Stellenbosch
South Africa
November
23th and 24th, 2023

12th IWACP

''Ways forward to promote resources equity:
The role of cleaner production and circular economy as moderator.
Action or Reaction to Save the Planet''

INTERNATIONAL WORKSHOP ON ADVANCES IN CLEANER PRODUCTION

Oral Presentation

Recovery of Rare Earth Elements from NdFeB Waste Magnets

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Introduction

Sc Y La Ce Pr Nd

Pm Sm Eu Gd Tb

Dy Ho Er Tm Yb Lu

Lanthanide series


- Hard Disk Drives


- Electric Motors

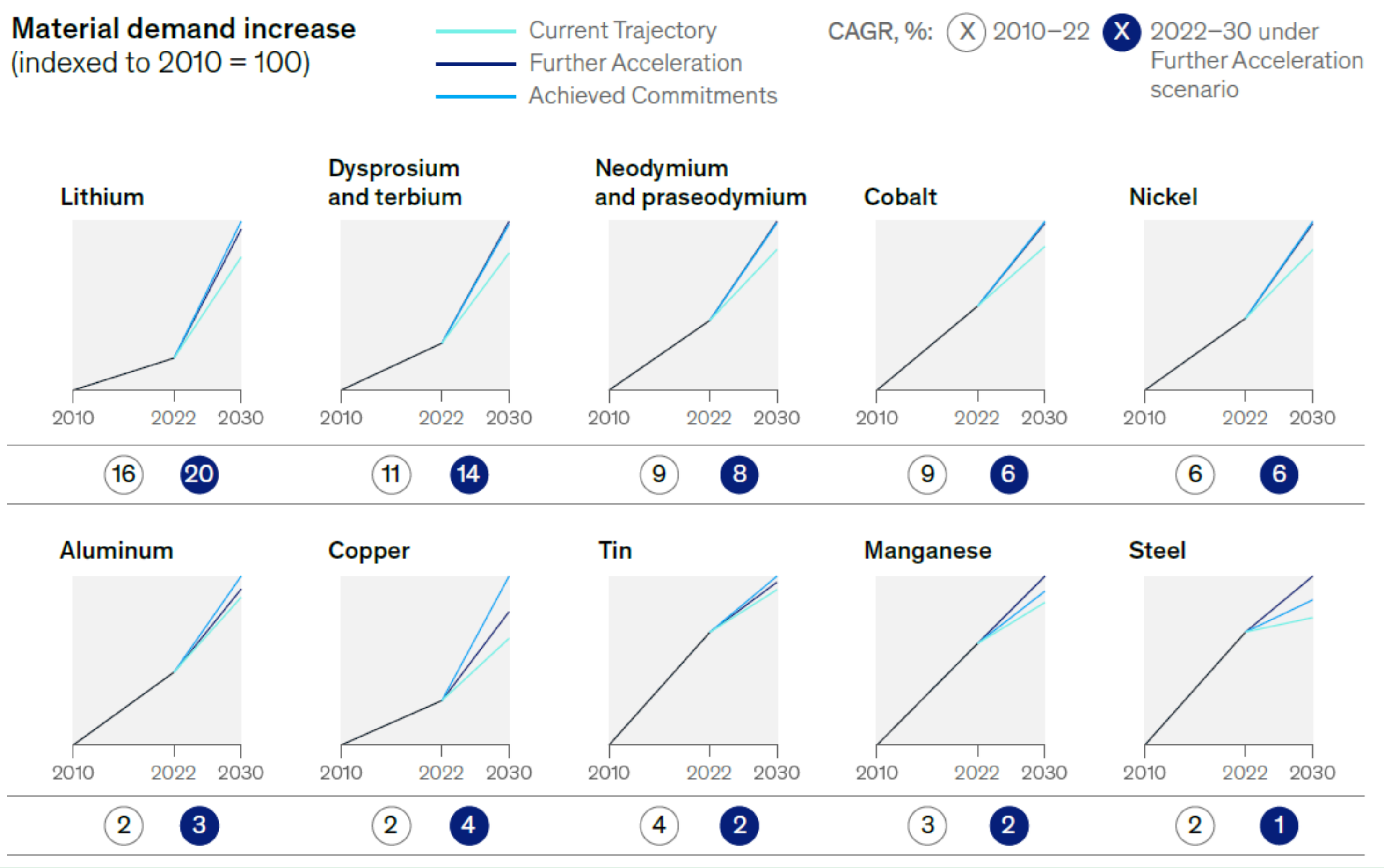

- Audio Systems


- Wind Turbines


- Magnetic bearings & couplings

Estimated increase in demand for REEs

By 2030, more than 50% of rare-earth elements, 55% of cobalt, and 36% of nickel will be consumed by BEVs and the associated charging infrastructure [2]



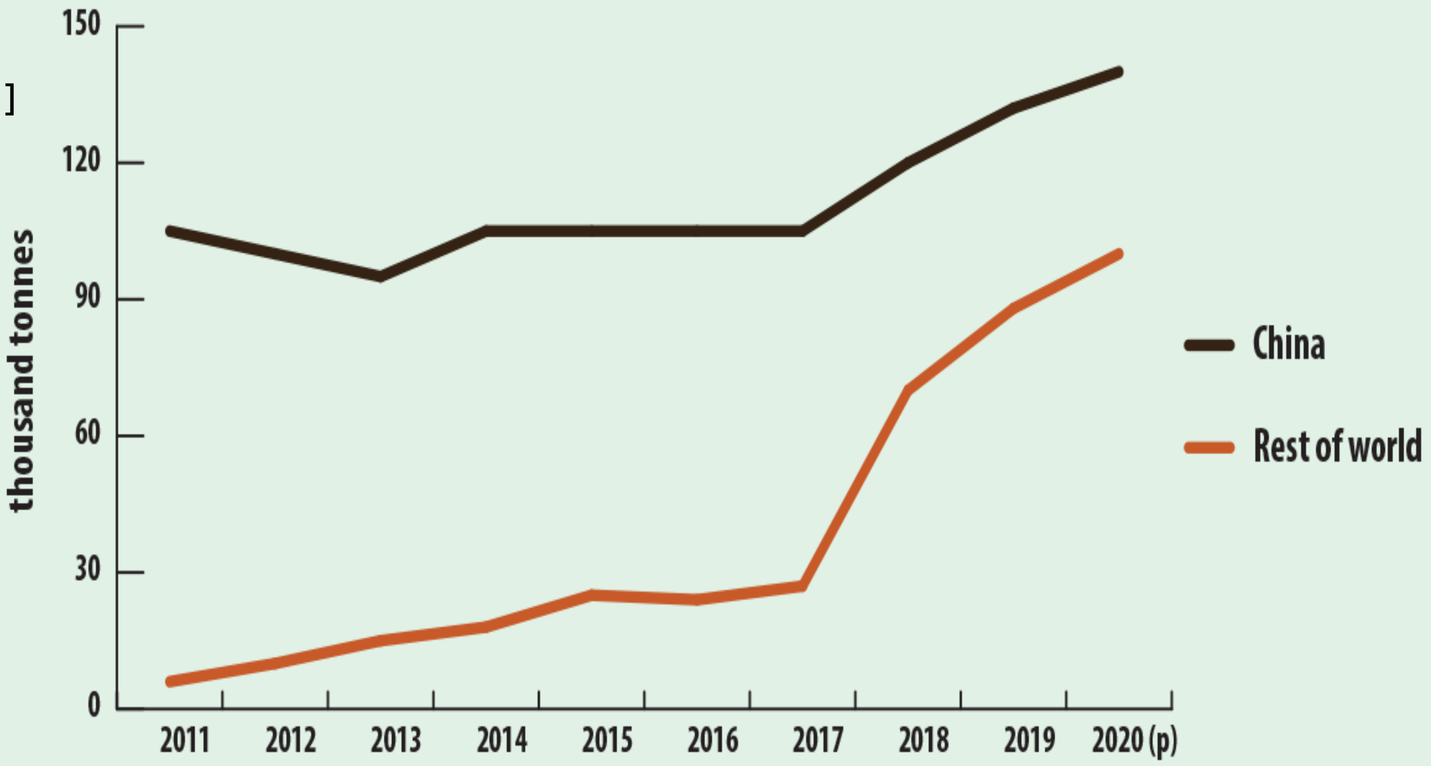
Estimated demand increase for critical minerals according to McKinsey [2]

[2] The net-zero materials transition: Implications for global supply chains; McKinsey on Risk,October 2022

Global Production of REEs

World production of REEs, by country in 2020 [1]

Country	Percentage of total production/%
China	57.5
United States	15.6
Myanmar	12.3
Australia	7.0
Madagascar	3.3
Other	4.2



World production of REEs , 2011-2020 [1]

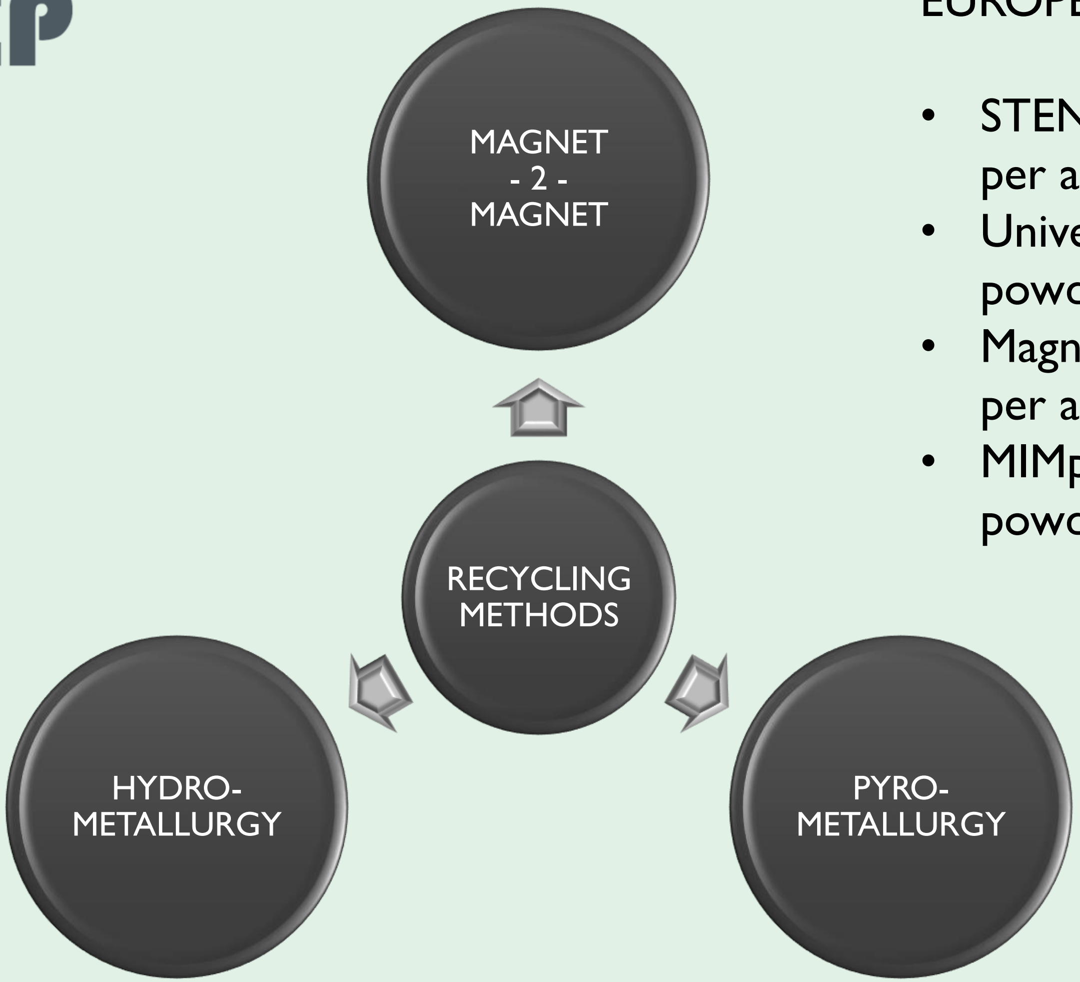
[1] Mineral commodity summaries 2022, U.S. Geological Survey

Environmental concerns

- Soil erosion
- Acidic effluents from mines
- Heavy metals pollution of bodies of water
- Decrease of biodiversity
- GHG emissions
- Negative impact on human health

Photo by Omid Roshan

Waste Permanent Magnets (WPM) recycling



EUROPEAN WPM RECYCLING PLANTS[3]

- STENA Recycling (Sweden) – 6 tonnes of NdFeB powders per annum
- University of Birmingham (UK) – 50 tonnes of NdFeB powders per annum
- Magneti Ljubljana (Slovenia) - 50 tonnes of NdFeB powders per annum
- MIMplus Technologies (Germany) – 10 tonnes of NdFeB powders per annum

[3] SusmagPro Plants

Hydrometallurgy

Methodology

- Collection
- Demagnetisation
- Comminution
- Leaching
- Extraction
- Precipitation

Risks

- Low waste collection
- Strong inorganic acids
- Expensive extractants
- Disposal of chemicals
- Leakages to the environment

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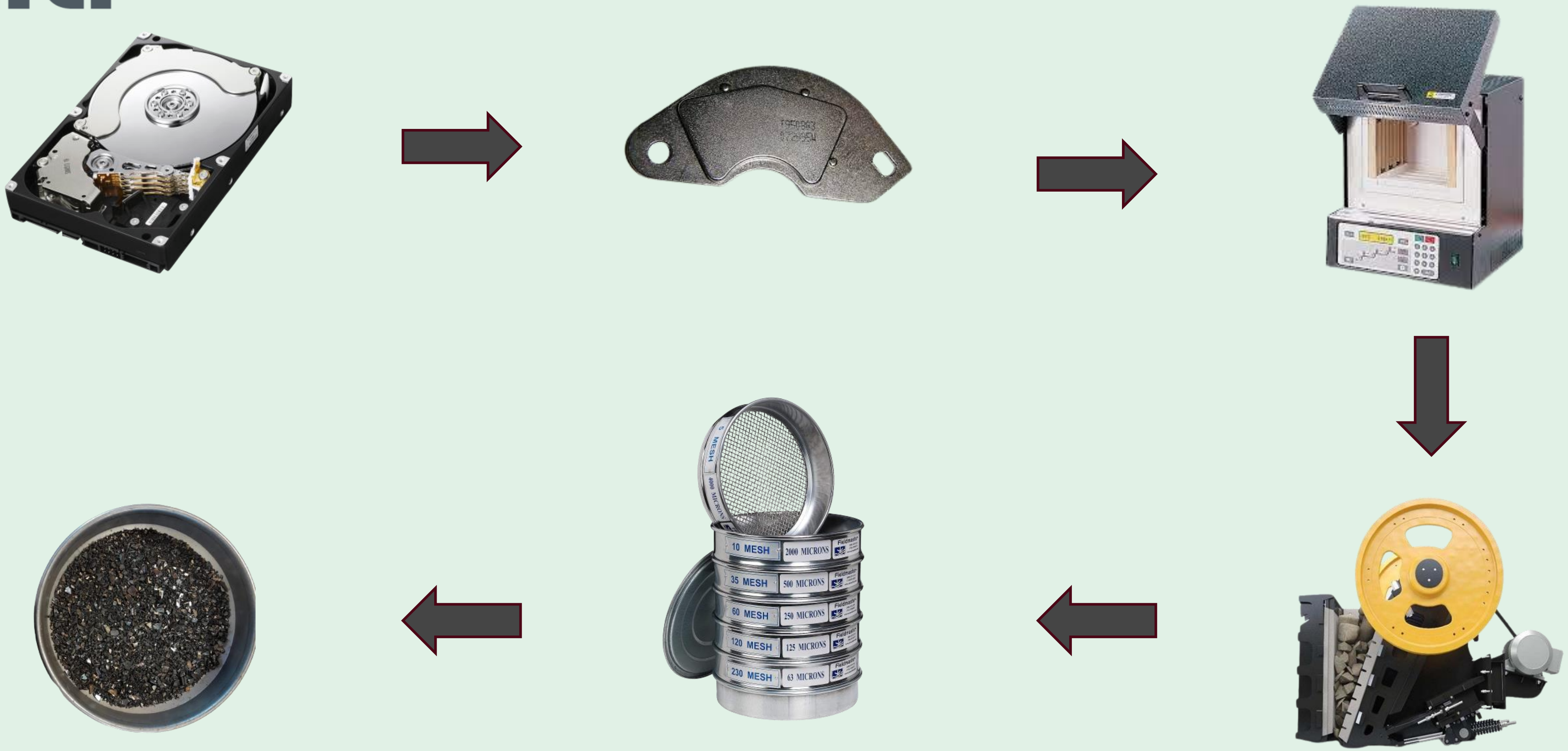
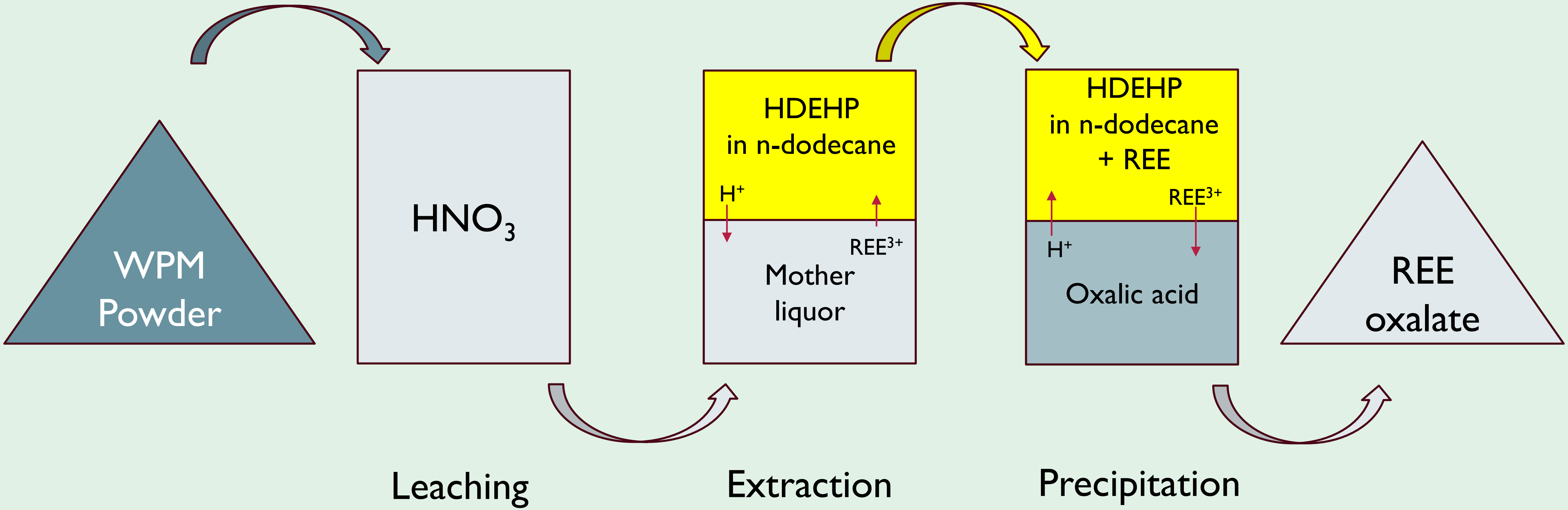
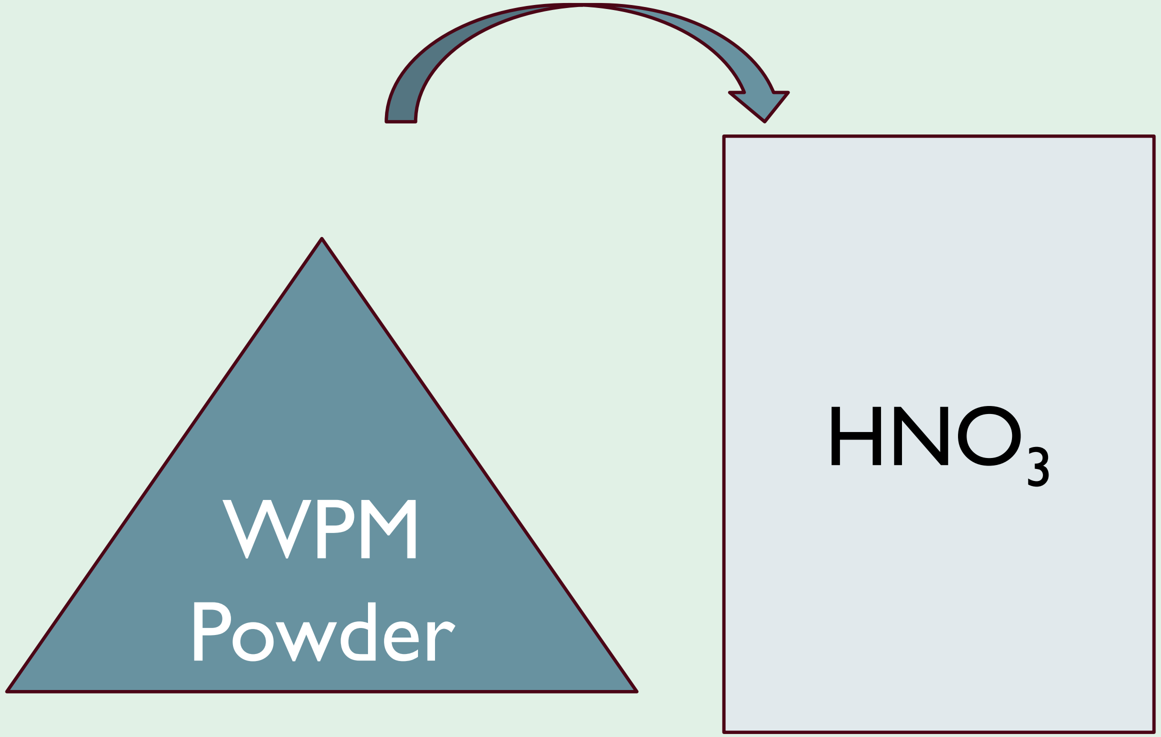
Collection, demagnetisation, comminution



Hydrometallurgy – process schematic



Hydrometallurgy – Leaching



Leaching - parameters

Temperatures
45°C and 60°C

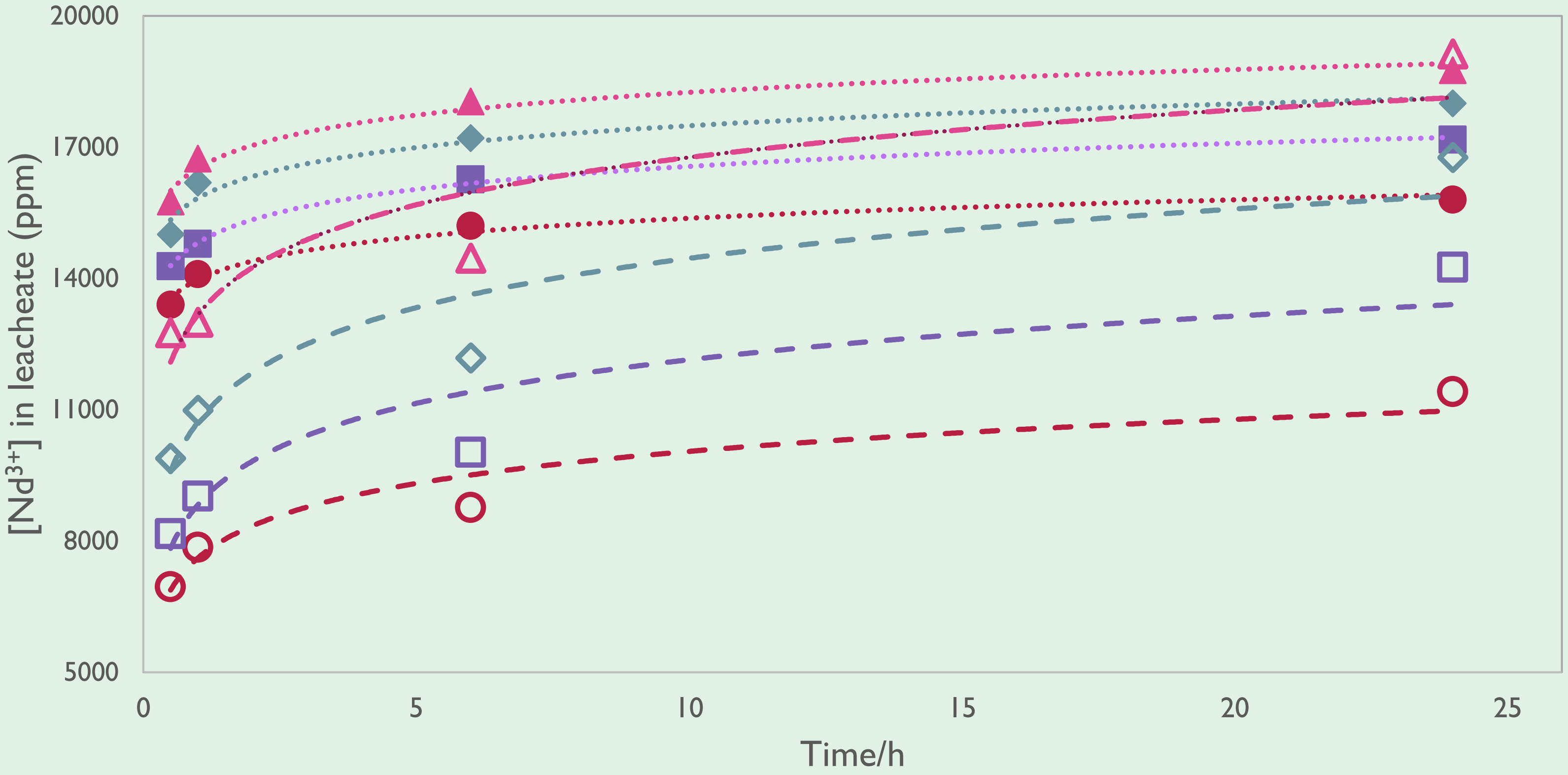
Particle Sizes
100-150 μm and ≥600μm

Nitric Acid Concentration
6.7M and 12.3M

Time
0.5h, 1h, 6h and 24h

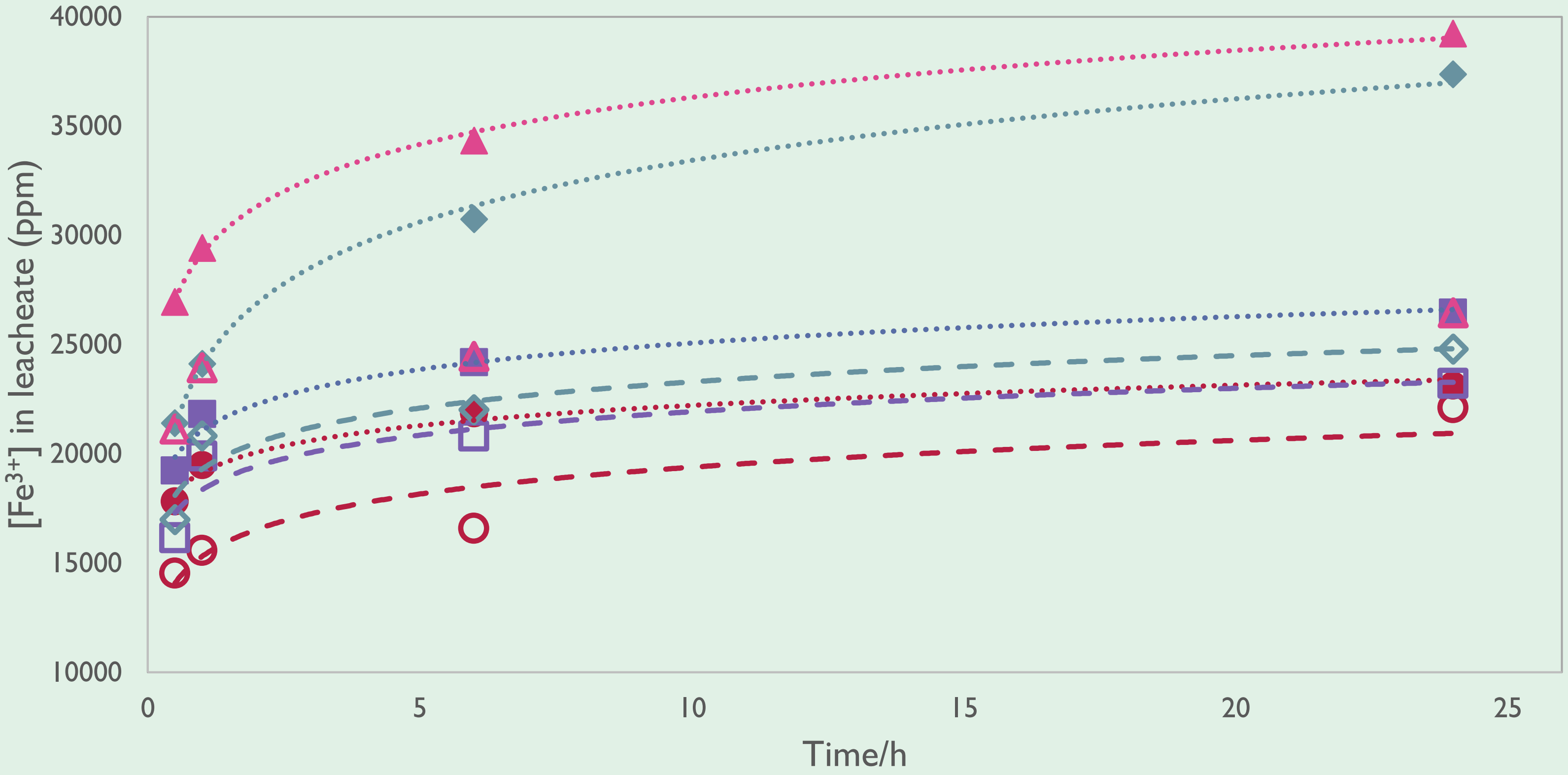
Each experiment was conducted using 1g of WPM powder in 50ml of acid

Leaching – Nd^{3+} results



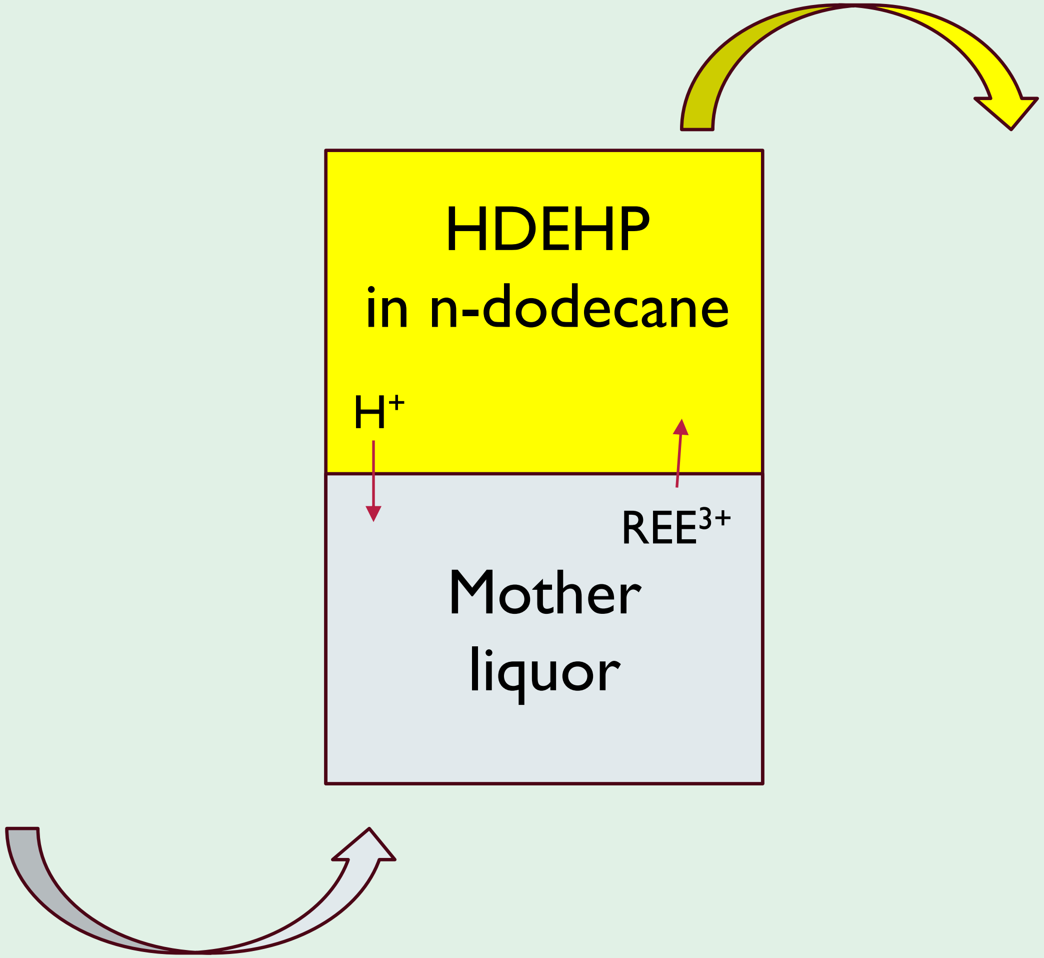
Nd^{3+} ions concentration in leachate after leaching experiments with HNO_3; Particle size (filled markers -100 - 150µm; open markers - 600 µm): ● – 45°C in 6.7M acid, ■ – 60°C in 6.7M acid, ♦ – 45°C in 12.3M acid, ▲ – 60°C in 12.3M acid

Leaching – Fe^{3+} results



Fe^{3+} ions concentration in leachate after leaching experiments with HNO_3; Particle size (filled markers -100 - 150μm; open markers - 600 μm): ● – 45°C in 6.7M acid, ■ – 60°C in 6.7M acid, ♦ – 45°C in 12.3M acid, ▲ – 60°C in 12.3M acid

Hydrometallurgy – Extraction



Extraction – parameters

Extractant concentration

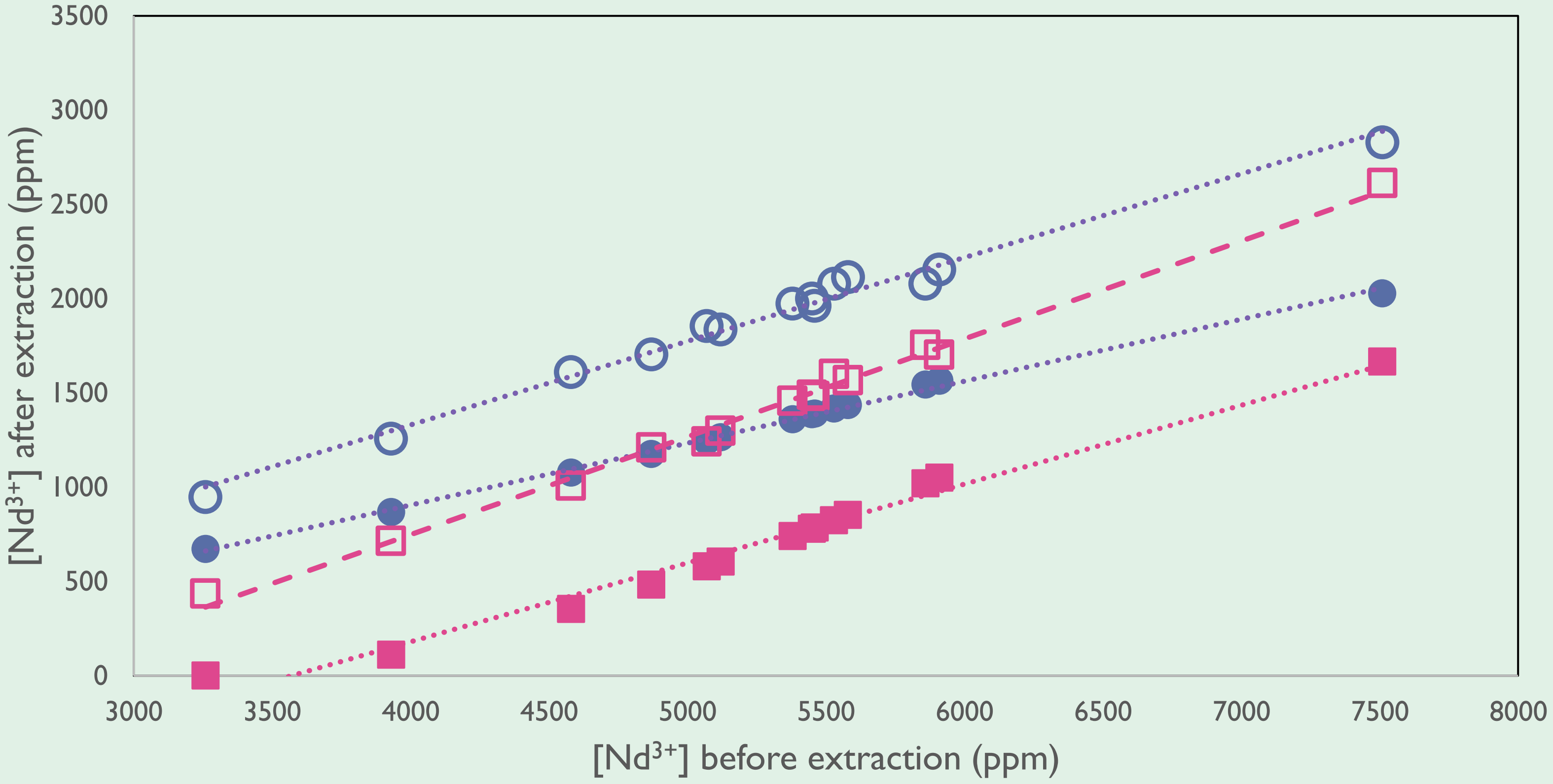
0.5M and 1M

Scale

10 and 100 ml

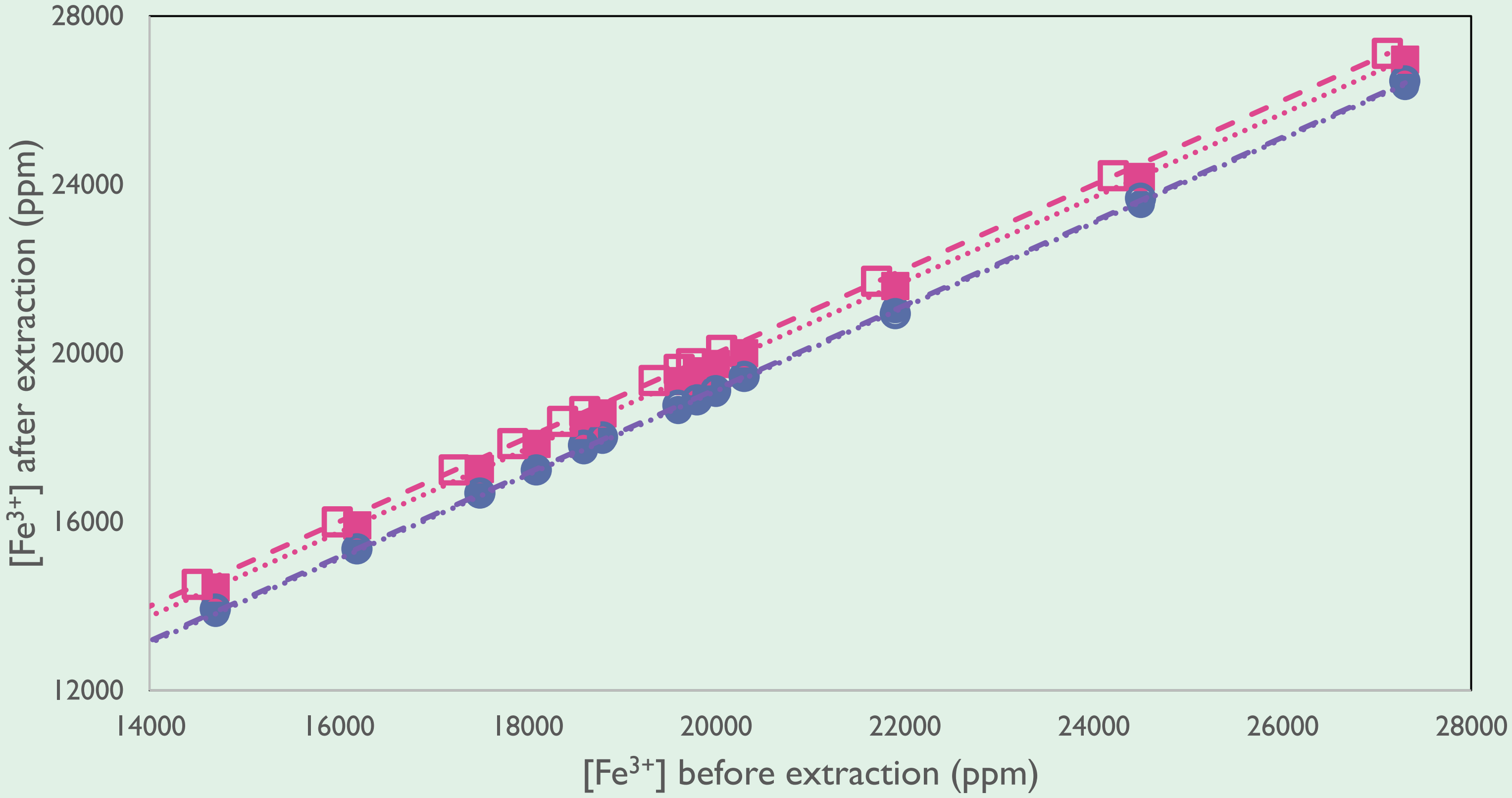
Each experiment was conducted using 1:1 volume ratio of organic and aqueous phases.

Extraction – Nd^{3+} results



Distribution of Nd^{3+} ions in extraction experiments using HDEHP in n-dodecane; ● – 0.5M HDEHP (10 ml), ■ – 1M HDEHP (10 ml), ○ - 0.5M HDEHP (100 ml), □ – 1M HDEHP (100 ml).

Extraction – Fe^{3+} results



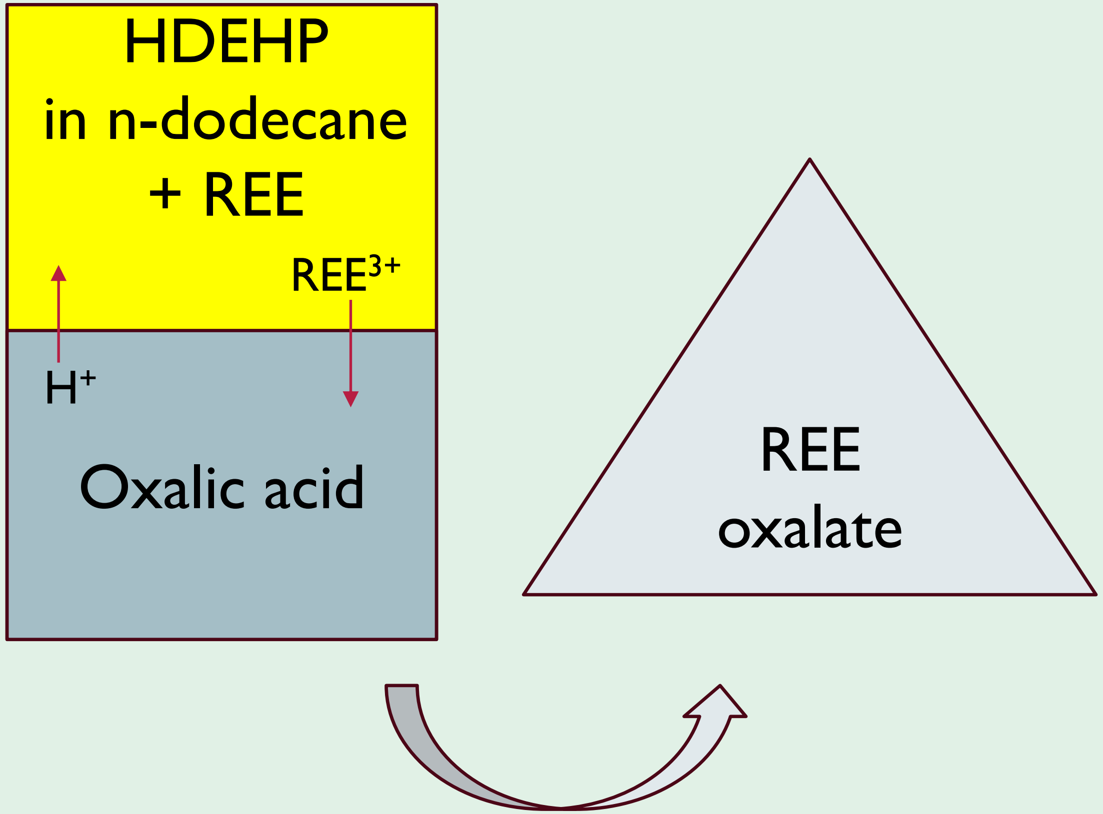
Distribution of Fe^{3+} ions in extraction experiments using HDEHP in n-dodecane; ● – 0.5M HDEHP (10 ml), ■ – 1M HDEHP (10 ml), ○ - 0.5M HDEHP (100 ml), □ – 1M HDEHP (100 ml).

Extraction – results

Recovery of Nd^{3+} and Fe^{3+} ions at a given HDEHP concentration

Ion	Scale	[HDEHP]/M	Recovery/%
Nd^{3+}	Small scale	1	77.82 – 99.99
		0.5	73.00 – 79.42
	Large scale	1	65.21 – 86.68
		0.5	62.33 – 70.95
Fe^{3+}	Small scale	1	1.23 – 1.89
		0.5	3.52 – 8.02
	Large scale	1	0.69 – 1.23
		0.5	3.09 – 6.68

Hydrometallurgy – Precipitation



Precipitation

Recovery of Nd^{3+} ions obtained after precipitation processes at a given HDEHP concentration (M) and various oxalic acid (OA) to organic phase (OP) volume ratios.

[HDEHP]/M	OA:OP ratio	Recovery of Nd^{3+}/%
0.5	1:1	71.18 ± 0.10
	2:1	90.86 ± 0.23
	5:1	95.54 ± 0.12
	10:1	96.37 ± 0.13
1	1:1	70.43 ± 0.11
	2:1	90.59 ± 0.34
	5:1	95.39 ± 0.22
	10:1	97.22 ± 0.09

Conclusions

- Optimal leaching conditions: 100-150 μm & 12.3M HNO_3 at 60°C for 24 hours.
- HDEHP was proven a good extractant.
- Precipitation with saturated oxalic acid solution showed > 95% recovery of Nd^{3+} ions using precipitant-to-extractant ratios above 5:1.
- Upscaling of the process is possible.

THANK YOU

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Hydrometallurgy – chemistry of the process

Ranges of concentrations of elements in NdFeB magnets [4,5,6]

Fe^{3+}	Nd^{3+}	Dy^{3+}	Pr^{3+}	B^{3+}	Sm^{3+}
~59-69%	~22-33%	~0.5-5%	~1-7%	~1-2.5%	~0.6-1.6%

$$RE + 3H^{+}X^{-}_{(aq)} \rightarrow RE^{3+}_{(aq)} + 3X^{-}_{(aq)} + 1.5H_{2\,(g)}$$

$$RE^{3+}_{(aq)} + 3H^{+}Y^{-}_{(org)} \rightarrow RE^{3+}Y^{-}_{3\,(org)} + H^{+}_{(aq)}$$

$$2RE^{3+}Y^{-}_{3\,(org)} + 3C_2H_2O_{4\,(aq)} \rightarrow RE^{3+}_{2}(C_2O_4)^{2-}_{3\,(aq)} + 6H^{+}Y^{-}_{(org)}$$

[4] Gruber, V., & Carsky, M. (2020). South African J. Chem. Eng., 33, 35–38.
[5] Lee, C.-H., Chen, Y.-J., Liao, C.-H., Popuri, S. R., Tsai, S.-L., & Hung, C.-E. (2013), Metall Mater Trans A, 44(13), 5825–5833.
[6] Reisdörfer, G., Bertuol, D., & Tanabe, E. H. (2019). Minerals Eng., 143, 105938.