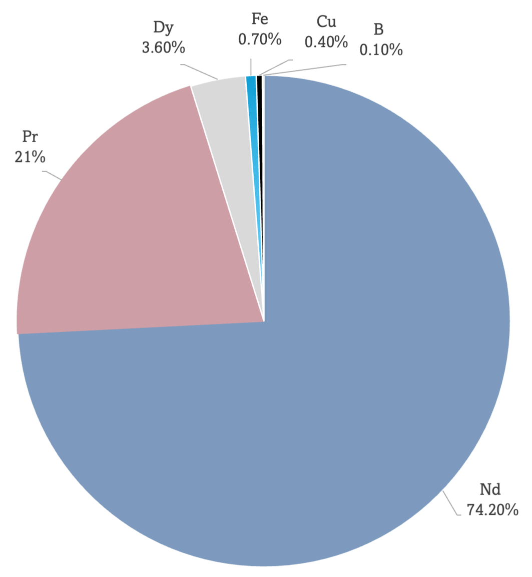


Figure 1. Elemental composition of the recovered REO determined by ICP-OES.

The recovered REO exhibited high purity, with Nd and Pr as the main constituents.

2 . High REE recovery (> 97%)

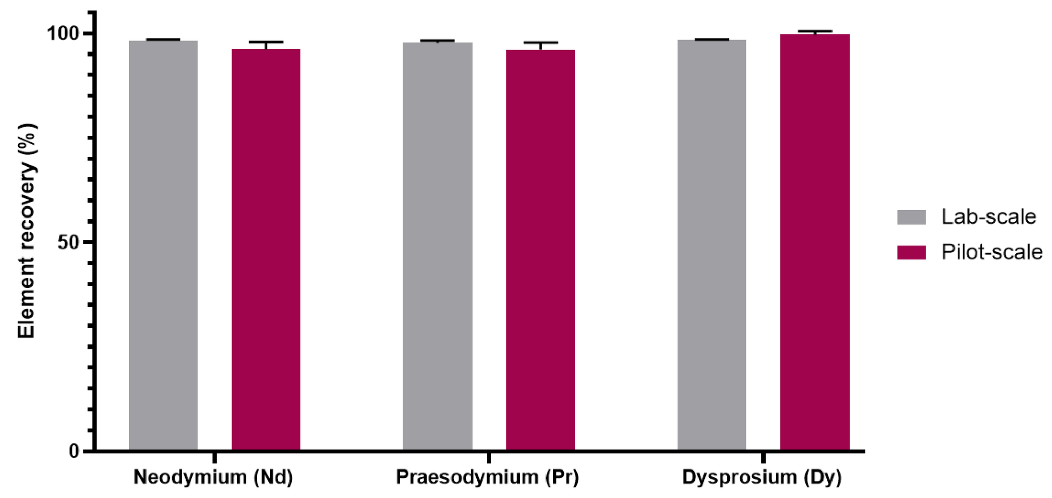


Figure 2. REE recovery efficiencies obtained at lab- and pilot-scale hydrometallurgical process.

3. Homogeneous elemental distribution

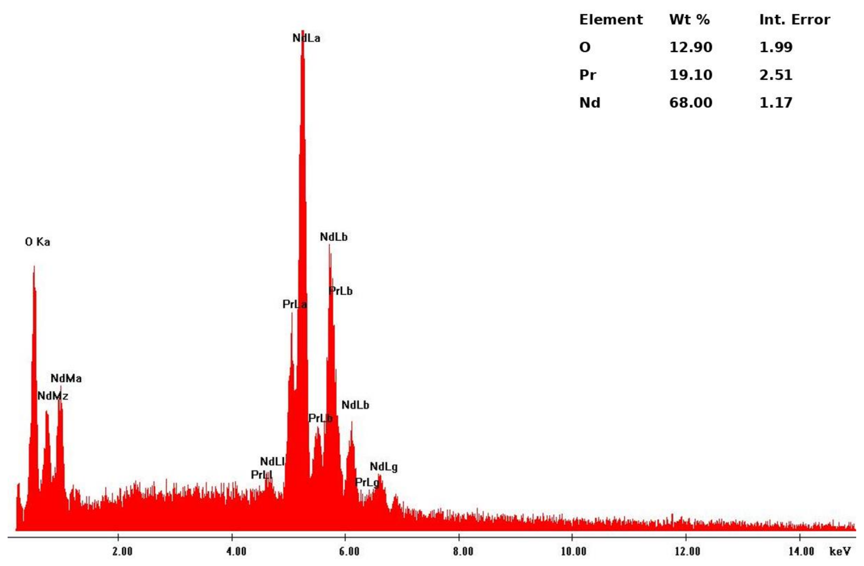


Figure 3. EDS analysis of the recovered REO, confirming the predominance of REE and the low concentration of impurities in the final product.

4. Good morphological consistency

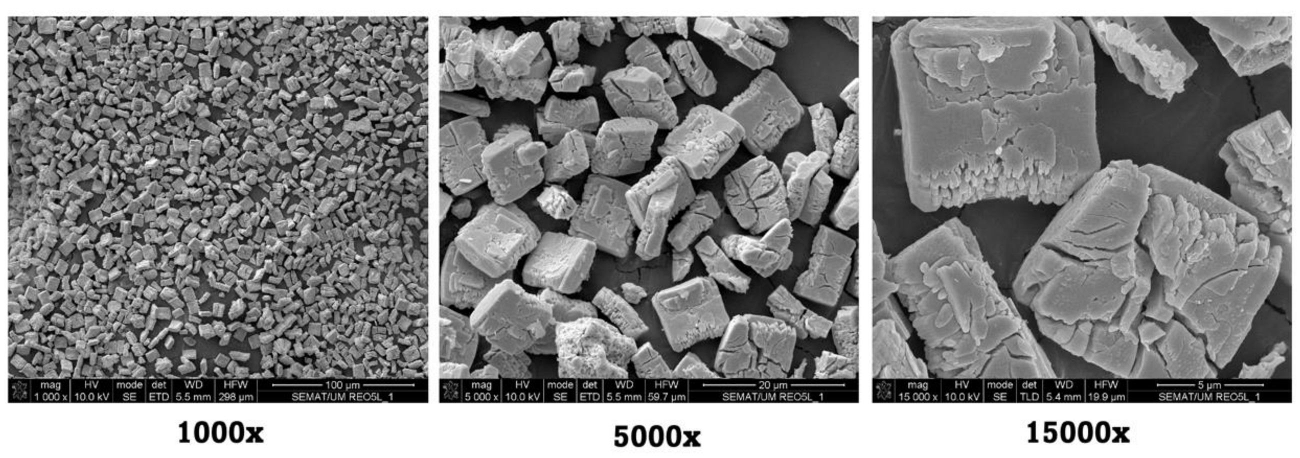
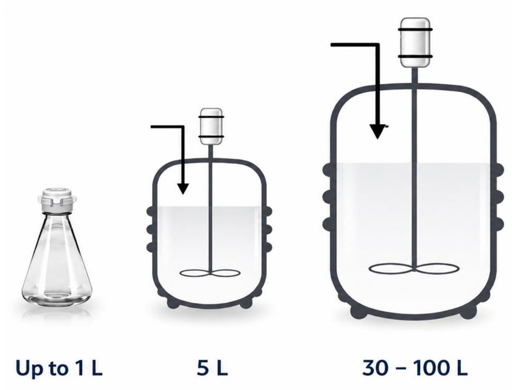


Figure 4. SEM images of the recovered REO particles.

Homogeneous particle morphology and microstructure consistent with high-purity REO.

5. Scalability



Pilot-scale validation confirmed the robustness and reproducibility of the process.

6. Environmental performance

Environmental indicator	Impact comparison: Mineral extraction (baseline)	Impact comparison: ReMag process (this work)	Reduction with ReMag process
Global warming potential (kg CO_2 eq)	17.096	7.5385	55.9% ↓
Eutrophication potential (kg PO_4^{3-} eq)	0.35048	0.01650	95.3% ↓
Fossil resource depletion (MJ eq)	183.00	92.20	49.6% ↓
Acidification potential (kg SO_2 eq)	0.10905	0.07393	32.2% ↓
Ozone depletion (kg CFC-11 eq)	1.08×10^{-8}	9.20×10^{-9}	14.8% ↓
Photochemical ozone creation (kg C_2H_4 eq)	5.24×10^{-3}	-1.11×10^{-2}	Improved to negative impact

Negative values indicate a net positive contribution (prevention of tropospheric ozone formation).

Figure 5. Life Cycle Assessment (LCA) results comparing the environmental performance of the ReMag process with conventional REE production.

Conclusion

- A pilot-scale hydrometallurgical process for NdFeB PM recovery was successfully demonstrated.
- **Recovery efficiencies above 95% and REO purities up to 99% were achieved.**
- LCA confirmed lower environmental impacts than conventional mineral extraction.
- Overall, the technology provides a promising pathway towards a circular and more resilient European REE supply chain, supporting the EU's CRMA objectives.

References

1. Balaram, V. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geoscience Frontiers 10, 1285–1303 (2019).
2. Schulze, R. & Buchert, M. Estimates of global REE recycling potentials from NdFeB magnet material. Resour. Conserv. Recycl. 113, 12–27 (2016).
3. European Commission. https://commission.europa.eu/index_en

Acknowledgments: This work was supported by the EIT RawMaterials Project ReMag (24620).

Supported by EIT RawMaterials Connecting matters
Co-funded by the European Union