Rare Earth Processing

Innovation Landscape Report

Contents

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1. Executive summary

This Innovation Landscape Report on Rare Earth Processing forms part of a series of reports into the UK Rare Earth Elements (REEs) Value Chain, commissioned by Innovate UK as part of the Circular Critical Materials Supply Chains (CLIMATES) Programme which was established to develop and support critical materials supply chains within the UK, beginning with REEs.

Other reports in the series include Rare Earth Exploration, Extraction, Beneficiation and Concentration, Rare Earth Circular Economy, Rare Earth Permanent Magnet Manufacturing and Rare Earth Permanent Magnet Alternatives.

Rare earth elements (REEs) are a set of 17 elements (the 15 lanthanides plus scandium and yttrium) with multiple technological applications. One of their most important uses is in the manufacture of a type of rare earth permanent magnet (REPM) used in electric motors for vehicles and wind turbines, composed of a Neodymium-Iron-Boron (NdFeB) alloy with small amounts (~1wt%) of other REEs such as Dysprosium (Dy) and/or Terbium (Tb) added to improve performance at elevated temperatures.

NdFeB magnets have amongst the highest magnetic energy densities which make them efficient converters of electrical to kinetic energy and vice versa. The demand for NdFeB magnets is set to rise substantially over the coming decades as the world expands certain industries, such as electric vehicles and wind energy generation.

REEs are present in a variety of mineral deposits such as monazite, bastnasite, and ion-adsorption clays. However, the REEs of economic importance (Nd, Dy, etc.) are only ever present in small concentrations (~15-25wt%) alongside relatively unimportant REEs such as La and Ce (and in the case of monazite, a fraction of radioactive thorium).

After beneficiation processes, usually performed at or near the mine site, a mixed rare earth concentrate (MREC) is produced, which then requires further processing to separate the REEs (Demol, J. et. al., 2019; Suli, L. M. et. al., 2017). This is a non-trivial process given the chemical similarities between REEs **– more information about the steps preceding processing can be found within the Innovate UK Rare Earth Exploration, Extraction, Beneficiation and Concentration report.**

The separation of the MREC into finished REE products such as Neodymium-Praseodymium (NdPr) is typically performed using solvent extraction. This is a capital, solvent and energy intensive operation that relies on a series of tanks (100s) and well-controlled chemical equilibria (Xie, F. et. al, 2014).

Other methods exist but are far less mature – innovation is required to develop these novel solutions that have the capacity to improve the reliability of the process, reduce carbon emissions and reduce costs (Deblonde et al., 2022; Opare et al., 2021; Pramanik et al., 2024).

Recycling of REEs from end-of-life (EoL) products also requires concentration and separation steps. Recycled feedstocks may differ from primary MREC by containing other metals and organic materials from the EoL products, depending on how these have been pre-processed (shredding, combination of different waste streams, etc.). **More information on REE recycling from EoL products can be found in the Innovate UK Rare Earth Circular Economy Report.**

In this report, we document the range of alternative technologies available to concentrate and separate REEs, from both primary and secondary sources. We cover both primary and secondary sources because of the overlap in applicability of the technologies and the potential for cross-sector development (i.e. between the mining and recycling industries).

2. Technology areas

In this section we introduce and discuss each REE processing technology area and their innovation potential, before concluding by discussing innovation opportunities utilising UK strengths.

Figure 1 shows the technology areas covered in this report and the assessed Technology Readiness Level (TRL) as they are applied to REE processing.

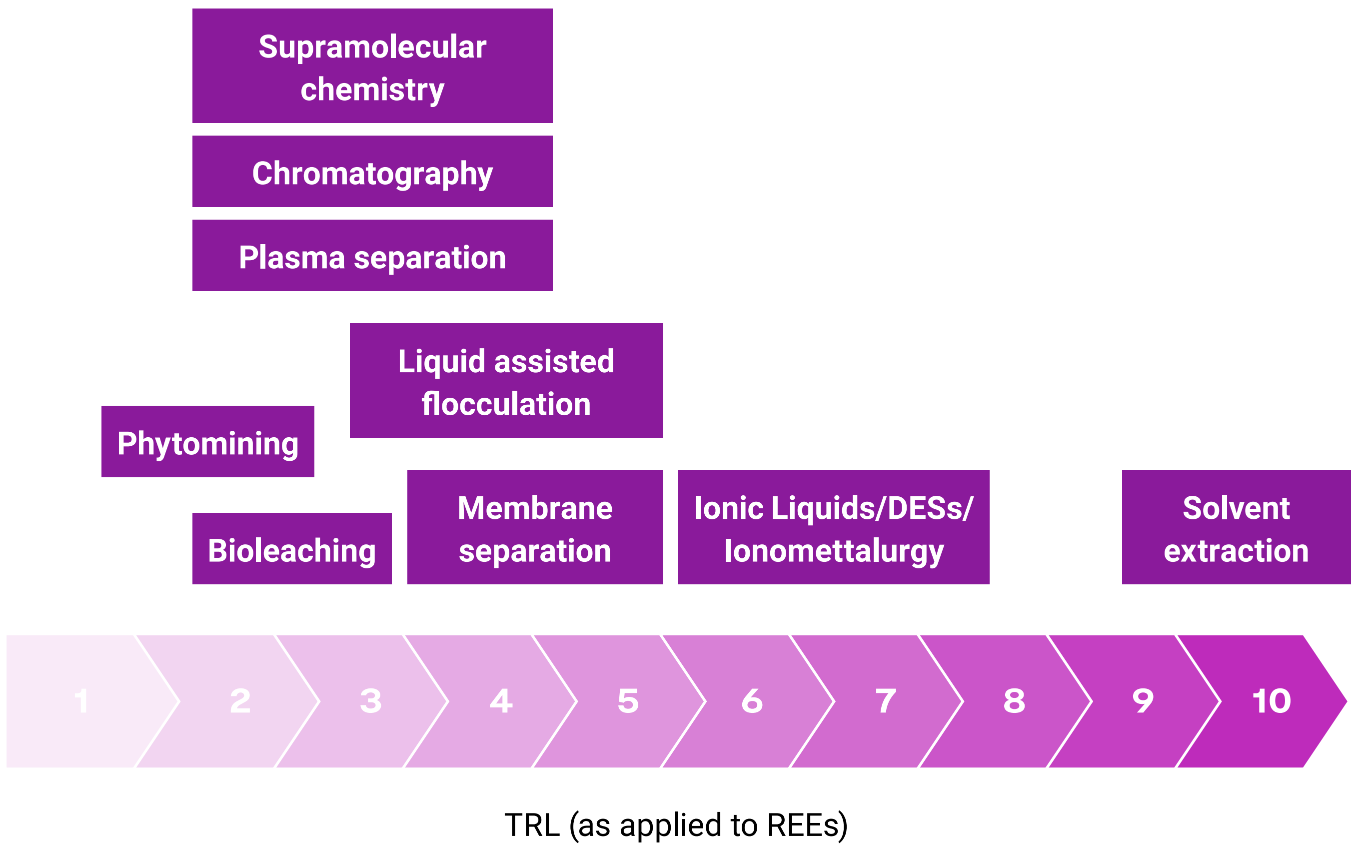


Figure 1 - Technology Readiness Level (as applied to REEs)

2.1 Solvent extraction (TRL 9 – mature)

2.1.1 Introduction

Solvent extraction (SX) is a widely used method for the separation and purification of REEs from ores, concentrates, and other materials (Xie et al., 2014). This process exploits the chemical similarities among REEs while leveraging their subtle differences in ionic radii and coordination chemistry to achieve separation. It is a critical step in the production of high-purity REEs for advanced technologies such as magnets, catalysts, and electronics.

The SX process involves the transfer of REEs between two immiscible phases: an aqueous phase containing dissolved metal ions and an organic phase containing extractants, which are specialised ligands that selectively bind to specific REEs.

Extractants commonly used include organophosphorus compounds like tributyl phosphate (TBP) or di(2-ethylhexyl) phosphoric acid (D2EHPA). These extractants form coordination complexes with REEs, enabling their transfer into the organic phase. Adjusting parameters like pH, temperature, and extractant concentration allows selective extraction of individual REEs based on their chemical properties.

Once extracted, REEs are stripped from the organic phase into a separate aqueous solution by changing the conditions, such as pH or the composition of the stripping agent. This process is repeated through multiple stages in a counter-current extraction system to achieve high-purity separation.

Solvent extraction offers several advantages, including scalability, efficiency in processing large volumes, and adaptability to complex feedstocks. However, it also has challenges.

The process requires significant quantities of chemicals and produces waste streams that need careful management. Additionally, the separation of heavy and light REEs requires numerous stages due to their similar chemical properties, making the process time- and resource-intensive.

2.1.2 Innovation opportunities

SX for REE processing is ripe for innovation, offering numerous opportunities to enhance efficiency, sustainability, and scalability. As the most mature and most-used technology globally, innovations in SX are essential to address its limitations and environmental challenges.

One area of opportunity lies in the development of greener extractants. Traditional extractants like phosphoric acid derivatives are effective but can be hazardous and generate significant waste. Alternatives such as bio-based or ionic liquid extractants offer improved selectivity and reduced environmental impact. Ionic liquids (see later section), for example, can be tailored for specific REEs, minimising chemical usage and enabling cleaner processes.

Process optimisation through automation and machine learning also presents significant potential. Advanced modelling tools can simulate extraction conditions to maximise efficiency and reduce the number of stages required for separation. Such innovations can lower costs and improve throughput.

Hybrid methods that integrate SX with other technologies, like membrane filtration or ion exchange, offer another promising avenue. These combinations can enhance separation efficiency, reduce solvent use, and streamline processing.

Finally, recycling solvents and incorporating circular economy principles can significantly improve the sustainability of SX operations, addressing the growing need for environmentally responsible REE production.

2.2 Ionic liquids/Deep eutectic solvents/Ionometallurgy (TRL 6/7 — emerging)

Introduction

Ionic liquids (ILs), deep eutectic solvents (DESs) and ionometallurgy represent innovative approaches in the field of metal recovery and processing, offering more sustainable and efficient alternatives to traditional methods (Deblonde et al., 2022).

Ionic liquids are salts in a liquid state at relatively low temperatures, typically below 100°C. They consist of organic cations and various anions, which can be tailored to achieve specific properties. ILs are known for their low volatility, high thermal stability, and ability to dissolve a wide range of materials. These characteristics make them ideal for metal recovery processes, such as leaching and extraction. ILs can selectively dissolve metals from ores and waste materials, facilitating their recovery with minimal environmental impact.

Deep eutectic solvents are a subclass of ILs, formed by mixing a hydrogen bond donor and a hydrogen bond acceptor, resulting in a eutectic mixture with a melting point lower than that of the individual components. DESs are gaining attention due to their low toxicity, biodegradability, and ease of preparation. They offer a green alternative to conventional solvents used in metal recovery. DESs have been successfully applied in the extraction of metals like copper, zinc, and gold from various sources, including ores and industrial waste. Their ability to operate under mild conditions and their tunable properties make them versatile for different metallurgical applications.

Ionometallurgy leverages the unique properties of ILs and DESs to develop more efficient and environmentally friendly metal processing techniques. This approach integrates the use of non-aqueous ionic solvents in metallurgical operations, such as leaching, electrowinning, and solvent extraction. Ionometallurgy allows for the selective recovery of metals at ambient temperatures, reducing energy consumption and minimising the use of hazardous chemicals. For example, ionometallurgy has shown promise in the recovery of precious metals like gold and platinum from complex ores and electronic waste. The process can be fine-tuned to target specific metals, enhancing the efficiency and selectivity of metal recovery

In summary, the use of ILs, DESs, and ionometallurgy in metal recovery and processing represents a significant advancement towards more sustainable and efficient practices. These technologies not only reduce the environmental impact of metal extraction but also offer the potential for recovering valuable metals from secondary sources, contributing to a circular economy.

Innovation opportunities

The innovation opportunities in ionometallurgy centre around finding, applying and optimising the right solvents and process steps for efficient processing of REEs from a variety of feedstocks to provide the advantages offered by ILs.

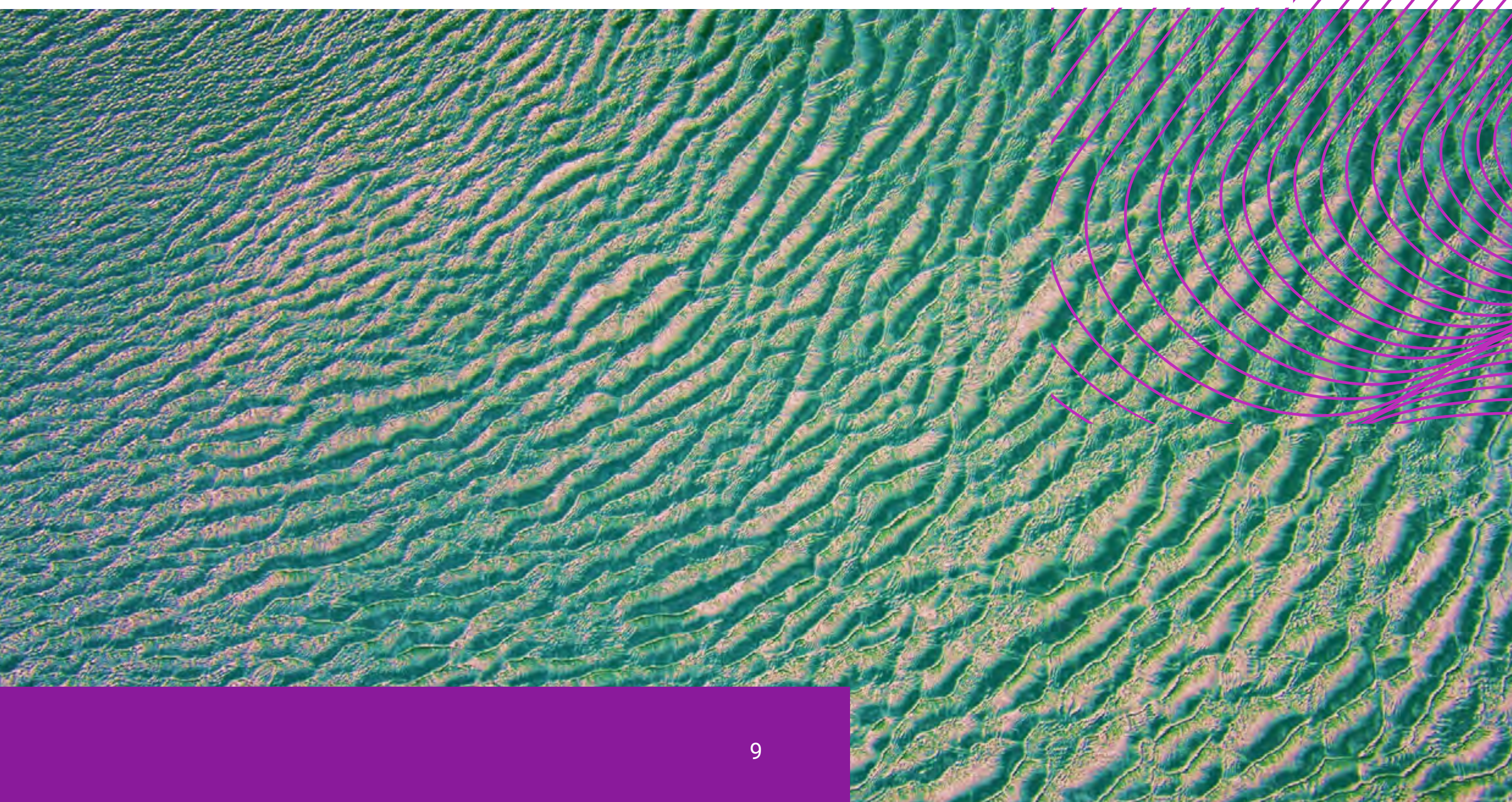
One key innovation opportunity lies in developing tailored ionic liquids or DES that selectively dissolve specific REEs from complex ores. This precision could reduce waste and improve recovery rates. Moreover, ionometallurgy enables lower-temperature processing, cutting energy costs and minimising greenhouse gas emissions.

Recycling REEs from electronic waste is another promising application. Ionometallurgical approaches can simplify the separation of REEs from other metals in devices like magnets and batteries, supporting circular economy goals.

Furthermore, the reuse of ionic solvents after extraction processes enhances sustainability.

Integrating ionometallurgy with advanced separation technologies, such as membrane filtration or electrowinning, could further enhance process efficiency. These innovations could lead to modular, scalable REE processing systems, reducing reliance on centralised facilities and enabling access to low-grade deposits.

Finally, the use of ILs and DESs in ionometallurgy allows for REE extraction at lower temperatures and pressures compared to conventional methods. This reduction in energy requirements makes the process more cost-effective and sustainable, aligning with efforts to reduce energy consumption and carbon emissions.



2.3 Plasma separation (TRL 3/4 – emerging)

Introduction

Plasma separation is an emerging technology that uses plasma (an ionised, high-temperature state of matter) to extract and purify metals from complex sources (Gueroult et al., 2018). Plasma systems can generate extreme temperatures exceeding 10,000°C, enabling the breakdown of chemical bonds in raw materials and the efficient recovery of valuable metals. This process is particularly useful for treating challenging feedstocks such as low-grade ores, industrial residues, and electronic waste.

In a plasma reactor, the target material is exposed to a high-energy plasma arc or jet, which heats the material to its vaporisation point. Metals can then be selectively recovered based on their boiling points, oxidation states, or other physical and chemical properties. For example, metals like zinc or lead, with lower boiling points, are recovered first, followed by higher boiling point metals like titanium or rare earth elements.

One of the major advantages of plasma separation is its versatility. It can handle a wide range of feedstocks, including mixed or contaminated materials that are unsuitable for conventional methods. Plasma processes also generate minimal chemical waste, offering an environmentally cleaner alternative to traditional extraction techniques. Furthermore, the high purity of recovered metals makes this technology attractive for critical applications, such as manufacturing high-performance alloys and electronic components.

However, the technology faces challenges, primarily high energy consumption and the need for sophisticated, costly equipment. These factors currently limit its adoption to niche applications or regions with affordable renewable energy sources. Ongoing research focuses on improving energy efficiency through better reactor designs, integrating plasma systems with renewable energy, and developing hybrid approaches that combine plasma with other separation methods.

Innovation opportunities

Plasma separation offers significant potential for the sustainable recovery of REEs, with opportunities for innovation to make their recovery more efficient, environmentally friendly, and economically viable.

One area of innovation is improving energy efficiency. Plasma processes require high energy input, but integrating renewable energy sources or advancements in plasma arc technology could lower costs and environmental impacts. Development of more efficient plasma reactors, such as those with advanced insulation or optimised plasma flow dynamics, can further reduce energy consumption.

Another opportunity lies in enhancing selectivity during separation. By tailoring plasma conditions, such as temperature and atmosphere composition, researchers can target specific REEs for recovery while minimising unwanted reactions or impurities. Incorporating computational modelling and machine learning can optimise these parameters for different feedstocks.

Hybrid systems that combine plasma separation with other methods, such as solvent extraction or ion exchange, can maximise recovery rates while reducing processing complexity. Moreover, scaling down plasma systems for decentralised recovery, such as in urban mining for electronic waste, opens possibilities for localised resource recycling.

2.4 Chromatography (TRL 3/4 — emerging)

Introduction

Chromatography is a powerful technique for separating and purifying metals based on their distinct chemical and physical interactions with a stationary and a mobile phase (Chen et al., 2019). Initially developed for organic compounds, chromatography has been adapted to metal separation in various fields, including environmental monitoring, industrial processing, and materials recycling. It offers a high degree of precision and is capable of isolating trace metal concentrations from complex matrices.

The basic principle of chromatography involves the distribution of metal ions between a stationary phase (a solid or liquid substrate) and a mobile phase (a liquid or gas). Separation occurs because different metal ions interact uniquely with the stationary phase, resulting in varying migration rates. Several types of chromatography are utilised for metal separation, including ion exchange, liquid-liquid, and high-performance liquid chromatography (HPLC).

Ion exchange chromatography is particularly effective for separating metal ions by exploiting their charge and size. This method is widely used for REEs, where small differences in ionic radii can be leveraged for precise separation. HPLC, on the other hand, allows rapid, high-resolution separation and is used in analytical applications to identify and quantify metal ions.

Chromatography offers significant advantages over traditional metal separation techniques, such as solvent extraction. It operates under mild conditions, produces minimal chemical waste, and allows the recovery of high-purity products. However, it faces challenges, including scalability for industrial applications and the cost of specialised equipment and materials.

With its adaptability and precision, chromatography is increasingly recognised as a versatile tool for sustainable metal recovery, particularly in applications requiring high purity or trace-level analysis.

Innovation opportunities

Innovation in chromatography for metal separation focuses on enhancing efficiency and sustainability. Advanced stationary phases, such as functionalised resins or nanomaterials, improve selectivity and capacity for target metals. Ligand-assisted displacement (LAD) chromatography uses aqueous solutions and recyclable chemicals, reducing the environmental footprint.

Further innovations in chromatography for REE separation include the use of neutral organic compounds, which enhance selectivity and efficiency. These compounds can be tailored to target specific REEs, improving the overall separation process. Research into these advanced techniques continues to evolve, promising more sustainable and cost-effective solutions.

2.5 Membrane and molecular imprinted polymers (MIPs) separation (TRL 3/4 — emerging)

Introduction

Separation technologies employing membranes and molecularly imprinted polymers (MIPs) have emerged as promising solutions for metal separation, offering enhanced selectivity, sustainability, and process efficiency (Asadollahzadeh et al., 2020; Hu et al., 2018).

Membranes are versatile materials capable of selectively separating metal ions based on size, charge, or chemical affinity. They can be engineered to operate under diverse conditions, making them suitable for both high- and low-concentration metal streams. Membrane-based separation processes, such as nanofiltration, reverse osmosis, and liquid membranes, offer advantages like reduced energy requirements and minimal chemical usage compared to traditional methods. Their scalability and modularity further make them attractive for industrial applications, ranging from metal recovery in hydrometallurgy to the purification of contaminated water.

Molecularly imprinted polymers, on the other hand, are synthetic materials designed with highly specific binding sites that mimic natural molecular recognition processes. Created through a template-based polymerisation process, MIPs can selectively recognise and bind target metal ions or metal complexes. This high specificity allows MIPs to effectively separate metals from complex mixtures, even at trace concentrations. Their robustness, chemical stability, and reusability make them particularly valuable for challenging separation tasks, such as the recovery of REEs or the removal of toxic metals from industrial effluents.

The integration of membranes and MIPs into hybrid systems represents a cutting-edge approach to metal separation. Combining the high throughput and operational simplicity of membranes with the unparalleled selectivity of MIPs can lead to transformative improvements in separation efficiency. For example, MIP-functionalised membranes can simultaneously filter and capture specific metal ions, streamlining the separation process and reducing waste generation.

Innovation opportunities

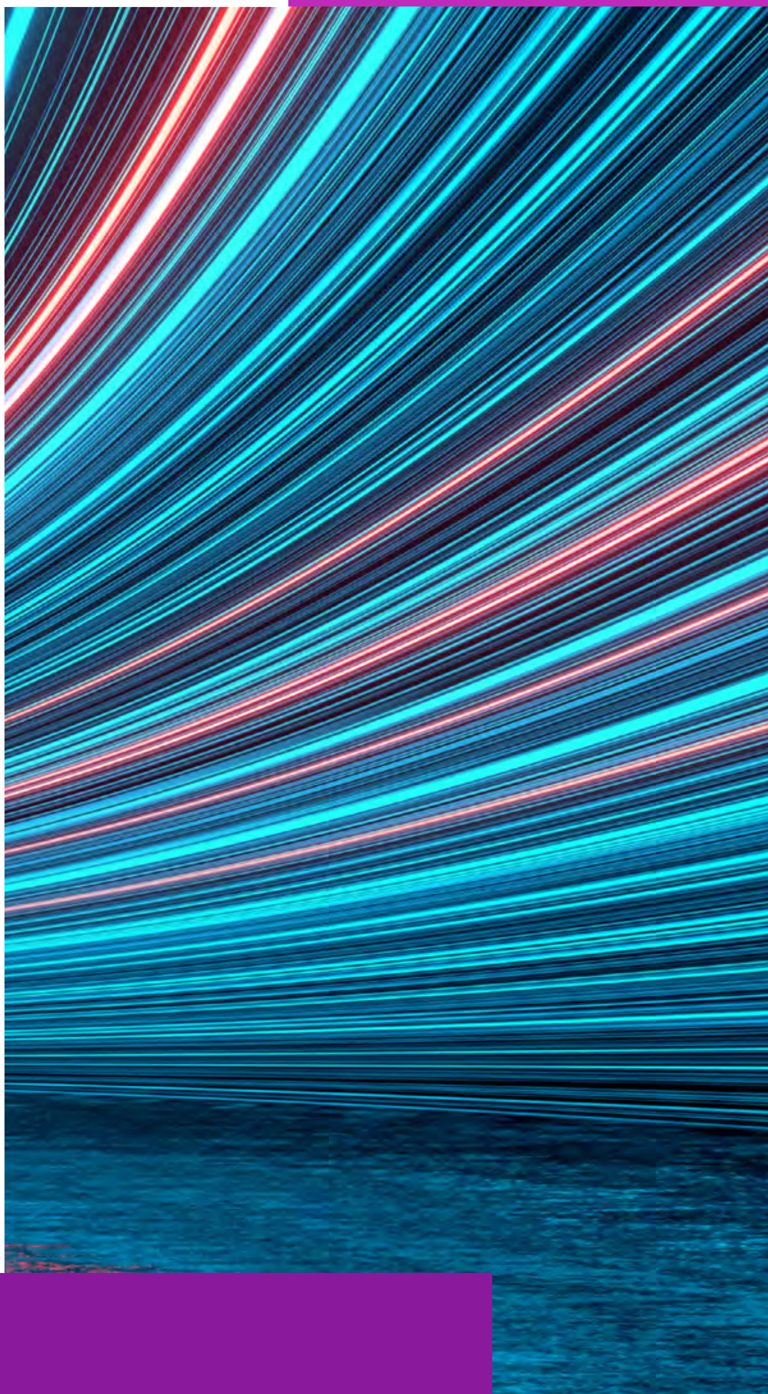
Membranes and molecularly imprinted polymers (MIPs) present significant innovation opportunities for REE processing by offering enhanced selectivity, efficiency, and environmental sustainability.

Membranes, particularly those tailored for nanofiltration or liquid-liquid separations, can be engineered to selectively transport REEs based on size, charge, or affinity. The development of functionalised or composite membranes incorporating advanced materials such as graphene or metal-organic frameworks (MOFs) holds promise for improving permeability and selectivity. Additionally, integrating these membranes into modular systems can enable on-site REE recovery from ores, industrial effluents, or recycled electronic waste.

MIPs, with their highly specific binding sites, offer unparalleled precision in REE separation, even in complex mixtures. Advances in polymer chemistry and nanotechnology can optimise MIPs for multi-ion systems, improving their efficiency in distinguishing between chemically similar REEs.

Combining MIPs with membrane technology to create MIP-functionalised membranes could revolutionise REE separation by enabling simultaneous filtration and selective capture, reducing energy and chemical consumption.

By addressing critical challenges in traditional REE separation, such as inefficiency and environmental impact, innovations in membranes and MIPs can significantly enhance resource recovery and support the transition to a sustainable, circular economy.



2.6 Ligand-induced selective flocculation (TRL 4 — emerging)

Introduction

Ligand-induced flocculation has emerged as a promising physico-chemical technique for selective metal recovery due to its high selectivity, operational simplicity, and environmental friendliness (Teh et al., 2016).

Flocculation is a process in which fine particles aggregate into larger clusters, or flocs, that can be easily separated from a liquid. In ligand-induced flocculation, this principle is adapted for metal recovery by using ligands (molecules with specific chemical structures that bind selectively to target metal ions). When ligands are introduced into a solution containing metal ions, they form metal-ligand complexes that precipitate or induce aggregation with the help of flocculants, resulting in the efficient separation of metals from the solution.

The specificity of ligands plays a critical role in this process, enabling the selective recovery of valuable metals, even from complex mixtures. Advances in ligand design, informed by computational chemistry and molecular modelling, have expanded the range of metals that can be targeted while improving separation efficiency. Tailored ligands can also be developed to operate under a variety of pH, temperature, and ionic strength conditions, broadening the applicability of this technique across different industrial streams.

One of the key advantages of ligand-induced flocculation is its potential to reduce the environmental footprint of metal recovery. By replacing harsh chemicals and energy-intensive processes, this method offers a greener alternative that minimises secondary waste generation. Furthermore, the reuse and recyclability of ligands and flocculants can enhance the sustainability and cost-effectiveness of the process.

Innovation opportunities

Ligand-induced flocculation presents significant innovation opportunities for the efficient and sustainable recovery REEs. The technique's ability to selectively bind and aggregate specific metal ions offers transformative potential in addressing the challenges of REE separation and recovery.

The design of tailored ligands is a key area for innovation. Advances in molecular modelling and synthetic chemistry enable the development of highly selective ligands that can distinguish between chemically similar REEs, improving separation efficiency. Furthermore, ligands engineered for operation in diverse conditions (such as acidic or saline environments) could expand the applicability of ligand-induced flocculation to a broader range of feedstocks, including low-grade ores and industrial effluents.

Hybrid systems that integrate ligand-induced flocculation with other technologies, such as membrane filtration or magnetic separation, offer another avenue for innovation. These systems could enhance recovery rates, reduce energy consumption, and enable the simultaneous recovery of multiple REEs.

Sustainability is also a driving force for innovation. Recyclable ligands and environmentally benign flocculants could minimise waste and reduce the ecological impact of the process.

2.7 Supramolecular chemistry (TRL 3 – novel)

Introduction

Supramolecular chemistry, the study of non-covalent interactions between molecules, offers a promising approach for the selective recovery of metals. This field focuses on designing host molecules that form reversible complexes with specific metal ions through interactions such as hydrogen bonding, electrostatics, van der Waals forces, and coordination chemistry. The ability to fine-tune these interactions allows for high selectivity, even in complex mixtures like industrial effluents or electronic waste.

Crown ethers, calixarenes, and metal-organic frameworks (MOFs) are examples of supramolecular systems that have been used in metal recovery. For instance, crown ethers can selectively bind alkali or alkaline earth metals based on ion size, while calixarenes and MOFs have been tailored to capture precious metals like gold and platinum. Supramolecular systems can also incorporate functional groups that enhance selectivity for REEs (O'Connell-Danes et al. 2022 & 2024).

One of the key advantages of this approach is its ability to operate under mild conditions, reducing energy use and environmental impact compared to traditional methods. Challenges include scalability, cost, and maintaining selectivity in large-scale operations. However, with continued research, supramolecular chemistry holds immense potential for sustainable metal recovery, aligning with goals of resource efficiency and circular economy practices.

Innovation opportunities

Using tripodal amido-arene ligands, a research group at the University of Edinburgh reports the ability to precipitate light REEs from mixed solutions, exploring the potential for both primary and secondary feedstocks.

This approach brings the advantage of being a one-pot method for selective REE extraction and the ligands are (in general) recoverable. The approach has been demonstrated at lab scale, so more work is needed to test the approach at larger scales, and with commercially relevant mixtures. The techno-economics may be challenging due to the high cost of synthesising the ligands, so designing ligands that can be synthesised cheaply at large quantities would be a solution to this. Further purification of the resultant REE oxides may be required before being (re)entered into the supply chain.

2.8 Bioleaching and biorecovery (TRL 3 – novel)

Introduction

Bioleaching, or microbial leaching, is an innovative and eco-friendly process for extracting metals from ores using microorganisms (Bonificio et al., 2016; Shi et al., 2023). Unlike traditional metallurgical methods such as smelting, which can release harmful emissions, bioleaching leverages the natural abilities of certain bacteria and archaea to dissolve and mobilise metals. This technique is particularly valuable for recovering metals like copper, gold, zinc, and uranium from low-grade ores, tailings, and even electronic waste, where conventional methods may be inefficient or uneconomical.

Bioleaching offers several advantages, including reduced energy consumption, lower greenhouse gas emissions, and the ability to operate on-site with minimal environmental disturbance. However, it also faces challenges such as slower reaction rates and sensitivity to environmental conditions. As technology advances, bioleaching is gaining recognition as a sustainable solution for resource recovery, especially in an era of depleting high-grade ore reserves and increasing focus on circular economies.

Innovation opportunities

Bioleaching is increasingly being explored for the recovery of REEs due to its potential for processing low-grade ores and waste materials with less environmental impact. Research demonstrates its application across various REE-containing resources, including monazite sand, red mud, bauxite, and coal fly ash.

For example, monazite, a primary REE resource, has been studied using fungi such as Aspergillus species and microbes like Acidithiobacillus ferrooxidans. These organisms produce organic acids that help dissolve REEs from the mineral matrix. However, bioleaching efficiency for monazite remains relatively low compared to secondary resources like industrial wastes, which are more amenable to microbial action.

Secondary resources, such as red mud and bauxite, have shown promise. In bauxite, bioleaching using Acidithiobacillus ferrooxidans or organic acids produced by fungi can recover significant proportions of REEs, particularly middle REEs like neodymium (Nd) and gadolinium (Gd). Recovery rates can range from 26% to over 60%, depending on the resource and bioleaching method.

This technique is still in its developmental stages, and challenges remain, including improving efficiency, reducing costs, and understanding microbial interactions at a molecular level. Nonetheless, bioleaching holds potential as an eco-friendly approach to REE recovery.

2.9 Phytomining (TRL 2/3 — novel)

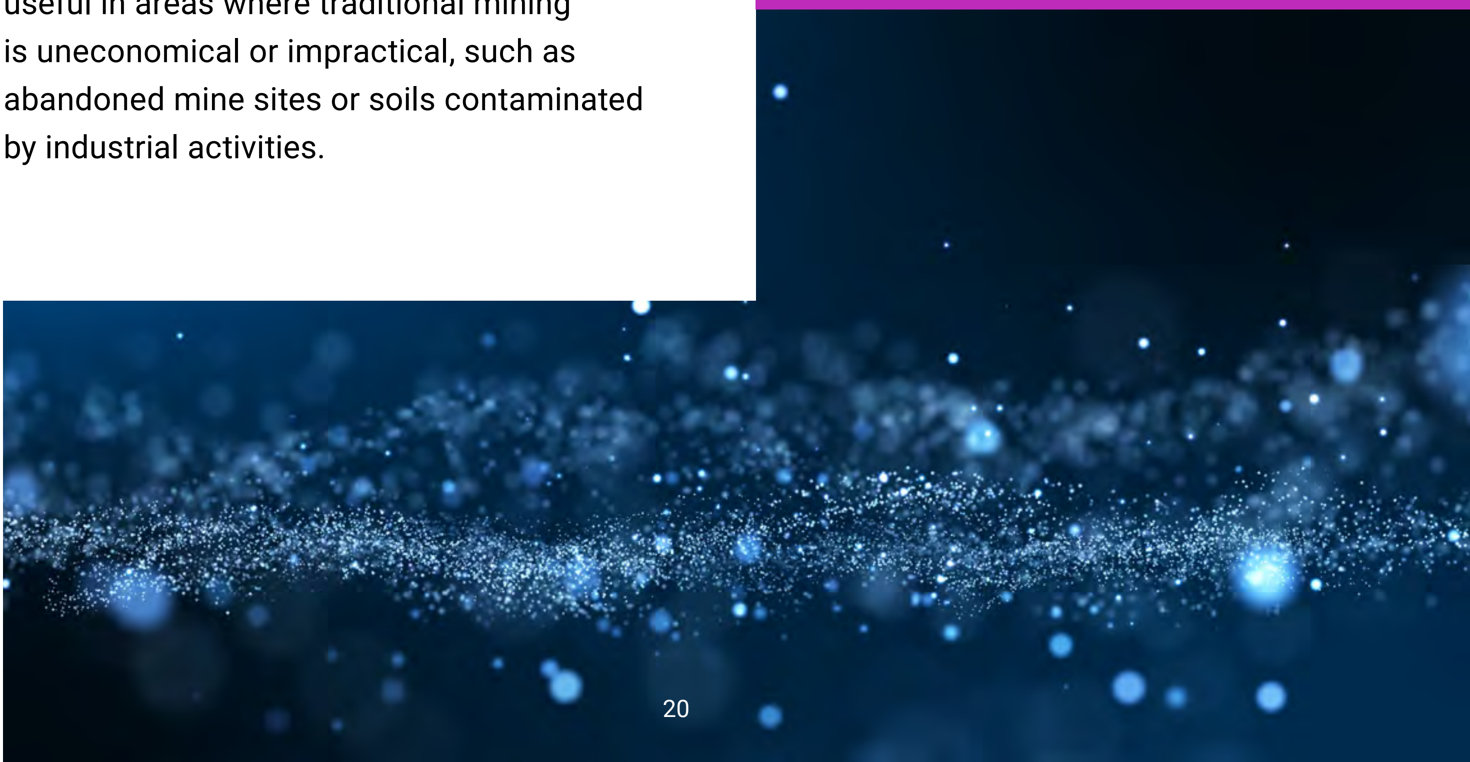
2.9.1 Introduction

Phytomining is an innovative and sustainable technology that uses hyperaccumulator plants to extract metals from soil, particularly in areas with low-grade or contaminated mineral deposits (Dinh et al., 2022). This process combines agriculture and metallurgy to recover valuable metals like nickel, cobalt, zinc, and even gold. It offers an eco-friendly alternative to traditional mining methods, reducing environmental degradation while promoting land rehabilitation.

Hyperaccumulator plants, such as the Alyssum species, absorb metals through their roots and concentrate them in their shoots and leaves. The harvested biomass is then incinerated to produce bio-ore or ash, which can be processed to extract the target metals. Phytomining is particularly useful in areas where traditional mining is uneconomical or impractical, such as abandoned mine sites or soils contaminated by industrial activities.

The advantages of phytomining include its ability to recover valuable resources while restoring degraded landscapes and mitigating environmental hazards. Additionally, it produces lower greenhouse gas emissions and minimises the need for chemical-intensive extraction processes. However, its limitations include slow biomass growth rates, variability in metal uptake depending on soil conditions, and the need for extensive land areas for economically viable operations.

With advancements in biotechnology and plant genetics, phytomining holds significant potential as a green solution for metal recovery and land restoration.



Innovation opportunities

Innovation opportunities in phytomining for REE recovery span several areas. The identification and genetic engineering of hyperaccumulator species tailored for REEs could dramatically improve the efficiency of metal uptake and accumulation. Advances in plant biotechnology, such as the manipulation of root systems and metal transporter proteins, could enable higher REE concentrations in plants, making phytomining commercially viable.

Developing optimal soil amendments and fertilisers to enhance REE bioavailability is another promising area. Innovative formulations could improve the mobility of REEs in soil, increasing their uptake by plants without degrading soil health.

Furthermore, integrating phytomining with downstream processes for REE extraction from biomass, such as bioleaching or pyrolysis, offers opportunities for a fully circular and environmentally friendly recovery system.

Phytomining also enables the remediation of REE-contaminated sites, addressing environmental concerns while providing a sustainable source of these critical materials. With advancements in plant science, soil chemistry, and extraction technologies, phytomining has the potential to provide a new mode of REE recovery, supporting resource sustainability and environmental stewardship.

3 Conclusion

The processing segment of the REE value chain is a significant contributor to carbon emissions, chemical use, and risk due to the widespread use of traditional separation approaches.

As new primary and secondary REE supply chains establish themselves in the UK, there is an opportunity to innovate and deploy a portfolio of processing technologies to significantly improve efficiencies, material recovery rates, and commercial and environmental performance – see Appendix A. for a list of current UK a cademic and commercial expertise in each technology area.

The application of digital process control technologies, and computer modelling for material discovery and formulation optimisation, is a key opportunity across most if not all of the REE processing technology areas.

As these technologies rely on the bespoke performance of either an individual molecule (e.g. a ligand or extractant), bulk chemical (solvent or ionic liquid), material (membrane) or biological organism (microbe or plant), digital tools can be used to design the best-performing versions of these. Moreover, the inline monitoring and management of chemical processes can bring additional efficiencies once these technologies are integrated into an engineered solution.

Another opportunity is in the manufacture of the chemicals and materials needed to perform the REE processing. The UK has significant infrastructure and expertise for the manufacturing of chemical and material products, largely based on historic investments in oil and gas, industrial chemicals (like coatings) and metals, which can be repurposed to produce the materials of the future. Coupled with expertise in green chemistry, the UK has an opportunity to produce these new chemicals and materials in a sustainable manner.

It will be important to perform sufficient technoeconomic analysis to identify the best technology or portfolio of technologies to process REEs from a variety of primary and secondary streams, ensuring that the best approach is chosen for the job. This, along with support for scaling the solutions to commercially relevant quantities, will enable the UK to become a leader in sustainable REE processing.

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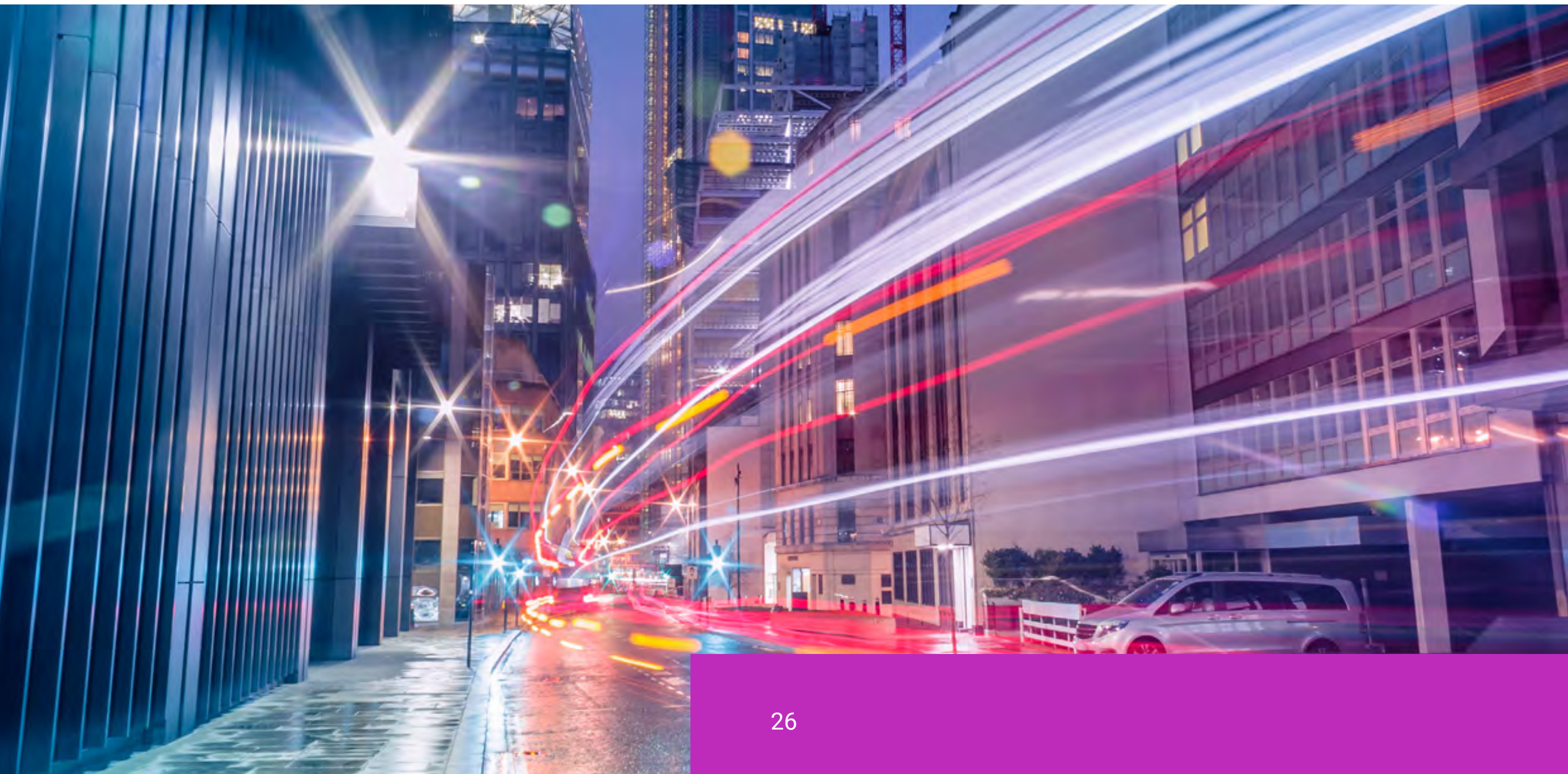
Appendices

Appendix A. UK position on processing technologies

The following table outlines the landscape of UK academic and commercial expertise across the REE processing technologies discussed in this report, with reference to key pieces of research.

Technology area	Academic expertise	Commercial expertise	Key projects/research papers
Solvent extraction	Uni. Edinburgh Uni. Manchester Uni. Sheffield Uni. Warwick	JM Iconichem Pensana Mkango Altilium Metals	**SCREAM** **ReREE**
Ionomettalurgy	Queens Uni. Belfast Imperial College Uni. Leicester Uni. York Uni. Manchester	Nanomox Ionic Technologies	**REEMAG** **A demonstration scale magnet recycling plant** **Recycling of REEs with ILs**
Plasma separation	York Plasma Institute @Uni. York Uni. Liverpool UCL	Lightning Machines Tetronics	**Opportunities for plasma separation techniques in rare earth elements recycling**
Chromatography	Uni. Edinburgh Queens Uni. Belfast UCL	JM Total Analytical Solutions (TAS) BASF	**Application of ionic liquid-liquid chromatography (ILLC) to extractions of metals**

Membrane seperation	Uni. Manchester Uni. Southampton	Evove Evonik Watercycle Technologies	**Inorganic 2D Materials for Selective Separation Membranes**
Ligand floc.	Uni. Oxford	Seloxium	**Mine to Magnets**
Supramolecular chem.	Uni. Edinburgh Uni. Cambridge		**A Simple Supramolecular Approach to Recycling Rare Earth Elements**
Bioleaching	Uni. Edinburgh Uni. Coventry Uni. Kent Uni. Durham Uni. East Anglia Uni. Nottingham	N2S	**Metals in Biology (E3B)** **Scaling-up Engineering Biology for Enhanced Environmental Solutions** **BEAR - Bioleaching and Electrodialytic Applications for metal Recovery from wastes**
Phytomining	Uni. York Brunel Uni. Uni. Nottingham Uni. Kent	Phyona	**Engineering Biology Mission Hub** **PhytoREE**



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