

Advancements in rare earth element (REE) extraction using green technologies: Practical strategies to adopt in the Australian context

R.A. Welter^{*}, A. McCoy-West, K. Shahbaz, I. Sanislav, H. McCoy-West, G. Vamvounis

College of Science and Engineering, James Cook University, Townsville, Queensland, Australia

ARTICLE INFO

Keywords:

Bioleaching
Ionic liquid
Deep Eutectic Solvent
Electrokinetic Mining
Green Solvents
Sustainable hydrometallurgy
Critical minerals

ABSTRACT

Australia holds the world's fourth-largest reserves of rare earth elements (REE) and is an important global producer. Historically, Australia has contributed approximately 5% of global REE extraction; however, its share has increased over time, reaching about 8% of global extraction in 2025. Currently, the REE mining sector is concentrated in Western Australia. However, other Australian states also have significant potential for REE mining. Queensland hosts a range of both clay-hosted and mineral-hosted REE ores, which importantly include both heavy-REE and light-REE enriched deposits. An advantage is that most of these ores are found near the surface, which significantly reduces extraction costs. However, the conventional REE extraction and purification technologies rely on toxic, corrosive and environmentally harmful reagents, which conflict with Queensland's strategic industrial priorities for sustainable and low-impact processing. This study explores different pathways (e.g. bioleaching, electrokinetic, organic acids and novel green solvents, including ionic liquids and deep eutectic solvents) in which efficiency and environmental care can coexist within economically feasible processes, depending on the mineralogy and physicochemical properties of the ores. Unlike previous reviews, this work provides a Queensland-focused comparison of green extraction routes, linking ore mineralogy with process selection to support practical decision-making for regional REE mining. All the routes were evaluated regarding the chemical mechanisms, thermodynamic properties, operational conditions, costs, efficiency, optimisation, scalability, sustainability and environmental impact. The analysis indicates that bioleaching and deep eutectic solvent systems offer the most promising near-term pathways for clay-hosted and tailings-derived REE, while hybrid approaches will be required for crystalline ores.

1. Introduction

Rare Earth elements are essential to modern green technologies due to their unique magnetic, optical, and thermal properties. They have been vastly applied across different industries, from defence to medical, for electrical vehicle motors, turbine generators, high-tech screens and displays, and catalytic converters for combustion engines, resulting in reduced gas emissions (Alonso et al., 2012; Binnemans et al., 2018). However, despite their importance for enabling green and clean technologies, the circular economy for the mining and refining of REE remains unsatisfactory due to current eco-unfriendly routes (Balaram, 2019; Jha et al., 2016). Although most REE occur predominantly in the trivalent state, a few (notably Ce, Eu, Sm, and Yb) display variable oxidation states, which affect solubility, complexation and leaching behaviour and therefore influence downstream hydrometallurgical efficiency (Balaram, 2019; Cicconi et al., 2021; Krishnamurthy and Gupta,

2015).

Processing REE ores requires several steps of which mining, beneficiation, hydrometallurgy, refining, and purification are potential environmental challenges. Firstly, mining requires different approaches due to the ore deposits' size and depth (Jha et al., 2016; McNulty et al., 2022). Queensland's deposits typically occur as surface to relatively shallow subsurface rather than deeper underground ores (Hughes et al., 2023; Huleatt, 2019). The advantages of mining in this case are that the process tends to be cheaper and has lower operational risks (Bridge, 2004; Hughes et al., 2023). However, there are disadvantages as well. Surface mining results in a larger area being explored, which disturbs the ecosystem, alters landscape structure, and causes soil erosion (Farjana et al., 2019; Worlanyo and Jiangfeng, 2021). Consequently, there is an increase in the spatial footprint of waste rock, contamination, acid mine drainage, and chemical dispersion into the surrounding ecosystem (Farjana et al., 2019). Regarding sub-surface mining,

^{*} Corresponding author.

E-mail address: rosilene.weltermgabs@jcu.edu.au (R.A. Welter).

<https://doi.org/10.1016/j.mineng.2026.110513>

Received 7 April 2026; Received in revised form 29 May 2026; Accepted 4 June 2026

Available online 29 June 2026

0892-6875/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

although less visually disruptive, it results in impacts such as subsidence, groundwater contamination and more energy requirement (Bridge, 2004; Dehkordi et al., 2024).

Beneficiation (e.g., crushing, grinding, flotation, magnetic separation, gravity separation) improves the physical properties of the ores, resulting in a better feedstock for the next step, hydrometallurgy, where REE are removed from the ores (Huang et al., 2015; Jha et al., 2016; McNulty et al., 2022). The most common hydrometallurgy mechanism is leaching (Huang et al., 2015; Ibad et al., 2024; Jha et al., 2016; Lakshmanan, 1992; Li et al., 2018; Wu et al., 2018). It is the crucial step to achieve higher efficient extraction processes. The next step is refining, in which the mixed leach solution rich in REE and impurities, is processed to separate the REE from other constituents (El Ouardi et al., 2023; Jha et al., 2016). The most common mechanism is liquid–liquid extraction, but other methods are promising, such as ion exchange, electrochemical methods, and membrane-based methods (El Ouardi et al., 2023; McNulty et al., 2022; Parhi et al., 2020). Although the extent of purification depends on the final application. The purification remains the most challenging stage due to the almost identical physicochemical properties of the REE (Binnemans et al., 2018; Krishnamurthy and Gupta, 2015). The application of microfluidic separation systems might offer a novel sustainable pathway to perform this step, providing high selectivity (Feng et al., 2025; Kolar et al., 2016; Santana et al., 2018).

Most of the methods introduced previously require hazardous and strong chemicals (Han et al., 2025; Jha et al., 2016; Khalid and Santos, 2025). Conventional REE leaching, for example, depends upon strong acids, such as sulfuric or hydrochloric acids, which result in soil and water contamination, fauna and flora damage, and air pollution (Farjana et al., 2019; Han et al., 2025; Jha et al., 2016). Thus, most of the countries, including Australia and the United States of America, send their REE feedstocks to other countries, where the REE extraction can proceed at low cost and with minimal environmental legislation (Barazi et al., 2025; Chen et al., 2024a; Mancheri, 2015; UFOP, 2020, 2016). China has dominated the separation and refining steps for decades, reaching about 97% of global REE processing in 2010 (Mancheri et al., 2019; Wübbeke, 2013). However, China has recently shifted some REE processing to Myanmar due to lower cost and weaker environmental regulations (Meehan and Lawn, 2024; Marsden, 2024). Currently, Myanmar is considered the largest supplier of heavy rare earth elements (HREE), with a growing market share (Chinkaka et al., 2023; Liu et al., 2023). Moreover, other countries have emerged as destinations for REE processing, such as Cambodia, Laos, and Madagascar (Chen et al., 2024a; Liu et al., 2023). Despite recent diversification, China still accounts for about 90% of global capacity for REE separation processes (Chen et al., 2024b; Mancheri et al., 2019).

Australia's REE market is dominated by Western Australia (WA) (Hoatson et al., 2011). The Mt Weld deposit (Eastern Goldfields) is one of the richest REE deposits over the globe. It has grades reaching up to 14% of total rare earth oxides (TREO) in the primary body that formed from a Proterozoic carbonatite intrusion and is rich in Nd and Pr (Jaireth et al., 2014). The Yangibana deposit (Gascoyne Province) is enriched with Nd, Pr, Dy and Tb, with the REE hosted in monazite and xenotime (Jaireth et al., 2014). There are also heavy-mineral sand deposits (monazite and xenotime) along the WA coastlines, such as Eneabba, Calypso, Eucla Basin and Perth Basin. Additional REE occurrences include lignite-associated deposits (e.g. Mulga Rock region) and pegmatite (Cooglegong-Pinga Creek region) (Hoatson et al., 2011; Jaireth et al., 2014).

Queensland is the second largest state in Australia and has several prospective REE ore deposits found in multiple types of ores (Hoatson et al., 2011; Jaireth et al., 2014). The region has a long and complex geological history (~2 Ga) and hosts a wide range of prospective resources, including clay-hosted deposits (e.g., Hughenden and Kennedy), phosphate-rich deposits (e.g., Georgina Basin), and legacy tailings, such as those at Mary Kathleen (Anenburg et al., 2021; Hoatson et al., 2011; Jaireth et al., 2014). Although a wide variety of ores are found across the

state, most of them are found at the near subsurface (<20 m), making extraction easier and generally cheaper with less environmental damage (Bridge, 2004; Hughes et al., 2023). Queensland also has another important advantage, which is the large mining experience in different metals (e.g. zinc, lead, and copper) (Golev, 2025; Hoatson et al., 2011; Hughes et al., 2023; Poulet et al., 2017). This knowledge in hydrometallurgy can be translated to the REE mining, but the need for sustainable and greener mining processes is required to improve the local market in accordance with government policies (Golev, 2025; Jha et al., 2016). In this pathway, different methods have already been tested at small scales such as microorganisms and organic acids (Gergoric et al., 2018; Rasoulnia et al., 2021). Moreover, other methods have been evaluated around the world, such as green solvents like ionic liquids (IL) (Alguacil et al., 2024; Li et al., 2020; Quijada-Maldonado and Romero, 2021) and deep eutectic solvents (DES) (Entezari-Zarandi and Larachi, 2019; Martín et al., 2023), electrokinetic leaching (Dushyantha et al., 2024; Kang et al., 2024), membranes (Abbasi et al., 2018; Carretas et al., 2023; Parhi et al., 2020) and microscale reactors (Feng et al., 2025; Kolar et al., 2016).

This review systematically examines green and emerging REE processing routes for Queensland ores, critically evaluating their performance across diverse ore mineralogy, operational conditions, thermodynamic behaviour, and scale-up potential. For the first time, these technologies are comparatively assessed within a unified framework that integrates technical efficiency, economic feasibility, and environmental performance, supported by targeted case studies. By explicitly aligning processing strategies with Queensland and northern Australia's geological characteristics and sustainability-driven policy requirements, this review provides practical, decision-oriented guidance for expanding the regional REE market under environmentally responsible conditions.

2. Geochemical context of rare earth elements (REE) ores

According to the International Union of Pure and Applied Chemistry (IUPAC), REE comprise the group of lanthanides, from La (lanthanum) to Lu (lutetium), plus Y (Yttrium) and Sc (Scandium) (Connelly, 2005). They exhibit unique and closely related physicochemical properties, particularly their magnetic, optical, and catalytic behaviour, which distinguish them from other metallic elements (Binnemans et al., 2018; Krishnamurthy and Gupta, 2015). In nature, they are usually found as trivalent ions (REE³⁺) and filled up to the 4f orbital, but their outer shell is similar (ds²), so there is not significant variation in the chemical properties, and only a slight variation due to the electrons contraction, resulting in a small variation in the ionic radii (Krishnamurthy and Gupta, 2015). This behaviour leads to a variation in mineral-melt partitioning, resulting in the REE elements being split into 2 groups: LREE (La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd) and HREE (Dy, Tb, Ho, Er, Tm, Yb, Lu and Y) (Anenburg et al., 2021; Bea, 1996). The concentration of LREE or HREE varies significantly due to these properties and their response regarding the Lanthanide Contraction (Goodenough et al., 2016; Hughes et al., 2007). The type and concentration of REE in different deposits are strongly controlled by the geochemical characteristics of their protoliths and by crystal–melt partitioning governed by equilibrium processes between minerals and molten fluids (Hoshino et al., 2016; McCoy-West et al., 2015). REE attachment to the ores can simplistically be divided into two main processes: surface adsorption in ores like ionic-hosted, and inside the crystal lattices of the ore minerals, such as phosphates, carbonates and silicates (Van Gosen et al., 2014a; Voncken, 2016). The most common minerals that can contain significant amounts of REE are monazite, xenotime and bastnaesite (Van Gosen et al., 2014; Voncken, 2016).

Monazite is a phosphate mineral (PO₄)⁻ and contains mostly LREE (Voncken, 2016). Xenotime is also a phosphate mineral and is a primary source of HREE (Voncken, 2016). Bastnaesite is a fluorocarbonate [(CO₃)F⁻] and the primary source of LREE, predominantly Ce, La, Pr and Nd

(Van Gosen et al., 2014b; Voncken, 2016). LREE form stronger complexes with CO_3^{2-} and F⁻ and are more suitable for crystallisation in minerals within the carbonatite environment, such as bastnäsite, or monazite (Anenburg et al., 2021; Williams-Jones et al., 2012). By contrast, HREE exhibit higher hydration energies and form weaker carbonate–fluoride complexes under equivalent physicochemical properties, which enhances their solubility in hydrothermal solutions (Harmon et al., 2013; Williams-Jones et al., 2012). As a result, HREE tend to remain more mobile in hydrothermal fluids and are preferentially incorporated into minerals such as zircon, xenotime, and garnet, which are commonly associated with granitic and metamorphic systems (Stroncik and Niedermann, 2016; Wang et al., 2017; Williams-Jones et al., 2012). In addition, chloride ligands can form stable aqueous complexes with REE, enhancing their mobility in hydrothermal fluids and contributing to their redistribution during fluid–rock interaction (Williams-Jones et al., 2012). Table 1

Light REE (LREE) are more abundant, more viable economically and usually more requested at the high-tech market (Goodenough et al., 2016; Voncken, 2016). However, both LREE and HREE are spread globally across various geological formations, with heterogeneous concentrations and fractions, and are necessary in different industries (Hoshino et al., 2016; Van Gosen et al., 2019). Exploring the geological characteristics and comprehending the REE ore mineralogy are vital to go further with the mining and extraction procedures (Krishnamurthy and Gupta, 2015; Jha et al., 2016).

2.1. Rare earth elements mineralisation in Queensland

Queensland has a complex geological history spanning approximately 1.9 Ga, with the Mt Isa Inlier (part of the North Australian Craton) forming its western core (Chandler and Spandler, 2020; Ewart, 1982). This complex framework encompasses a wide range of near-surface mineral systems, including phosphate deposits, volcanic-hosted systems, heavy-mineral sands, clay-hosted deposits, and phosphorite-hosted apatite (Dutkiewicz et al., 2015; Valenta et al., 2021). As a result, REE show a heterogeneous distribution across Queensland, reflecting the diversity of geological settings and deposit types (Hoshino et al., 2016; Valenta et al., 2021).

2.2. Clay-hosted

The Hughenden region, located between Mount Isa and Townsville, has clay-hosted ores with resources at about 150 Mt and has been the focus of the Kennedy Project (Bradley and Read, 2024; Valenta et al., 2021). These deposits are typically associated with kaolinite-rich clay systems containing REE, including both light and heavy REE (e.g. Dy, Tb, and Y), and represent a relatively uncommon deposit type outside Asia (Goodenough et al., 2016; Yang et al., 2013). The mineralisation occurs close to the surface, with REE reported from the topsoil to depths of approximately 2–4 m in the Hughenden area (Bradley and Read, 2024). Similar but higher-grade ion-adsorption clay deposits are found in Jiangxi Province (China), which represents a major global source of HREE such as Dy and Tb (Goodenough et al., 2016; Yang et al., 2013). Although both regions contain near-surface ore deposits, Chinese ion-adsorption deposits are generally thicker and more laterally extensive, whereas deposits in Queensland tend to be shallower and more limited in vertical extent (Li et al., 2019; Valenta et al., 2021; Yang et al., 2013).

2.3. Sedimentary phosphorite hosted

Phosphorite deposits in the Georgina Basin, located in northwestern Queensland, form part of extensive Palaeozoic sedimentary sequences and are known to host REE, commonly associated with phosphate minerals (Dutkiewicz et al., 2015; Lisitsin and Valetich, 2022; Valenta et al., 2021). These sediments normally have high porosity, increasing the internal mass transfer of post-depositional fluids, promoting an

enrichment of REE (Dutkiewicz et al., 2015; Emsbo et al., 2015; Föllmi and Föllmi, 1996; McArthur and Walsh, 1984). Also, phosphorite deposits are dominated by carbonate-fluorapatite that hosts P_2O_5 (28–35 wt%), generally with a structure as $\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$ (McArthur and Walsh, 1984; McConnell, 1973). Apatite contains two calcium structural sites Ca(I) and Ca(II). In both cases, there are lattice defects that accommodate ions with radii closer to Ca, such as LREE (La^{3+} , Ce^{3+} , Nd^{3+} , Pr^{3+}), which are preferable instead of Ca due to their higher charge (Cloud, 1987; Hughes and Rakovan, 2002; McConnell, 1973; Pan and Fleet, 2002).

From a global perspective, phosphorite sediments are widely utilised as a source of fertiliser and a substantial by-product potential for LREE recovery (Emsbo et al., 2016, 2015). REE-bearing deposits are found, for example, in Morocco, where phosphate beds containing approximately 22–28 wt% P_2O_5 are mined at a rate of about 30–35 Mt/year using open-pit and underground methods (Amirah, 2024; Chlahbi et al., 2023; Daafi et al., 2014; Pistilli, 2024). Florida (USA, ca. 29–33 wt% P_2O_5) has phosphate ores distributed in extensive sedimentary basins, with extraction of about 10–15 Mt/year using dragline strip mining (Van Gosen et al., 2019). Compared to these sites, the Georgina Basin (Queensland, ca. 34–35 wt% P_2O_5) has more modest mining activity (~0.8 Mt/year), with phosphorite deposits that locally contain elevated REE concentrations and occur in relatively shallow profiles (Amirah, 2024; Hughes et al., 2023; Pistilli, 2024; Willin, 2022).

2.4. Peralkaline and volcanic-hosted

Peralkaline volcanic deposits are present worldwide, and the REE deposits are both on the surface and underground (Cui and Zhang, 2008; Krishnamurthy and Gupta, 2015). Round Top (USA) and Foxtrot (Canada) ores are near-surface, allowing relatively low-cost open-pit mining despite moderate TREO concentrations (600 ppm – Dy, Tb, Y, Gd) (Alonso et al., 2012; National Minerals Information Center, 2025). The Peak Range Volcanics (Central Queensland) have surface deposits with moderate grade (1000 ppm of TREO – Dy, Gd, and Y). It extends widely in a near-horizontal manner near the top, reducing operational mining costs. However, due to the lower grade, a large volume must be mined, which in turn tends to increase costs and environmental challenges (Chandler and Spandler, 2020; Valenta et al., 2021).

2.5. Granite-hosted

The Sybella Granite, located about 20 km southwest of Mount Isa, hosts a REE deposit characterised by weak-acid-soluble fluoro-carbonate minerals hosted in low-acid-consuming granite. The REE ores are found from the surface along a 14 km (“Sybella – REO Discovery Northwest QLD | Red Metal Ltd, 2025). Two broad zones, each 1 km wide, have been identified through drilling, with local high-grade breccia zones. Preliminary work suggests favourable processing characteristics, driven by the solubility of the dominant REE minerals and the benign geochemical signature of the host granite (Jackson and Emery, 2024; Valenta, 2021). Sybella shows similarities to Strange Lake (Canada) and Khaldzan Buregte (Mongolia), both peralkaline granite systems enriched in soluble REE minerals (Huston, 2024; Liu et al., 2023; Pistilli, 2024).

2.6. Heavy-mineral sands

The Cape York Peninsula hosts heavy mineral sand deposits containing monazite and xenotime, typically developed in coastal dune systems with total heavy mineral contents of approximately 1–1.5%, and therefore representing a potential source of both LREE and HREE + Y (Hitchman, 2018; Poulet et al., 2017; Valenta et al., 2021; von Gneilinski, 2015). The deposits in this area are formed by the erosion of granitic and metamorphic rocks (Hitchman, 2018; Poulet et al., 2017; Van Gosen et al., 2014b). The Urquhart Point deposit contains approximately 2.8–3.2 Mt of heavy mineral sand ore, which includes a mineral

Table 1
Comparison of representative rare earth element (REE) deposits in Queensland and their global analogues.

Deposit type	Location (Queensland)	Lithological host	REE-bearing minerals ¹	REE fractionation pattern	Global analogue	Ref
Granite-hosted (weak-acid soluble)	Sybella Granite (Red Metal discovery, Mt Isa region)	Sybella & Templeton granites; altered granite breccias	Fluorocarbonates (bastnäsite-group), minor monazite	LREE-dominant to mixed ²	Strange Lake (Canada); Khaldzan Buregtei (Mongolia)	(Chakhmouradian and Wall, 2012; Huston, 2024; Pistilli, 2024; Poulet et al., 2017; Valenta et al., 2021)
Heavy mineral sands	Sandy Mitchell (Ark Mines)	Coastal/alluvial mineral sands	Monazite (LREE), xenotime (HREE + Y)	Mixed	Chavara Monazite Sands (India); Manjary Monazite Sands (Madagascar)	(Jackson and Emery, 2024; Lucas, 2015; Poulet et al., 2017; Valenta et al., 2021)
Heavy mineral sands	Cape York Peninsula	Detrital heavy-mineral sands	Monazite, xenotime	Mixed	Chavara Monazite Sands (India); Myeik Monazite Sands (Myanmar)	(Jackson and Emery, 2024; Liu et al., 2023; Meehan and Lawn, 2024; Pistilli, 2024; Poulet et al., 2017; Rohner, 2023; Marsden, 2024; Valenta et al., 2021)
Clay-hosted	Kennedy Project	Kaolinite-halloysite regolith over granite	Surface-adsorbed REE	HREE-enriched	Longnan Ion-Adsorption Clays – Jiangxi (China)	(Bradley and Read, 2024; Li et al., 2019; Poulet et al., 2017; Valenta et al., 2021)
Clay-hosted	Hughenden	Deeply weathered granite; kaolinitic profiles	Adsorbed REE	HREE-enriched	Xunwu Ion-Adsorption Clays – Jiangxi (China)	(Bradley and Read, 2024; Kynicky et al., 2012; Valenta et al., 2021)
Peralkaline volcanic system	Peak Range Volcanics	Aegirine-riebeckite-bearing peralkaline rhyolites	Eudialyte-like phases	Mixed (LREE > HREE)	Round Top (USA); Nechalacho (Canada)	(Chandler and Spandler, 2020; Poulet et al., 2017; Spandler et al., 2020; Valenta et al., 2021)
Phosphorite-hosted	Georgina Basin (Ardmore, Phosphate Hill)	Marine phosphorites (CFA)	Apatite; secondary REE phosphates	LREE-dominant	Khouribga Phosphorites (Morocco); Bone Valley Phosphorites (USA)	(Huleatt, 2019; Huston, 2024; McNulty et al., 2022; Nkrumah et al., 2021; Pistilli, 2024)
Skarn/IOCG-related uranium-REE ⁴	Mary Kathleen (orebody)	Calc-silicate skarns overprinted by IOCG fluids	Allanite, apatite (CFA), monazite, bastnäsite	LREE-dominant; low HREE	Bayan Obo (China)	(Emsbo et al., 2016; Hughes et al., 2023; Hughes and Munro, 1965; Lottermoser and Ashley, 2005; Nkrumah et al., 2021; Poulet et al., 2017)
Tailings	Mary Kathleen mill residues	U-REE processing tailings	Fine-grained allanite + apatite	LREE-dominant, minor Y	Mountain Pass Tailings (USA)	(Lottermoser and Ashley, 2005; Nkrumah et al., 2021; Valenta et al., 2021; Vaughan et al., 2024)
IOCG with REE halo	Milo (GBM Resources)	IOCG breccia system	Disseminated REE phosphates; apatite; Y-P-REE halo	LREE-dominant	Olympic Dam REE Halo (Australia)	(Hoatson et al., 2011, 2011b; Huleatt, 2019; D Huston, 2024; S Jaireth et al., 2014; Queensland critical minerals prospectus, 2025; Rohner, 2023; P Rohner, 2023; Valenta et al., 2021)
IOCG with REE enrichment	Andy's Hill (Hammer Metals)	Hematite-magnetite IOCG ± breccias	Ce-La enrichment in alteration zones	LREE-dominant	Kiruna IOCG-REE Halo (Sweden)	(Huleatt, 2019; Huston, 2024; Pistilli, 2024)
IOCG / alteration zone	Koppany	Sulphide-carbonate altered volcanics	Ce-La-Nd-Pr	LREE-dominant	Cloncurry IOCG-REE Halo (Australia)	(Huleatt, 2019; Huston, 2024)
Skarn-associated REE	Mount Dorothy	Secondary copper-cobalt breccias	Y-rich + HREE-bearing phases	HREE-enriched	—	(Beckton and Hatcher, 2011; Poulet et al., 2017)
REE nodules (surface)	Coorabulka	Surface nodules over Allaru Mudstone	REE-Y phosphates	Mixed	—	(Nkrumah et al., 2021; Poulet et al., 2017; Queensland critical minerals prospectus, 2025; von Gnielinski, 2015)
REE surface lag + phosphates	Valroy	Surface lag over mudstones	REE-Sr-P-Pb enrichment	Mixed	—	(Branch and Humphries, 2012; Nkrumah et al., 2021; Poulet et al., 2017)
Phosphorite-xenotime Y deposit	Korella (PHM South)	Phosphate + xenotime-rich horizon	Xenotime (Y + HREE), apatite	HREE-enriched	Browns Range (Australia)	(Branch and Humphries, 2012; Hughes et al., 2023; Huleatt, 2019; Nkrumah et al., 2021; Poulet et al., 2017; Spandler et al., 2020)
U-REE-Cu breccias	Elaine Dorothy (Elaine 1/2/3)	Breccia zones near Mary Kathleen	TREO + U + Th; allanite + apatite	LREE-dominant	Olympic Dam Peripheral REE Zone (Australia)	(Beckton and Hatcher, 2011; Hughes et al., 2023; Huleatt, 2019; Spandler et al., 2020)

¹REE – Rare Earth Elements, ²LREE – Light Rare Earth Elements, ³HREE – Heavy Rare Earth Elements, ⁴IOCG – Iron Oxide Copper-Gold.

assemblage dominated by zircon and rutile with minor monazite and xenotime (Delzoppo, 2013). The Colmer Point deposit contains significant heavy mineral resources, including approximately 4.08 Mt of ilmenite, 1.02 Mt of zircon and 0.36 Mt of rutile (von Gnielinski, 2015). Although these deposits are considered moderate grades, similar monazite-rich coastal placers in India (e.g. Odisha and Kerala) have been commercially exploited for decades, demonstrating the economic viability of comparable ore types (Knorsch et al., 2025; Lucas, 2015; Poulet et al., 2017; Valenta et al., 2021).

2.7. Iocg-related rare earth elements halos

The Cloncurry district hosts multiple Iron-Oxide-Copper-Gold (IOCG) systems, several of which display peripheral REE enrichment associated with hydrothermal alteration halos (Beckton and Hatcher, 2011; Rohner, 2023; Valenta et al., 2021). Although not currently considered standalone REE ore bodies, these halos contain allanite, apatite and fluorocarbonate minerals capable of hosting LREE (Beckton and Hatcher, 2011; Rohner, 2023). Similar IOCG-related REE systems occur at Olympic Dam (Australia) and Norrbotten (Sweden), where REE enrichment accompanies Fe-oxide-alkali metasomatism (Hoatson et al., 2011; Huleatt, 2019; Huston, 2024; Liu et al., 2023). In Queensland, these signatures remain under-explored but may represent long-term potential for by-product REE recovery linked to copper extraction (Huston, 2024; Queensland critical minerals prospectus, 2025).

2.8. Tailings and historical mine wastes

The Mary Kathleen (MK) ore deposit in northwest Queensland (Mount Isa-Cloncurry mineral province) is historically known for its U extraction, with approximately 9 Mt of ore mined; however, processing of the ore resulted in the accumulation of REE-enriched tailings, with total REE concentrations of up to ~ 3 wt%, predominantly composed of LREE (mainly Ce, La, Nd, and minor Pr) (Nkrumah et al., 2021; Poulet et al., 2017; Vaughan et al., 2024). The deposit was mined by open-pit methods to a depth of approximately 230 m, and it is mineralogically dominated by allanite with minor apatite and monazite (Costelloe, 2003; Hughes and Munro, 1965). The REE were incorporated into the lattices of allanite crystals through coupled substitution of REE³⁺ for Ca²⁺, reflecting the strong structural compatibility of LREE in allanite and their relatively high mineral-melt partition coefficients (D values) compared to HREE (Chakhmouradian and Wall, 2012; Hoshino et al., 2016; Hughes et al., 2007). A similar substitution mechanism occurs in apatite, where REE³⁺ can replace Ca²⁺, leading to preferential incorporation of LREE; in contrast, monazite is a primary REE phosphate mineral in which REE are structural constituents, and Ca occurs only as a minor impurity (Chakhmouradian and Wall, 2012; Hoshino et al., 2016; Hughes et al., 2007). A comparable ore is found in Bayan Obo (Mongolia, China – Bastnäsite, monazite, fluorocarbonates), containing ~ 40 Mt of rare earth oxides, and it is considered the largest REE deposit in the world (Chakhmouradian and Wall, 2012; Drew et al., 1990; Ma et al., 2024; Zhou et al., 2020). The deposit extends from near-surface to depths of approximately 300 m and is responsible for a substantial proportion of global REE supply, producing on the order of 100,000–120,000 t of TREO/year. In contrast, the Mary Kathleen operation was significantly smaller in scale, with total ore extraction of approximately 9 Mt over its operational lifetime (Chakhmouradian and Zaitsev, 2012; Pistilli, 2024). The extraction processes differ between the two ores. At Bayan Obo, processing typically involves magnetic separation followed by flotation, and subsequent acid or alkaline cracking prior to solvent extraction, reflecting the complex multi-stage beneficiation and hydrometallurgical flowsheet required for REE recovery (Drew et al., 1990; Zhou et al., 2020). In contrast, at Mary Kathleen, REE remain largely in tailings following uranium production and may be recovered through targeted hydrometallurgical leaching routes. (Nkrumah et al., 2021; Vaughan et al., 2024, Vaughan et al.,

2021). In China, the iron is separated by magnetic process, followed by flotation for REE and Nb, acid/alkaline cracking and solvent extraction (Chao et al., 1997; Drew et al., 1990).

2.9. Economic diversification and supply chain security

The global market of REE has increased by 175% between 2005 and 2023 (National Minerals Information Center, 2024; Hammarstrom et al., 2017; Zhu, 2024) reaching a production of 353 kt and valued at USD 6 billion (National Minerals Information Center, 2024; Mandaokar, 2023; Zhu, 2024). Although cerium (Ce) dominates the global REE market in terms of production volume, Nd, Pr, Dy and Tb are regarded as the most strategically valuable REE because of their critical applications in high-performance permanent magnets, which are strongly desired for magnet technologies (Golev, 2025; Mandaokar, 2023). In 2023, this market was driven by China (~70%), followed by the USA (~12%) (National Minerals Information Center, 2024). Australia was responsible for about 17 kt, which represents about 5% of the global market, with the mining coming basically from Western Australia (Mount Weld – Lynas Rare Earths). Currently, Mount Weld represents about 3% of global reserves and 8% of extraction (Golev, 2025). Queensland has no significant extraction of REE, but the resources are estimated to reach about 4% of global reserves.

Despite China producing 70% of the global REE, more than 60% is reserved for internal consumption, which means that more than 42% (160 – 170 kt/year) of the world's REE market remains in China. Its domestic industries are focused on different sectors such as hybrid vehicles, wind power, electronics, defence, and robotics; by applying mainly Nd, Pr, Dy, Tb, Eu, Sm, and Y (Golev, 2025; National Minerals Information Center, 2025; Zhu, 2024), as shown in Table 2. Moreover, China controls about 90% of the global refining process (Barazi et al., 2025; National Minerals Information Center, 2024). The imbalanced market between China and Western countries, as described in detail in Table 3, highlights the geopolitical risks for some countries like the USA and Australia due to the potential supply chain disruptions and price volatility. However, Australia, like several other Western countries, faces challenges arising from the implementation of quotas, licensing requirements, and taxes, driven by the need to conserve limited REE resources for domestic use and to mitigate the environmental impacts associated with mining and refining REE (Balaram, 2019; Barazi et al., 2025).

To strengthen Australia's capacity to respond to global market demand while addressing national environmental challenges, the development of a domestic REE processing sector is essential. Queensland presents significant opportunities for REE extraction due to the diversity of ore types present in the region, together with its well-established mining and metallurgical infrastructure. These assets can be leveraged to support the development of a fully integrated REE value chain, rather than relying solely on experience gained from processing other commodities.

3. Rare earth elements extraction and processing technologies

Processing and separation of REE require several steps from mining to purification. The main steps are described in Fig. 1. The mining step depends on where the REE are found: underground or at the surface. When near to the surface, as seen in Queensland, the processes tend to be cheaper and less complex as they require less drilling, blasting and diesel consumption; although this does not necessarily mean they are environmentally cleaner overall (Arienzo et al., 2022; Liu et al., 2025; Dehkordi et al., 2024). Open-pit mining typically generates substantially larger disturbed areas, higher rates of waste-rock removal, increased dust and particulate emissions, and greater risks of surface-water and groundwater contamination, particularly where REE are associated with phosphates, apatite, clays or weathered profiles (Dehkordi et al., 2024; Shiksha, 2025; Haque et al., 2014). These factors can offset the apparent

Table 2

Crustal abundance, market distribution, global production, and major industrial applications of rare earth elements (REEs) (Barazi et al., 2025; Falconnet, 1985; Golev, 2025; Hidayat, 2025; Huleatt, 2019; Huston, 2024; Jaireth et al., 2014; Mancheri, 2015; Mandaokar, 2023; National Minerals Information Center, 2024; Pistilli, 2024).

Element	Crustal abundance (%) ¹	Global market ²	Global Production (t/year) ^{3, 4}	Use in Industry	Most Common Source (Country) ⁵
Sc	9.3%	1.0%	20	Ceramics, alloys	China, Australia, Ukraine
Y	14.0%	6.0%	10,000	Catalysts, magnets	China, Malaysia, Myanmar
LREE					
La	12.7%	10.0%	12,000	Catalysts, glass	China, USA, Myanmar
Ce	29.6%	20.0%	24,000	Chalco-catalysts, glass polishing	China, USA, Myanmar
Pr	3.8%	10.0%	5000	Magnets, lasers	China, USA, Myanmar
Nd	15.7%	30.0%	16,000	Permanent magnets, EV motors	China, Australia, USA
Sm	3.4%	2.0%	1,000	Magnets, reactors	China, Australia, USA
HREE					
Eu	0.6%	2.0%	500	Phosphors, lasers	China, Australia
Gd	3.4%	3.0%	1,000	MRI contrast agents, alloys	China, Australia
Tb	1.8%	5.0%	600	Phosphors, magnetostrictive alloys	China, Myanmar, Australia
Dy	2.1%	8.0%	1,300	High-temperature magnets	China, Myanmar, Australia
Ho	0.7%	0.5%	400	Lasers, calibration	China, Australia
Er	1.4%	0.5%	800	Fiber-optics, lasers	China, Australia, Ukraine
Tm	0.1%	0.5%	100	Portable X-rays, lasers	China, Australia
Yb	1.4%	0.5%	500	Stainless steel, sensors	China, Australia
Lu	<0.1%	0.5%	100	PET detectors, catalysts	China, Australia

¹Relative proportion of each REE in the Earth's upper crust, based on averaged geochemical models (Rudnick and Gao, 2003). Values represent approximate abundance and may vary slightly between datasets. ²Approximate share of each element in global REE demand by volume. ³Approximate share of each element in global REE demand by volume 2023–2024, aggregated from major producers. ⁴China remains the dominant producer of most REE (>70% of global supply), particularly for HREE-rich ion-adsorption clays processed in Jiangxi and Guangxi. ⁵Indicates the leading producing countries for each individual REE. For Scandium (Sc) and Yttrium (Y), production may include by-products from bauxite, titanium slags, and IAC leachates.

Table 3

Global rare earth elements (REE) production, reserves, refining capacity, domestic consumption, and exports by major producing countries (2024). (Barazi et al., 2025; U.S. Geological Survey, 2025).

Country	Extraction (kt TREO)	Refining	Reserves (kt TREO)	Internal Market (kt TREO/year)	Exports (kt TREO/year)
China	270	~90%	44,000	160–170	100–110
USA	45	<10%	1,900	~30	~15
Myanmar ^a	31	~0%	Not identified	<1	~30
Australia	13	<5%	5,700	~1	12
India	2.9	<1%	6,900	~2	~1
Russia	2.5	<1%	3,800	~1.5	~1
Brazil	0.8	<1%	21,000	~0.5	~0.3
Global	390	100%	130,000	195–205	185–195
Total					

¹Myanmar is listed as a major source of several HREE because it supplies 30–35 kt TREO/year of ion-adsorption clay concentrates to China. However, Myanmar does not have officially reported “resources” because extraction occurs in informal, non-JORC operations without geological modelling or resource estimation. Nearly 100% of Myanmar's concentrates are exported to China for refining.

reduction in energy intensity compared with underground mining. The second step consists in the beneficiation, where the REE-rich minerals are concentrated. After, the material enters the hydrometallurgy stage.

Leaching is the most common one, and it is applied to dissolve the REE. Depending on the ore type, leaching reagents may include inorganic acids (e.g. H₂SO₄, HCl, HNO₃), alkaline reagents or a previous cracking treatment (e.g. NaOH), ammonium salts ((NH₄)₂SO₄) for ion-adsorption clays, or organic complexing agents. This is an important step and is responsible for the biggest environmental damage (Balaram, 2023; Bridge, 2004; Haque et al., 2014). Currently, due to the environmental regulations, most western countries, including the USA send their REE-rich mineral concentrates to China as the processing steps from hydrometallurgy onwards are cheaper and faster (Barazi et al., 2025; Hammarstrom et al., 2017; IEA, 2020). The next step is refining, which involves advanced technologies to separate REE into high-purity concentrates. Finally, purification ensures the separation of individual ultra-pure oxides.

3.1. Mining and beneficiation methods for rare earth elements deposits in Queensland

As described previously in Section 2.1, Queensland ores are typically surface and shallow subsurface. The most common types of deposits are clay-hosted and heavy mineral sands. However, unlike the classic ion-adsorption clays from South China, recent studies demonstrate that the Queensland occurrences are better classified as non-ionic residual REE deposits, formed by deep weathering of REE-bearing parent rocks rather than by true ion-exchange mechanisms (Huleatt, 2019; Knorsch et al., 2025). These deposits contain REE predominantly in amorphous or nano-crystalline phases, phosphate residua and Fe–Mn

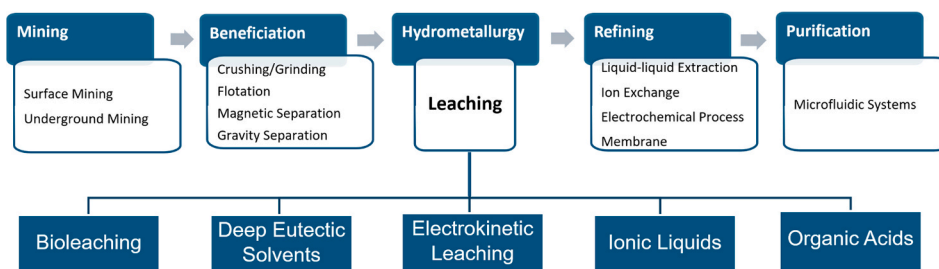


Fig. 1. General processing pathway for rare earth element (REE) production and representative leaching technologies under development.

oxyhydroxides, rather than loosely adsorbed onto clay surfaces, meaning that conventional ion-exchange leaching does not apply, and higher-acidity or alternative reagents are required to mobilise the REE (Goodenough et al., 2016; Knorsch et al., 2025).

These characteristics support low-cost mining operations by enabling free-digging methods, lowering energy and water demands, and minimising environmental disturbance, which in turn simplifies post-mining land and ecosystem restoration (Goodenough et al., 2016; Knorsch et al., 2025). Another potential REE source is by-product recovery, for example, phosphorites and tailings. It also has a low cost, since the mining infrastructure for other primary commodities already exists (Muddanna and Baral, 2021). Moreover, using existing tailings reduces the need to characterise new ores, reduces the environmental impact, and supports the circular economy by reprocessing waste streams (Haxel et al., 2022).

Queensland's current mining infrastructure for commodities such as vanadium, bauxite, coal, and phosphate provides a strong foundation that can be readily adapted to REE extraction, significantly lowering upfront costs associated with equipment, workforce training, and operational development. The vanadium deposits (Julia Creek area) and bauxite (Weipa area) are at very shallow depths (0 to 4 m) and require free-digging methods and are mined with scrapers, excavators, front-end loaders, and dozers. A similar approach has been applied at the Kennedy Project, which is currently at the exploration and pilot stage of REE in ion-adsorption clays (Valenta et al., 2021). The mining of coal (Bowen Basin – up to 50 m depth) and phosphate (Georgina Basin – 10 to 12 m depth) is made by strip mining, dragline, bucket wheel excavators, shovels, and large hydraulic excavators. Queensland is one of the global leaders of coal and phosphate mining by these methods. Thus, these are mature technologies with local expertise and the ability to deal with a large volume of ores, allowing co-production of REE (Hughes et al., 2023; Lazzarini, 2024).

A second common type of ore found in Queensland is the heavy mineral sands. Currently, this type of ore has been explored for zircon, ilmenite and rutile from coastal sediments (Cape York area – 3 to 5 m depth) (Bradley and Read, 2023; Poulet et al., 2017). These ores are mainly monazite and xenotime-bearing sands with an important LREE endowment. The extraction of commodities has been made by hydraulic dredging (cutter suction dredge), and wet separation (floating concentrator) followed by enrichment using wet high-intensity magnetic separators and gravimetric spiral separation. These methods do not need drilling or blasting, are low-cost and low-energy, and can be applied straight away for REE in parallel to the other commodities (Bradley and Read, 2023; Lazzarini, 2024).

Hard-rock ores are found in Mount Isa (200 – 300 m depth) and Mary Kathleen (150 m depth) areas, where U, Au, and Cu have been mined, and these deposits form large-scale open-pit (Poulet et al., 2017; Lazzarini, 2024). The mining is made by drilling (rotary and blast hole drills), hydraulic excavators, and large wheel loaders. The same techniques can be applied to allanite and apatite ores containing REE, as at Bayan Obo (China). The advantage in this case is the high scalability and co-mining of multiple commodities. Mary Kathleen is also well known due to the tailing reprocessing growing capacity of LREE (Ce, La, Nd) and a lower environmental footprint than opening a new mine site (Bradley and Read, 2023; Golev, 2025; Lazzarini, 2024). The mining method is made by reprocessing fine material already ground and stored in tailing dams, by dredge or excavators, followed using pumps and piping systems, thickeners and filters, agitation tanks and solvent extraction (Lottermoser and Ashley, 2005).

3.2. Eco-friendly hydrometallurgical extraction of rare earth elements

For deposits where REE are structurally incorporated within mineral lattices, such as in silicates and phosphates, REE may occur either as essential structural constituents (e.g. monazite) or through coupled substitution for cations such as Ca^{2+} (e.g. in allanite). This configuration

requires aggressive hydrometallurgical steps to break the lattice and release REE. These ores typically require pre-treatment by roasting or calcination, followed by strong acid or alkaline leaching under relatively harsh conditions, and subsequent purification via solvent extraction or ion exchange. As a result, developing eco-friendly processing routes is more challenging for these systems. Nevertheless, such approaches are critically important, as lattice-bound REE minerals—including allanite, monazite, xenotime, and apatite—are dominant in several Queensland deposits (e.g. Mary Kathleen, Cape York, and the Georgina Basin) (Emsbo et al., 2015; Hughes et al., 2023; Hughes and Munro, 1965; Hughes and Rakovan, 2002; Knorsch et al., 2025). Despite their prevalence, these ores remain comparatively under-studied due to their mineralogical complexity, further highlighting the need for targeted research.

Conversely, ores where the REE are bound on the surface by their charges and electrostatic forces, such as clay-hosted, do not require as corrosive leaching reagents (Kynicky et al., 2012). In this case, environmentally friendly reagents such as ammonium salts or organic acids are sufficient to achieve high extraction efficiency of the ionically bound REEs (Qu and Lian, 2013; Yang et al., 2013). This approach eliminates the need for lattice breakdown, reducing reagent consumption, energy use, and overall environmental impact (Balaram, 2019; Kynicky et al., 2012). Consequently, there has been significant interest in applying environmental approaches to this type of ore. Thus, the hydrometallurgical route in Queensland varies from high-intensity, chemically aggressive processing for lattice-bound REE minerals to milder and more selective leaching approaches for ionically bound REE, as widely reported in REE processing studies (Binnemans et al., 2018; Jha et al., 2016).

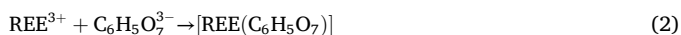
3.2.1. Bioleaching

Bioleaching is facilitated through the metabolic activity of the microorganism producing organic acids (e.g. acetic, gluconic, citric, and oxalic) to convert insoluble minerals, such as those containing REE, to soluble metal ions (Brisson et al., 2016; Rawlings and Johnson, 2007; Rawlings and Silver, 1995; Rohwerder et al., 2003; Vera et al., 2022) that can form complex chelated structures (Christenson and Schjiff, 2011). They also work by solubilising phosphates, making it a promising method for crystal- REE^{3+} such as monazite (Brisson et al., 2016). It is considered an environmentally sustainable and cost-effective method for extracting REE from different sources (e.g., low-grade ores, industrial wastes, and tailings) (Bosecker, 1997; Jones and Santini, 2023; Rohwerder et al., 2003). Furthermore, most of the microorganisms applied for REE bioleaching provide selectivity between HREE and LREE, and bioremediation potential, simultaneously extracting valuable metals and stabilising their residues (Ren et al., 2009; Sarkodie et al., 2022).

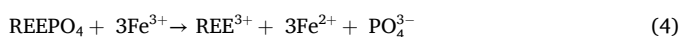
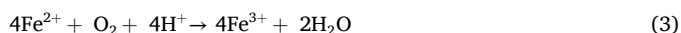
Bioleaching efficiency depends on the mass transfer diffusion in the system between the phases, type of microorganism, and operational parameters. At laboratory and pilot scale, bioleaching of REE-bearing materials has achieved from tens to over ninety per cent extraction, depending on the ore type and microorganism, for example, up to 83% La and 23% Ce from spent fluid catalytic cracking (FCC) catalyst with *Acidithiobacillus ferrooxidans*, and ~ 80–95% La, Nd and Y from ion-adsorption type REE ores using *Acidithiobacillus ferrooxidans*, and pyrite (Muddanna and Baral, 2021; Rasoulnia et al., 2021; Zhao et al., 2025a). However, it remains challenging to scale up this process to an industrial scale (Prodius et al., 2020; Rohwerder et al., 2003). The main difficulty at larger scale arises from pH and oxygen gradients, which develop because the mild agitation, essential for microbial viability, provides insufficient mass transfer, ultimately reducing system homogeneity (Rasoulnia et al., 2021; Rawlings and Johnson, 2007). Another challenge arises from the inherently slow kinetics of both microbial growth and leaching, which often require residence times of several days to achieve optimal recovery. This, in turn, necessitates large reactor volumes, extensive plant footprints, and batch or cascade reactor configurations, leading to increased capital expenditure (Christenson and

Schijf, 2011). Moreover, microbial growth and leaching can occur simultaneously in a one-step bioleaching process, or they can be separated into a two-step approach in which leaching is performed after an initial microorganism cultivation stage (Johnson, 2014; Rawlings and Silver, 1995). The one-step process requires fewer steps and non-dedicated vessels for each step, increases the adsorption on the surface, reduces the mass transfer limitations, but the presence of metals during the cultivation stage can reduce microbial growth rate and slow the leaching kinetics due to their inhibitory or toxic effect on the microorganisms at the inoculation stage (Bosecker, 1997; Jones and Santini, 2023; Rohwerder et al., 2003). The two-step process requires more space and dedicated vessels; however, the reaction kinetics of both processes can be optimised by applying the optimal operational conditions to each step (Brisson et al., 2016; Dusengemungu et al., 2021; Owusu-Fordjour and Yang, 2023; Rohwerder et al., 2003).

Bioleaching processes can be mediated by various microorganisms, including *chemolithoautotrophic* bacteria and *archaea*, as well as heterotrophic fungi. Heterotrophic fungi such as *Aspergillus niger* and *Penicillium simplicissimum* are the most commonly used in REE focused bioleaching (Brisson et al., 2016; Dusengemungu et al., 2021; Owusu-Fordjour and Yang, 2023; Reed et al., 2016; Shi et al., 2023). The overall mechanism can be summarised as a combined biochemical dissolution process driven by organic acid secretion, redox changes, and metal–ligand complex formation at low pH (typically pH 2.0–3.0 for optimal REE dissolution) (He et al., 2025; Liu et al., 2025). The fungi metabolise organic carbon sources via glycolysis and the tricarboxylic acid (TCA) cycle, secreting large amounts of citric, oxalic, gluconic, and lactic acids into the medium (Bosecker, 1997; Gadd, 2007). The acids act by acidolysis (Equation 1), lowering the pH and promoting proton attack on mineral lattices, and by complexation (Equation 2), where organic anions chelate REE³⁺ ions released from mineral surfaces, keeping them in solution (Barmettler et al., 2016; Liang et al., 2024). In addition, oxalate and citrate ligands form stable soluble complexes with lanthanides, enhancing mobilisation from phosphates, carbonates, or clays (Rasoulnia et al., 2021).



Chemolithoautotrophic bacteria (e.g. *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Leptospirillum ferrooxidans*) are the most commonly used bacteria in REE bioleaching. These microorganisms obtain energy from the oxidation of iron ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$) and reduction of sulphur ($\text{S}^0 \rightarrow \text{SO}_4^{2-}$), generating ions that act as leaching agents (Equation 3) (Johnson, 2014; Rohwerder et al., 2003). The presence of sulphate ions results in a corrosive environment and enhances REE solubilisation from phosphates and carbonates via indirect leaching mechanisms (Rohwerder et al., 2003; Vera et al., 2022). The cation generated (Equation 4) is used again as the feed for the first reaction by the microbe and restarting the process by sustaining a cyclic redox process indeterminately (Bosecker, 1997).



Regarding selectivity, bioleaching tends to favour LREE over HREE. This is due to the larger ionic radii and weaker complex stability constants of LREE–citrate or LREE–oxalate complexes, which promote faster dissolution and diffusion (Brisson et al., 2016; Owusu-Fordjour and Yang, 2023; Rasoulnia et al., 2021). However, mixed acid systems or the presence of gluconic acid can improve HREE mobilisation by shifting the complexation equilibria (Azimi, 2025; Dong et al., 2023; He et al., 2025; Yaraghi et al., 2019). Co-culture strategies, combining bacteria and fungi, and extending residence times can partially bridge the gap faced by individual microbes, enhancing the extraction of both REE groups.

Bioleaching has shown measurable extraction efficiencies across different ore types, including phosphate-rich minerals (30–70% REE recovery under fungal systems) (Ma et al., 2023; Qu and Lian, 2013) carbonate-bearing hosts (40–65% depending on acidity and ligand availability), (Dong et al., 2023; Rasoulnia et al., 2021), and ionic-hosted deposits (60–94% depending on microbial species and residence time) (Brown et al., 2023; Owusu-Fordjour and Yang, 2023; Rohwerder et al., 2003). These types of ores are abundant in Queensland, particularly in the Kennedy and Georgina regions, making fungal bioleaching a promising green route for local REE extraction.

Bioleaching works well at mild operational conditions (T: 25–35°C, aerobic conditions), as described in Table 4. However, considering that most of the microbes prefer acid environment, pH between 1.5 and 3, higher efficiency could potentially be achieved (Dong et al., 2023; Ren et al., 2009). *A. niger* leached ~ 31% of total REE from coal fly ash at pH 2.5, 30°C, 14 days (Ma et al., 2023), while *Penicillium tricolour* leached ~ 70% of REE from red mud at pH 2.8 and 28°C (Qu and Lian, 2013). In ion-adsorption type rare earth ores bioleached with *Acidithiobacillus ferrooxidans* at initial pH 2.0, REE recoveries above 90% for La, Nd and Y, and ~ 77% for Ce have been reported (Zhao et al., 2025a). Other parameters include the solid particle size distribution, the metallic matrix, the presence of radioactive compounds, and the pulp density (Rasoulnia et al., 2021). For fungi, the oxalic and citric acids are the most common and efficient organic acids produced by the microbes (Ma et al., 2023; Qu and Lian, 2013). The kinetic efficiency tends to be low and durations up to 10 to 20 days can be required to reach the extraction equilibrium (Zhang et al., 2018). Qu and Lian (2013) compared the efficiency of solely bioleaching against the use of pre-culturing as pre-treatment, with the two procedures producing comparable extraction efficiencies, leaching about 70% of the REE (pH 2.8 and 28°C) (Qu and Lian, 2013). More recently, Wang et al. (2025c) showed that *A. niger* extracted up to 94% of REE, corroborating the fact that over time the bioprocess has become more efficient and could be industrially feasible in the future. Bacterial leaching results in higher efficiency in the presence of sulphur and iron, with *Acidithiobacillus ferrooxidans* achieving 60–70% Dy and Y recovery and 40–50% La and Ce extraction from ion-adsorption clays at 30°C, pH 2.0, within 14 days (Wang et al., 2025c). *Acidithiobacillus ferrooxidans* oxidizes $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ and $\text{S}^0 \rightarrow \text{SO}_4^{2-}$, creating ferric ions and acidity that promote acidolysis and redoxolysis of REE-bearing minerals, while *A. thiooxidans* enhances sulphur oxidation and acid generation in mixed cultures (Dong et al., 2023; Rohwerder et al., 2003). *Leptospirillum ferrooxidans*, an obligate iron oxidiser, is particularly active at higher redox potentials ($E_h > 600$ mV) and contributes to the rapid regeneration of Fe^{3+} under aerobic conditions.

Thermodynamically, this process tends to be endothermic ($\Delta H > 0$), as energy is required to disrupt mineral lattice bonds and mobilise REE³⁺ ions from the solid matrix. The proton attack step, observed by fungus leaching, is the limiting step and has a Gibbs free energy (ΔG) between + 120 and + 180 kJ/mol (Rasoulnia et al., 2021). However, the environment acidification (pH < 3) and complex formation with organic ligands, such as citrate ($\log \beta_1 \approx 6.4\text{--}7.2$) or oxalate ($\log \beta_1 \approx 7.5\text{--}8.3$), decrease the ΔG , making the reaction more favourable (Wang et al., 2025c). These two mechanisms act complementarily: sustained proton activity drives continued mineral surface attack, while REE–ligand complexation lowers the chemical activity of dissolved REE³⁺ species, shifting the dissolution equilibrium towards the aqueous phase. Here, $\log \beta_1$ refers to the first-step stability constant of the REE–ligand complex, defined as $\log \beta_1 = \log([\text{REE-L}]/([\text{REE}^{3+}][\text{L}]))$, which quantifies the affinity of the ligand (L) for complexing REE³⁺ ions; higher values indicate more stable complexes and therefore greater solubilisation efficiency. For bacteria, the process has one spontaneous step, the redox (ΔG : –100 and –200 kJ/mol), resulting in the ferric diproton being constantly regenerated, which maintains the chemical mechanism active (Rohwerder et al., 2003).

The infrastructure required for bioleaching is simpler than that for

Table 4
Summary of bioleaching approaches for rare earth element (REE) extraction.

Ore Type / Feed	Solvent / Agent	REE Analysed	Operational Conditions	Leaching Efficiency (%) ¹	Ref
Coal fly ash, bastnäsite-bearing rock	Organic acids (citric, gluconic) from <i>Aspergillus niger</i>	Mixed REE (focus on LREE)	30°C; pH 2.5–3.0; 10–14 days	30% total REE; Ce, Nd, La most soluble	(Ma et al., 2023)
Ion-adsorption clays	<i>Acidithiobacillus ferrooxidans</i> (sulphur-oxidizing bacteria, in-situ sulfuric acid generation)	Dy, Y, La, Ce	25–35°C; pH 2–3; 7–14 days	Dy, Y: 60–70%; La, Ce: 40–50%	(Wang et al., 2025c)
Mixed metal tailings (ion-adsorption and oxide phases)	<i>Acidithiobacillus ferrooxidans</i> + fungi consortium	La, Ce, Nd, Y	30°C; pH ≈ 2.0; 10–14 days	70–80% REE removal from tailings	(Dong et al., 2023)
Phosphate rock (apatite–dolomite matrix)	<i>Acidithiobacillus ferrooxidans</i>	Y, La, Ce, Nd	30°C; pH 2.0; 14 days (1% pulp density)	Y 36%; La 37%; Ce 28%; Nd 33%; Total REE ≈ 28–46%	(Tian et al., 2022)
Red mud (bauxite residue)	Organic acids from <i>Penicillium tricolor</i>	Ce, Nd (LREE)	28°C; pH 2.8; 14 days	60% Nd, 70% Ce	(Qu and Lian, 2013)
Red mud (bauxite residue)	<i>Penicillium</i> sp. / <i>Aspergillus niger</i> (fungi, organic acid secretion: citric, oxalic)	Y, Dy, La, Ce	25–30°C; pH 2.5–3.0; 7–10 days	Higher for HREE (Y, Dy) than LREE	(Qu and Lian, 2013)
Spent fluid catalytic cracking catalyst (SFCCC)	<i>Acidithiobacillus ferrooxidans</i> (adapted strain aAF20)	La, Ce	30°C; pH 2 ± 0.2; Fe ²⁺ = 8.84 g/L; 1–7% pulp density; 15 days	La 83%; Ce 23% (La ≈ 11.5 mg/g SFCCC; Ce ≈ 0.21 mg/g SFCCC)	(Muddanna and Baral, 2021)
Zircon (7.3 g REE kg ⁻¹); gibbsite shale (Um Bogma Formation)	<i>Acidithiobacillus ferrooxidans</i>	Mixed REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Y)	32°C; pH ≈ 2; 10 g/L pulp; batch 10 days	Total REE 80%; LREE (La, Pr, Nd) ≈ 90% max	(Barmettler et al., 2016)

¹ Overall, unless elements specified.

the traditional acid pathway. The system, including vessels, reactors and mass transfer equipment, does not need to be developed to resist corrosion, high pressure or temperature (Rasoulnia et al., 2021). However, because the reaction kinetics are slower, and high efficiency is only achieved after several days, rather than a few hours as with acid, the system requires larger volume vessels, and greater plant footprint to accommodate more reactors working in parallel. Consequently, the larger plant footprint required to compensate for slow kinetics increases infrastructure costs, as materials and process streams must be transported over longer distances within the facility (Owusu-Fordjour and Yang, 2023).

Reagent consumption requirements are approximately 70% lower for bioleaching than for conventional acid leaching, due to the microbially generated acids and the reduced need for externally supplied reagents (Rasoulnia et al., 2021). The reagents required for bioleaching include those for culture maintenance, process monitoring, and pH and oxygen control (Owusu-Fordjour and Yang, 2023; Rasoulnia et al., 2021). The main consumable for heterotrophic fungal systems is the carbon source, generally glucose or sucrose (10 – 40 g/L). It can represent up to 60% of total operational expenditure (OPEX) (Owusu-Fordjour and Yang, 2023). Using industrial by-products such as molasses, corn-steep liquor, or lignocellulosic hydrolysates can significantly reduce nutrient costs (Rasoulnia et al., 2021). The chemolithoautotrophic bacteria rely on inexpensive inorganic substrates but require continuous aeration and agitation, which together account for about 30 – 40% of OPEX. The slow kinetics of bioleaching increase the expenses with power to maintain the system under agitation, aeration and constant temperature for about 10 to 20 days. Even though the energy requirements for microbes' systems operating are reported to be less than 10% of those of autoclave-based acid leaching (Zhang et al., 2024). Scale-up introduces additional expenses associated with maintaining pH, oxygen, and nutrient gradients, thereby increasing both energy and water requirements.

Bioleaching is a more sustainable process than traditional methods. Direct effects include less waste generation and preservation of the surrounding environment. Indirectly, bioleaching reduces overall power demand, minimises the need for complex hazard-mitigation systems and requires simpler infrastructure, as the process operates at ambient pressure and relatively low temperatures. It is also well-suited for low-grade ores and tailings, and its carbon source can be supplied by inexpensive organic waste streams, further lowering environmental impact. Thus, when the whole chain is analysed, the carbon footprint can be

reduced drastically and even if it is more complex and has longer kinetics, the final power balance is positive.

Despite the limitations, ongoing genetic and process optimisations further promote bioleaching performance, positioning it as a promising green technology for REE extraction in future industrial applications (Joshi et al., 2025). In Queensland, bioleaching offers a promising low-impact pathway for REE extraction from phosphate-rich and lateritic ores such as those found in the Mary Kathleen tailings and Georgina Basin regions, and from clay-hosted deposits in northern Queensland.

3.2.2. Deep eutectic solvents

DESs have emerged as a greener and sustainable pathway for metal leaching. Deep eutectic solvents were developed as a new generation of green solvents to overcome key limitations of ILs, including high cost, complex synthesis, toxicity concerns, and limited biodegradability. DESs are formed by mixing at least two compounds in specific molar ratios, typically a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA). Strong hydrogen-bonding interactions between the HBDs and HBAs disrupt the orderly crystallisation of the individual components, leading to lattice frustration, charge delocalisation, and a significant depression of the DES melting point. This results in the molecules intercalating with one another, causing frustrations in the natural crystallisation of the components and delocalising charges. This prevents solidification, resulting in mixtures with melting points significantly lower than those of the individual components. As a result, DESs remain liquids at temperatures well below the melting points of their constituent compounds and exhibit distinctive physicochemical properties, including low vapour pressure, wide liquid-phase temperature ranges, low flammability, and, in many cases, good stability in the presence of water (Abbott et al., 2006; Alguacil and Robla, 2023; Amal et al., 2021; Li et al., 2022; Martín et al., 2023; Shakiba et al., 2023). With almost endless combinations of chemicals and molar ratios, DESs are considered versatile “designer solvents,” enabling them to have a wide and growing range of applications across science and industry. DESs have been explored for their potential in green chemistry, energy storage and conversion, catalysis, biotechnology and bioprocessing, biomass pretreatment, pharmaceutical and drug formation, food and nutraceutical processing, electrochemistry and electrodeposition, carbon capture, material synthesis, metal recovery, polymer recycling, analytical chemistry, environmental remediation, and nanotechnology (Ferreira and Sarraguça, 2024; Hansen et al., 2020; Ling and Hadinoto, 2022; Lomba et al., 2021; Perna et al., 2020; Prabhune and Dey, 2023;

Sharma et al., 2023; Smith et al., 2014).

For leaching applications, four solvent properties are particularly critical: (1) low viscosity, which enhances mass transfer and accelerates dissolution; (2) sufficient thermal and chemical stability together with low vapour pressure, ensuring the solvent remains liquid, non-volatile and operationally safe under typical processing conditions; (3) tunable acidity and complexation capability, which control proton activity and ligand formation with REE^{3+} ; and (4) environmental compatibility, meaning that the solvent should exhibit low toxicity, be readily synthesised from inexpensive precursors, and be recyclable to minimise waste generation. Collectively, these attributes underpin the growing relevance of DESs as sustainable alternatives to conventional mineral acids. Advanced computational modelling software, such as Conductor-like Screening Model for Real Solvents (COSMO-RS®), enables researchers to formulate and predict the physicochemical properties of DESs and allows specific reactions to be simulated by analysing the molecule interactions and thermodynamic properties. Using this approach, Afridi et al. (2024) identified choline glycinate, choline oleate, and choline decanoate as green solvents comparable to $(\text{NH}_4)_2\text{SO}_4$ to leach REE while maintaining biodegradability and negligible toxicity (Afridi et al., 2024). Entezari-Zarandi and Larachi (2019) formulated a DES composed of choline chloride, urea, and malonic acid. It was able to leach more than 80% of Sm-, Nd-, and Y-bearing carbonate salts, while La and Ce carbonates exhibited significantly lower solubility (<40–50%), thereby evidencing the intrinsic selectivity of DESs systems for HREE. This selectivity was also observed during dissolution of multicomponent carbonate mixtures and bastnäsité, confirming that DESs can promote early-stage fractionation among REE groups, depending strongly on feedstock mineralogy and carbonate availability (Entezari-Zarandi and Larachi, 2019).

Leaching REE by acidic DESs generally proceeds through three main steps: 1) acidolysis; 2) complexation and 3) ion-exchange, as shown in Fig. 2. In this process, the HBD, typically an organic acid, provides protons that cleave REE–O bonds in phosphate or carbonate matrices (acidolysis), releasing REE^{3+} ions into solution. The HBA, commonly a quaternary ammonium salt, stabilises the liberated REE^{3+} ions through ion–dipole interactions and coordination with chloride or carbonyl-

containing ligands, thereby preventing precipitation and promoting further complexation. Following acidolysis, ion-exchange reactions can further enhance REE release from mineral surfaces, particularly in phosphate, carbonate, and ion-adsorption-clay systems. These processes typically occur under relatively mild operating conditions compared with conventional mineral-acid leaching (Shakiba et al., 2023). Temperatures between 25 and 90°C are usually enough to reach high efficiency (Li et al., 2022; Shakiba et al., 2023). The temperature is more important to reduce the DESs viscosity and enhance the diffusivity than to promote the leaching. Thus, synthesising a DES with low viscosity can be a key to drastically reduce the need for heating. A pH between 2 and 4 increases the proton availability, promoting partial dissolution of phosphate (and carbonate) matrices while minimising hydrolysis of REE^{3+} ions (Shakiba et al., 2023). The optimal solid to liquid ratio is between 1:5 to 1:10 w/v, depending on the viscosity of the liquid (Amal et al., 2021; Sarker et al., 2025; Shakiba et al., 2023). More viscous DESs require a higher solid-to-liquid ratio, and additional temperature adjustment to better match the viscosity and enhance the mass transfer. The processing time is usually between 2 and 6 h for pre-treated ores (e. g., alkali-roasted, mechanically activated, or thermally cracked to weaken the REE–O lattice) and > 12 h for untreated ores. High recoveries have been demonstrated in simplified feedstocks; for instance, NdFeB magnets dissolved almost completely, yielding 97.6% Nd after 4 h at 80°C in a TEAC–LA DES, although this reflects the inherently reactive, metal-rich nature of magnet alloys rather than the behaviour expected for refractory REE minerals (Shuping et al., 2025). Similarly, high recoveries have been achieved when carbonate ores are mechanically activated prior to DESs leaching, with Li et al. (2022) reporting 88% dissolution of Y from mechanically activated carbonates. Mechanical activation involves high-energy milling that introduces lattice defects, amorphization, and microcracks, which increase surface area and weaken REE–O bonds. These structural changes substantially enhance mineral reactivity and mass-transfer kinetics during leaching, leading to higher extraction efficiencies than those obtained from untreated ores (Li et al., 2022). As a result, mechanical activation is considered a critical pretreatment step for lattice-bound REE minerals prior to DES leaching.

Li et al. (2022) obtained 88% Y recovery in 12 h from mechanically activated carbonates. An alkali roasting pretreatment can enhance acidic leaching (Li et al., 2022). Sarker et al. (2025) pretreated Fe-rich tailings by KOH roasting at 250°C for 30 min and subsequently leaching at 70°C using ChCl: PTSA DES (choline chloride: p-toluenesulfonic acid, 2:1) and achieved about 95% recovery of REE (predominantly Nd and Pr) from tailings (Sarker et al., 2025).

Selectivity toward REEs varies with the hydrophobicity of the DES, with HREEs generally showing higher solubility in hydrophobic DESs (HDESs) than LREEs. This behaviour is attributed to the stronger complexation tendency of HREE ions, which arises from their smaller ionic radii and higher charge density (Guidugli and Reza, 2025). In HDES systems, HREE–solvent interactions are often stronger due to the higher charge density and smaller ionic radii of HREE ions, which promote the formation of stable inner-sphere complexes with the DES hydrogen bond donor–acceptor network (Guidugli and Reza, 2025). Although HREEs possess more negative hydration enthalpies, their stronger coordination with DES ligands can offset dehydration penalties and favour transfer into the organic phase. This enhanced complexation lowers the effective energy barrier for the ion-exchange step, making phase transfer more thermodynamically favourable (Entezari-Zarandi and Larachi, 2019; Shakiba et al., 2023). In contrast, LREE, with larger ionic radii and lower charge density, typically form weaker solvent complexes and show less favourable transfer into hydrophobic phases (Entezari-Zarandi and Larachi, 2019). Consequently, a clear lanthanide contraction effect emerged, whereby HREEs consistently achieved higher extraction efficiencies under identical conditions (Guidugli and Reza, 2025; Shakiba et al., 2023). Thus, while hydrophobicity influences solvent stability and phase separation, the extraction selectivity between

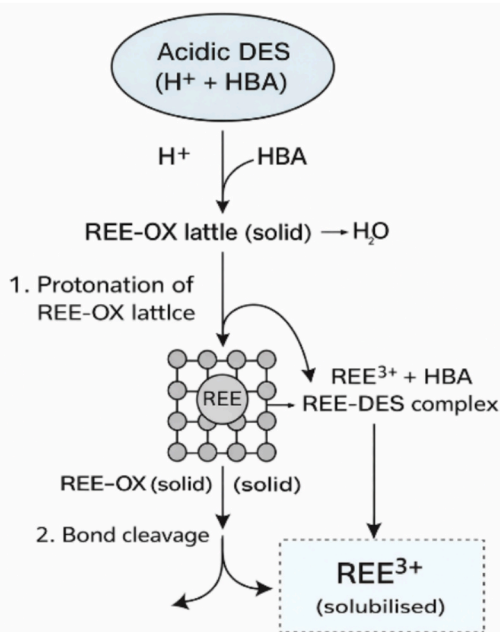


Fig. 2. Schematic illustration of REE oxide dissolution in acidic deep eutectic solvents (DESs) through lattice protonation, bond cleavage, and REE–DES complex formation.

Table 5

Key physicochemical properties affecting REE extraction selectivity in DES (Guidugli and Reza, 2025; Marcus, 1991; Pelaez et al., 2012; Shannon, 1976).

REE Group	Ionic Radius (VIII-coordination, pm)	Hydration Enthalpy (ΔH_{hyd} , kJ/mol)	Extraction Trend in DES
LREE (La–Nd)	116–112	–3650 to –3600	<ul style="list-style-type: none"> • Low extractability • Strong hydration • Weaker complexation
MREE (Sm–Dy)	110–105	–3570 to –3500	<ul style="list-style-type: none"> • Moderate extractability • Transitional behaviour
HREE (Ho–Lu + Y)	104–100	–3480 to –3350	<ul style="list-style-type: none"> • High extractability • Easy dehydration • Strong complexation

LREE and HREE is primarily thermodynamically driven by ion–solvent interaction energies and hydration structure modifications (Guidugli and Reza, 2025). Another aspect is that increasing surface area and diffusion flux through the boundary layer results in an increase in solubilisation, resulting in higher leaching efficiency. Li et al. (2022) evaluated Y dissolution in a ternary DES (ChCl–urea–malonic acid). Under agitation, the apparent activation energy decreased from 83.9 to 37.4 kJ/mol because stirring disrupts the stagnant boundary layer at the solid–liquid interface, increases collision frequency, and improves molecular mobility within the viscous DES. This enhancement of mass transport reduces the diffusion resistance and accelerates the overall leaching rate (Li et al., 2022). It indicates that, by reducing the viscosity of the DES, higher efficiencies can be achieved due to variations in the system's mass transfer. As demonstrated by Khalid et al. (2023), the leaching process is endothermic ($\Delta H > 0$) at room temperature (RT), reflecting the energy demanded to disrupt REE–O bonds and overcome the solvation barrier imposed by the viscous DES matrix; however, above 60°C, the entropic gain associated with increased molecular mobility outweighs the enthalpic penalty, driving ΔG below zero and rendering the reaction spontaneous (Khalid and Santos, 2025). These findings indicate that the mass transfer can limit the REE leaching by DESs, and the solvent must be synthesised considering the importance of its viscosity. By reducing the viscosity, the expenses associated with a heating step would be reduced and thus, higher overall efficiency could be possible.

Table 6

Summary of deep eutectic solvent (DES) approaches for rare earth element (REE) extraction..

Ore Type/Feed	Composition and HBA:HBD ratio	REE Analysed	Operational Conditions	Leaching Efficiency (%) ¹	Ref
A-type granites	ChCl + Urea (1:2)	General REE	20–100°C; pH ~ 2; <300 min	>50%	(Amal et al., 2021)
Caustic-treated monazite	ChCl + Lactic acid	Ce, La, Nd	25°C; pH 2; < 300 min	> 90	(Shakiba et al., 2023)
Rare-earth carbonate	ChCl + Urea + Malonic acid	Y	80°C; pH 2.5–3; 720 min	85.2%	(Li et al., 2022)
Model oxides/synthetic ores	ChCl + Urea (1:2)	General REE	50–70°C; pH ≈ 2–4.9; 120 min	< 90%	(Abbott et al., 2006)
Mixed oxides	ChCl + Malonic acid (1:1)	Ce, Nd, La	50°C; pH 3–4; 120 min	> 85%	(Abbott et al., 2006)
Phosphor residues	Betaine + Propanedioic acid	Y, Eu	90°C; pH 3; 150 min	Y 99.4%, Eu 93.1%	(Alguacil and Robla, 2023)
Red mud/phosphor waste	ChCl + Glycerol/Betaine	Ce, Nd, La, Y	60–90°C; pH 2–4; 180 min	85–95%	(Alguacil and Robla, 2023)
NdFeB waste	Tetraethyl-ammonium chloride + Levulinic acid	Nd	80°C; 240 min	97.6%	(Shuping et al., 2025)
KOH roasted Fe-rich mine tailings containing REE minerals	DES (ChCl:PTSA 2:1) after KOH roast	TREE from Fe-rich REE tailings	25–70°C	95%	(Sarker et al., 2025)

¹ Overall, unless elements specified.

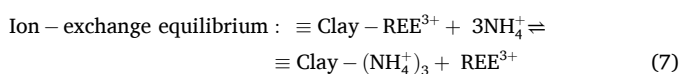
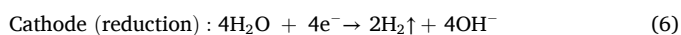
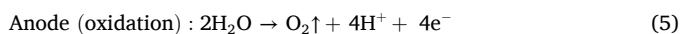
The optimal operational conditions for different feedstocks are shown in Table 6. Usually, temperatures between 60 and 90°C are enough to result in a high efficiency (Liu et al., 2024; Sarker et al., 2025; Shuping et al., 2025; Sobri et al., 2024). This is because it reduces the viscosity of DESs and increases the diffusion and transport of REE ions and protons between the bulk DESs and the mineral surface, which governs the rate at which leaching reactions proceed (Amal et al., 2021; Hansen et al., 2020; Perna et al., 2020). Leaching kinetic equilibrium generally occurs in about 5 h, being as fast as the traditional acid pathway, and a better option than bioleaching as previously discussed. Lower pH (< 4) increases the efficiency of REE dissolution by favouring the first step of the chemical mechanism of leaching (Kaplan et al., 2025; Liu et al., 2024; Sarker et al., 2025; Shuping et al., 2025). The use of KOH as pretreatment can help to roast the lattice crystals, however, the DES by itself tends to be enough depending on the pKa of HBA present in the solvent (Kaplan et al., 2025; Sarker et al., 2025).

Leaching with DESs can offer lower environmental impact and improved safety compared with conventional acid leaching using H₂SO₄ or HCl, particularly due to their low volatility and reduced corrosiveness (Amusa et al., 2026; Prabhune and Dey, 2023; Zante and Boltoeva, 2020). DESs are typically synthesised from relatively inexpensive chemicals; however, the overall process may involve additional costs associated with solvent preparation, larger processing footprints, and sustained energy input for heating and viscosity control (Entezari-Zarandi and Larachi, 2019; Hansen et al., 2020; Martín et al., 2023; Perna et al., 2020; Sharma et al., 2023). However, due to lower waste treatment costs and environmental damage mitigation, the synthesis step costs are lower, resulting in an economically competitive option. Moreover, several DES systems demonstrate good recyclability, maintaining high performance across multiple reuse cycles. For example, ChCl: lactic acid DES maintains > 90% of its leaching performance over 5–6 cycles, ChCl: urea DES maintains > 95% efficiency across four cycles, and ChCl: malonic acid DES remains above 85% efficiency for at least three cycles (Alguacil and Robla, 2023; Shuping et al., 2025). This recyclability, combined with the fact that DESs operate under mild temperature and pressure, reduces operational costs significantly, similar to bioleaching. It is also an environmentally friendly option considering that DESs tend to be biodegradable and less hazardous due to the hydrogen-bonding interactions between HBA and HBD (Abbott et al., 2006; Martín et al., 2023; Pieckowski et al., 2025; Zante and Boltoeva, 2020). This type of processing would be suitable for the clay-hosted and monazite-bearing ores found in Queensland's Kennedy region.

3.2.3. Electrokinetic mining

Electrokinetic mining (EKM) is another method that has emerged to remove metals from ores as a promising replacement for traditional methods that require strong acids (Amusa et al., 2026; Pires et al., 2023). The main idea is to apply a controlled low-voltage electric field across the REE feedstock to promote the transport of metallic ions, such as REE, from the solid matrix toward the electrode surfaces and into a recoverable aqueous phase, typically the analyte solution (Acar and Alshwabkeh, 2002; Wang et al., 2024). The feedstock can be ionic clays, groundwater, surface water, tailing, or soil (Warner, 2025). The most important criteria are that the feed material consists of finely milled particles and that the target metal is ionically bound. For crystalline mineral-based REE ores, EKM is insufficient to leach REE, since they are stuck within robust crystal lattices, unless an optimised beneficiation has been applied before the leaching, enriching the feedstock and drastically reducing the particle size to a range of 20–50 μm (Acar and Alshwabkeh, 2002; Virkutyte et al., 2002; Watts and Fisher, 2021; Xu et al., 2025). In this case, part of the metals would be exposed and able to be removed from the crystals. Another option to improve leaching efficiency of crystalline REE-bearing minerals, is combining EKM with a second method such as an organic acid (Maes et al., 2017), alkaline roasting or mechanochemical activation (Khalid and Santos, 2025; Shakiba et al., 2023). For example, NaOH-treated monazite undergoes phase transformation to $\text{REE}(\text{OH})_3$, in which the phosphate matrix is broken down and replaced by more soluble rare earth hydroxides, which are more soluble under electric-field-driven extraction conditions (Khalid and Santos, 2025; Shakiba et al., 2023). Li et al. (2022) combined EKM and DES to extract REE. Initially REE extraction was between 28 and 32%; however, after reducing particle size, it was possible to reach up to 72% of REE leaching (Li et al., 2022). Xu et al. (2025) and Wang et al. (2023) reported that integrating EKM with ammonium-sulphate electrolyte systems improved desorption, enhanced the mass transfer and consequently achieved leaching efficiencies of 70–85% for LREE (La, Ce, Nd) and up to 90% for HREE (Dy, Y) under electric-field gradients of 1–2 V/cm at 30–60°C (Wang et al., 2023; Xu et al., 2025). These combined approaches extend EKM potential beyond ion-adsorption clays toward hard-rock REE deposits, representing a key frontier for sustainable, reagent-efficient extraction technologies. Other multipronged approaches can still be investigated, such as EKM in the presence of ILs, microorganisms or enzymes.

The EKM process consists of three main steps: electromigration, electrolysis and ion exchange, as outlined in Equations 5–7. The presence of water in the ores is crucial, as it promotes oxidation/reduction reactions that result in ions (anode/cathode) responsible for the transport of ionic metals. At the anode, protons are generated by oxidation and pH decreases, and these protons displace REE^{3+} from the negatively charged adsorption sites on the mineral surfaces, causing their desorption into the porewater film. At the cathode, hydroxide ions increase alkalinity, leading to REE^{3+} be exchanged, favouring the leaching (Wang et al., 2024, 2023). At this stage, an electrolyte, such as a salt, is required to drive the ion-exchange reaction. Ammonium ions (NH_4^+) are the most common to replace REE^{3+} at adsorption sites, releasing the REE^{3+} into solution. Next, the electric field accelerates the mass transport and promotes the ion exchange by driving NH_4^+ toward the anode and mobilising the free REE^{3+} toward the cathode (Wang et al., 2025a; Xu et al., 2025).



The optimal operational conditions for different REE extractions by EKM are described in Table 7. The system usually does not need heating,

although increasing temperature can improve ions transport within the solvent or optimise the system in case of joined methods. A slightly acidic pH (4 – 6) is required to allow protonation (Dushyantha et al., 2024; Wang et al., 2024). The time required depends on the size of the particles, the metallic mass transfer diffusion, and the water content (Wang et al., 2025a; Xu et al., 2025). Bench and pilot scales can reach maximum efficiency after a few hours, significantly shorter than required during bioleaching extractions (Wang et al., 2025a,b; Wang et al., 2024). In a large-scale (14 tons) experiment, it was possible to reach 90% REE extraction efficiency after 264 h (Wang et al., 2025b; Xu et al., 2025). The variable oxidation states of some REE also interfere with the efficiency. Pires et al. (2023) achieved an efficiency of 79% for Ce^{4+} and less than 50% for LREE^{3+} (47.7% of La^{3+} and 35.1% of Nd^{3+}) after 240 h of EKM in the presence of 0.1 M acetic acid and a voltage of 1.0 V/cm. However, the $+4$ oxidation state is only possible for Ce under oxidising conditions in an aqueous environment and for a short time. The lower oxidation state species Ce^{3+} (ΔH : –695 kJ/mol, ΔG : –670 kJ/mol, ΔS : –180 J/mol.K) is thermodynamically more stable than the Ce^{4+} (ΔH : –500 kJ/mol, ΔG : –450 kJ/mol, ΔS : –300 J/mol.K), so, even resulting in higher efficiency, this approach is not feasible for other REE (Dean and Lange, 1998).

Usually, EKM is fast, does not disturb or damage the surrounding environment through extensive excavation, requires fewer chemicals, is less hazardous to flora and fauna, and remains highly selective and efficient even in heterogeneous ore bodies (Dushyantha et al., 2024; Wang et al., 2023; Xu et al., 2025). Large-scale pilots have been successfully evaluated. Pilot- and industrial-scale operations resulted in extraction efficiency > 95% for REE, whilst using 80% less chemicals and 70% faster when compared to traditional acid-leaching methods by using sulfuric and nitric acids (Xu et al., 2025). Despite its promising performance and environmental advantages, it also presents several challenges. First, it requires more power than traditional methods, and insufficient control of the electric-field distribution, moisture content, and ionic conductivity can increase energy consumption by ca. 50% due to energy being dissipated through water electrolysis and ohmic heating (Xu et al., 2025). A second aspect is that the electric field must be tailored to different types of ores based on their characteristics, such as porosity, moisture content, particle size distribution, mineral composition, and contaminants. Consequently, additional preparation time is required for each deposit to optimise the system and achieve suitable operating conditions.

Costs associated with EKM encompass power supply, electrodes, monitoring system, and water management. The high demand for power can indirectly increase greenhouse gas emissions as the mining industry usually uses conventional electricity generators (e.g., coal and oil) (Wang et al., 2025a; Xu et al., 2025). In this scenario, Queensland does not have a sustainable circular economy as the electricity comes mostly from coal and natural gas (Understand the electricity supply system | Homes and housing | Queensland Government, 2025). Nevertheless, Queensland's substantial solar and wind resources, particularly across the North West Minerals Province where REE deposits are concentrated, present a credible pathway to decarbonise EKM operations; the renewable energy infrastructure already being developed in the region to support critical minerals processing is discussed in detail in Section 6 (Queensland Department of State Development, 2023; Powerlink Queensland, 2024). Another factor that can increase costs and timing is finding the proper operational conditions, mainly the voltage of the system and the electric-field conditions. The EKM process is highly sensitive to the mineralogy and the physicochemical variability of the ore, including changes in moisture content, porosity, conductivity, clay content, and ionic composition (Dushyantha et al., 2024; Wang et al., 2024; Warner, 2025; Xu et al., 2025). In addition, the system requires careful electrode management to prevent degradation and corrosion during extended operation, which can alter conductivity and reduce electric field uniformity. These challenges highlight the need for optimised electrode materials, dynamic voltage control, and improved

Table 7

Summary of electrokinetic approaches for rare earth element (REE) extraction.

Ore Type / Feed	Solvent / Electrolyte	REE Analysed	Operational Conditions	Leaching Efficiency (%) ¹	Ref
Ionic adsorption clay (China)	0.3 mol/L (NH ₄) ₂ SO ₄	Y, Dy, Gd, Nd, Sm	25°C; pH 4.5–5.5; 120–180 min; 20 V DC	85–95% / Y ≈ 90%	(Kang et al., 2024)
Ionic adsorption deposits (industrial scale, China)	(NH ₄) ₂ SO ₄ 0.3 M – electrolyte circulation system	Total REE	Ambient T; pH ≈ 5; continuous mode; 12 V DC	95%	(Warner, 2025)
Ionic adsorption clay	(NH ₄) ₂ SO ₄ 0.3 M + pH control electrodes + anion membrane	Y, Dy	25°C; pH 5–6; 300 min; 15 V DC	92–96%	(Wang et al., 2024)
Ionic clay (Guangdong)	0.5 mol/L (NH ₄) ₂ SO ₄ + citric acid (0.1 M)	Ce, La, Nd	30°C; pH ≈ 4; 300 min; 15 V DC	70–80%	(Wang et al., 2023)
ion-adsorption ore (Southern China)	(NH ₄) ₂ SO ₄ 0.3 M + NH ₄ Cl 0.05 M	Y, Ce, Nd, Sm	25°C; pH 4.8; 180 min; 12 V DC	88–94%	(J. Xu et al., 2025)
Weathered crust soils (HREE-rich)	0.5 mol/L (NH ₄) ₂ SO ₄ + 0.05 mol/L MgSO ₄	Y, Dy, Gd, Nd	25°C; pH ≈ 5; 240 min; 10 V DC	90–95%	(Wang et al., 2025a,b)
Weathered granite clay	(NH ₄) ₂ SO ₄ (0.2–0.5 mol/L) + Na ₂ SO ₄ 0.1 M	Y, Nd, Sm	20–30°C; pH ≈ 5; 180 min; 12 V DC	90% (Y), 82% (Nd)	(Xu et al., 2025)
Weathered bauxite ore	(NH ₄) ₂ SO ₄ 0.5 M + citric acid 0.05 M	Y, Dy, Gd	25°C; pH 4.5; 200 min; 10 V DC	85–93%	(Corner, 2025)
Monazite ore powder (bench scale)	(NH ₄) ₂ SO ₄ + H ₂ O (no additives)	La, Ce, Nd	20–25°C; pH ≈ 6; 240 min; 12 V DC	75–85%	(Maes et al., 2017)
Monazite sand and bastnäsite mix	(NH ₄) ₂ SO ₄ + NaCl (0.1 M) + ethanol interface	Ce, Nd, Y	25°C; pH 5.5; 300 min; 10 V DC	85%	(Maes et al., 2017)

¹ Overall, unless elements specified.

water–energy management strategies to enhance the long-term stability and scalability of EKM for REE extraction (Wang et al., 2023; Xu et al., 2025). On the other hand, other costs are reduced, such as chemicals, waste treatment, environment restoring, specialized labour training, insurances, infrastructure due to the high hazardous and toxicity of chemicals required as in the traditional methods.

3.2.4. Ionic liquids leaching

ILs are salts composed entirely of organic or inorganic ions that are thermally stable, easily soluble, non-flammable, non-volatile, with melting points below 100°C, and most importantly, have high ionic conductivity. They can be synthesised by combining different ions that are chosen for a specific task, such as preferential REE leaching. In this case, the use of biodegradable environmentally friendly compounds can be attractive for Queensland. They can be used as a primary extractant, by donating sites or as a diluent, working as an ion-pairing medium, improving selectivity and mass transfer (Alguacil et al., 2024; Do-Thanh et al., 2023). Their dual ionic–molecular nature allows them to dissolve both polar and nonpolar species, facilitating direct coordination with REE ions (Quijada-Maldonado and Romero, 2021).

Their unique physicochemical properties reduce hazards usually found in regular solvents by decreasing volatile emission, corrosion, thermal instability, high temperatures, and environmental damage. ILs can also be reused in multiple cycles, reducing the operational costs, and consequently mitigating the initial costs associated with solvent synthesis (Alguacil et al., 2024). Most of the systems retain > 90% extraction efficiency for 4–8 consecutive cycles (Alguacil and Robla, 2023; Khalid and Santos, 2025). Some bifunctional ILs maintain performance for at least five extraction–stripping cycles with < 2% efficiency loss, as demonstrated for Nd, Sm, and Eu (Prusty et al., 2022). In more robust phosphonium- and imidazolium-based systems, up to 10 cycles were reported when periodic regeneration was applied (Quijada-Maldonado and Romero, 2021).

Through design task-specific ionic liquids, the incorporation of coordinating groups such as phosphoryl, amide, or carboxylate functionalities into the cation or anion structure enables the formation of inner-sphere complexes with trivalent REE ions, increasing both selectivity and loading capacity (Do-Thanh et al., 2023). This structural property allows fine-tuning solvation energy, hydrophobicity, and donor strength, improving phase separation, and selective separation between LREE and HREE (Alguacil et al., 2024).

However, large-scale application of ILs remains highly challenging, and to date they have seen very limited industrial deployment in mineral

processing. The synthesis of high-purity ILs typically requires multiple reactions and purification steps, which increases cost and process complexity. In addition, while fluorinated ILs have demonstrated strong performance at laboratory scale, their use substantially reduces overall process sustainability due to environmental persistence and higher production burdens (Do-Thanh et al., 2023). Another aspect is that they normally have high viscosity, which increases the mass transfer resistance. As viscosity increases, the diffusion coefficient of metal ions decreases, leading to a transition from a reaction-controlled to a diffusion-controlled leaching regime. This mass-transfer limitation reduces leaching efficiency, unless additional energy (e.g., heating or agitation) is supplied to overcome diffusional resistance (Quijada-Maldonado and Romero, 2021). The presence of highly coordinating anions such as [PF₆]⁻ (hexafluorophosphate) and [TF₂N]⁻ (bis(trifluoromethylsulfonyl)imide) can lead to hydrolytic instability and partial degradation under acidic aqueous conditions which difficult the solvent recycling, its long-term reuse, and low biodegradability (Alguacil et al., 2024; Do-Thanh et al., 2023). Thermodynamically, IL-based REE leaching is generally characterised by a positive enthalpy of mixing ($\Delta H > 0$), reflecting the considerable energy required to dehydrate REE³⁺ ions from their aqueous coordination shell and transfer them into the high-density, high-ionic-strength IL phase. This enthalpic barrier, compounded by the inherently low mass transfer coefficients of viscous IL systems, means that spontaneity ($\Delta G < 0$) is typically only achieved at elevated temperatures, where the entropic contribution from ion desolvation and increased configurational disorder becomes the dominant thermodynamic driving force (Alguacil et al., 2024). Thus, although being a good option at laboratory scale, the viability of the IL for industrial-scale applications currently remains unfeasible economically and environmentally (Alguacil et al., 2024; Do-Thanh et al., 2023; Quijada-Maldonado and Romero, 2021).

The mechanism of REE leaching by ILs is made up of three main steps: ion exchange, coordination complexation, and solvation equilibria. The cation–anion of ILs drives the chemical speciation of REE ions in the solution (Do-Thanh et al., 2023). Two of the most common ions, imidazolium [TF₂N]⁻, and phosphonium [PF₆]⁻, usually act as primary ligands, binding to the REE³⁺ through oxygen donors while the cations stabilise the complex through electrostatic interactions (Quijada-Maldonado and Romero, 2021). This dual approach produces a synergistic effect between ion pairing and ligand exchange, whereby the solvent lowers the dielectric constant of the medium, increases REE activity, and facilitates their desolvation from the aqueous phase (Do-Thanh et al., 2023).

Generally, the operational conditions for ILs leaching are mild temperature (25–80°C), acidic environment (pH < 2–3), and a high efficiency (>90%) can be reached in only a few minutes (Abbasi et al., 2018; Panda and Mishra, 2024; Prusty et al., 2022). Table 8 shows the optimal operational conditions for different REE:IL pairs. The temperature impact varies depending on the type of IL chosen and the thermodynamic properties of the system. ILs synthesised with trihexyltetradecyl-phosphonium ([THAH]⁺) and di-(2-ethylhexyl) phosphate ([DEHP]⁻) applied to Y(III) leaching is an endothermic system (ΔH : 27 kJ/mol) with positive entropy (ΔS : 120.54 J/K.mol) indicating that temperature affects significantly the system efficiency (Panda and Mishra, 2024). At lower temperatures (25–35°C), the system is endothermic and non-spontaneous; however, by increasing the temperature (~60°C), the molecular disorder increases and becomes the major factor driving the reaction resulting in a spontaneous reaction. The IL [TOAH]⁺[OHex]⁻ (Trioctylammonium O-hexanoate) and [TOAH]⁺[ODec]⁻ (Trioctylammonium O-decanoate) were applied to Nd, Sm, Eu and all combinations (IL-REE) resulted in negative enthalpy and entropy (Prusty et al., 2022). It demonstrates that the processes in this case are exothermic, and molecular disorder reduces over time, indicating that the process is more effective at lower temperatures than higher ones. These conclusions are corroborated by the experimental results, which show that at 25°C all REEs reached extraction efficiencies of around 60%, while at 55°C efficiencies decreased by at least 30% across all species (Prusty et al., 2022). The opposite thermodynamic behaviour of different ILs and REE is mainly due to the ionic structure and molecular interaction governing the IL-REE complexation. The [THAH][DEHP] system results in dehydration of solvated REE³⁺ ions and subsequent coordination with oxygen donor of phosphate groups in a viscous and hydrophobic ionic matrix. To reorganise the shell structure, the IL requires energy while releasing water molecules to the bulk phase, which consequently increases the molecular disorder. Processing

by [TOAH][OHex] and [TOAH][ODec] are driven by ion-pair formation and electrostatic interactions instead of complexation. This mechanism releases energy to stabilise the REE³⁺ complexes.

Beyond temperature-dependent behaviour, pH also plays a critical role in governing IL-REE interactions, particularly through protonation-competition effects. At pH 1 the extraction of Y(III) was limited to 40%, while at pH 3 efficiency rose sharply to 98% (Panda and Mishra, 2024). This effect is due to the competition between the metal ion and the proton in the aqueous phase. The dilution of the IL phase with a second solvent also influences leaching efficiency. A second solvent can be considered to reduce the systems' viscosity or increase the solubility of the leached REEs and consequently improving the mass transfer. Panda and Mishra (2024) observed that the solubility of Y(III) in different co-solvents affected the REE extraction efficiency (kerosene: 96%, chloroform: 76%, hexane: 73%, heptane: 13%). The system polarity and dielectric constant of all the elements involved impact the efficiency, as shown by Prusty et al. (2022), where the REE extraction efficiency increased as the dielectric constant reduced from $\epsilon = 14$ to $\epsilon = 4$.

Extraction efficiency also depends on system stability, which is currently a barrier for industrial applications. The decline across multiple reuse cycles depends on the physicochemical stability of the ILs under specific operational conditions. Most of the phosphonium- and ammonium-based ILs undergo anion hydrolysis and cation oxidation, especially in the presence of residual oxygen or moisture, resulting in progressive degradation, and consequently reducing the effectiveness of the leaching. For example, [N4444]⁺[DODGA]⁻ (Tetrabutylammonium dioctyl diglycolamate) and [N1888]⁺[DODGA]⁻ (Methyltrioctylammonium dioctyl diglycolamate) mixture shows a 50% decrease in extraction efficiency from the first and fifth cycles (Dai et al., 2023). In contrast, ILs such as pyridinium carboxylic acids and dialkylammonium DEHO retain similar extraction efficiencies over

Table 8
Summary of ionic liquid approaches for rare earth element (REE) extraction.

Ore Type / Feed	Solvent	REE Analysed	Operational Conditions	Leaching Efficiency (%) ¹	Ref
Acetate media	Benzyltributylammonium decanedioate	Sm(III)	RT; pH 5.5; Standard	98%	(Alguacil et al., 2024)
Bauxite residue (red mud)	[Hbet][Tf ₂ N]	Lanthanides, Y, Sc	75–85°C; pH 2.0; 180 min	26%	(Davris et al., 2016)
Coal fly ash	[Hbet][Tf ₂ N]	Sc, Y, Nd, Sm, Gd, Dy, Yb	60–80°C; variable pH; 30 min	44–66% total REE	(Alguacil et al., 2024)
Eu–U binary system	[N ₄₄₄₄] ⁺ [DODGA] ⁻	Eu(III), U(VI)	RT; 4–5 M HNO ₃ ; Standard	D _{Eu} = 13; $\beta_{Eu/U}$ = 60.35	(Alguacil et al., 2024)
Eu–U binary system	[N ₁₈₈₈] ⁺ [DODGA] ⁻	Eu(III), U(VI)	RT; 4–5 M HNO ₃ ; Standard	D _{Eu} = 9; $\beta_{Eu/U}$ = 55.4	(Alguacil et al., 2024)
Radioactive waste	Oxoacetate-functionalized ionic liquid	Mixed REE	–	–	(Bie et al., 2024)
Ion-adsorbed REE ore leachate	Tetraheptylammonium oleate (TO)	Nd ³⁺	RT; pH 0.24; < 1 min	9.83%	(Li et al., 2020)
Ion-adsorbed REE ore leachate	Tetraheptylammonium oleate (TO)	Nd ³⁺	RT; pH 1.82; < 1 min	≈ 100%	(Li et al., 2020)
Ion-adsorbed REE ore leachate	Tetraheptylammonium linoleate (TL)	Nd ³⁺	RT; pH 1.82; < 1 min	≈ 100%	(Li et al., 2020)
Ion-adsorbed REE ore leachate	Tetraheptylammonium “cooking oil” (TC)	All REE	RT; variable pH; < 1 min	100%	(Li et al., 2020)
Phosphogypsum leachate Synthetic solution	[P ₆₆₁₄][NO ₃] Cyphos® IL-101	La, Ce, Nd Th(IV)	50°C; multi-cycle (9 ×) RT; pH 2; Standard	93% (after 9 cycles) $\beta_{Th/Ce}$ > 5000; $\beta_{Th/La}$ > 1000	(Tilp et al., 2024) (Alguacil et al., 2024)
Synthetic solution	Pyridinium carboxylic acid IL	Y ³⁺	RT; pH 2.5; Standard	98.5%	(Do-Thanh et al., 2023)
Synthetic solution	Dialkylammonium DEHP	Nd(III)	RT; pH 4; Standard	≈ 100%	(Alguacil et al., 2024)
Synthetic solution	DGA-based TSILs	Lanthanides	RT; variable acid; Standard	~100 × D vs TODGA	(Do-Thanh et al., 2023)
Synthetic solution	[TOA-D2]	Nd(III), Sm(III), Eu(III)	25–35°C; pH 2–3; Standard	51–69%	(Alguacil et al., 2024)
Synthetic nitrate solution	[THAH][DEHP]	Nd(III)	25–35°C; pH 3; Standard	99%	(Alguacil et al., 2024)
Synthetic nitrate solution	Tri-n-octylamine-octanoic acid	Y, Eu, Gd, Tb	–	–	(Kozhevnikova et al., 2023)
Synthetic nitrate solution	[THAH][DEHP]	Y(III)	45–55°C; pH 1–3; Standard	High	(Alguacil et al., 2024)

multiple cycles as their acidic functional groups and cationic frameworks remain stable after hydrolysis and oxidation (Carretas et al., 2023). However, this is only achieved when leaching occurs in the presence of inorganic acids, such as HCl and H₂SO₄, because these acids maintain IL ionic strength and prevent degradation through consistent protonation that blocks anion discharge (Barrueto et al., 2022; Carlesi et al., 2016; Wstawski et al., 2021).

The physicochemical characteristics of REE ores strongly impact overall leaching efficiency and system stability across multiple cycles. The most important aspects are the ionic radius and ligand field strength, as they determine the metal–ligand coordination complexes. For example, HREE have smaller ionic radii and higher charge densities, enhancing electrostatic attraction and orbital overlap with hard donor groups such as carboxylates, phosphates, and amides and strong acidic conditions. Consequently, stronger complexes with oxygen-donor anions, that promote slower kinetic reactions and less efficient leaching. Tetraheptylammonium linoleate (TL) and [C₄mim⁺][Tf₂N⁻], for example, resulted in almost 100% of extraction at pH of 1.82 favouring the leaching of HREE rather than LREE (Alguacil, 2024; Alguacil et al., 2024; Alguacil and Robla, 2023). Conversely, LREEs result in weaker coordination complexes, which result in faster kinetics (Alguacil et al., 2024). In this case, systems with low acidities are desired. For example, CMPO-based and phenanthroline-dicarboxamide ILs in the presence of 6 M HCl resulted in higher efficiency of LREE preferentially over the HREE (Do-Thanh et al., 2023).

Environmentally, ILs tend to be better than traditional ones, such as H₂SO₄ or HCl. Overall, they tend to reduce volatile organic compounds emissions, minimise waste, work at mild temperatures, saving energy, and can be applied for lower grade feedstocks supporting circular recovery from secondary REE sources (Alguacil et al., 2024; Do-Thanh et al., 2023; Li et al., 2020). However, each IL must be analysed individually as the biodegradability, toxicity, stability, and volatility varies due to the chemicals applied in the IL synthesis. Many ILs still rely on non-biodegradable halogenated or fluorinated anions, such as [PF₆]⁻ and [Tf₂N]⁻, that are potentially toxic (Bie et al., 2024).

The economic aspects regarding the ILs application on a large scale remain a challenge. The systems using ILs have positive aspects such as high selectivity, being environmentally friendly, and reduced OPEX due to the mild operational conditions required. However, some aspects remain as a critical barrier to large-scale implementation, such as high costs involved in the ILs synthesis, lower stability across the cycles even though a high initial efficiency is usually achieved, the partial biodegradability. Additionally, synthesis and purification of task-specific ILs remain energy- and cost-intensive, and degradation during repeated cycles generates waste requiring management (Davris et al., 2016).

3.2.5. Organic acids leaching

The use of organic acids (e.g. citric, oxalic, acetic, lactic and tartaric) for REE leaching is an environmentally friendly alternative to traditional strong inorganic acids (Lazo et al., 2017; Liu et al., 2025; Ray et al., 2025; Zhao et al., 2025c). They can be applied to different sources such as ionic-clay ores, crystal-REE ores, tailings, and e-waste (Artiushenko et al., 2024; Lazo et al., 2017; Liu et al., 2025; Ray et al., 2025; Sakr et al., 2025; Turanov et al., 2018; Zhao et al., 2025c). They can dissolve REEs from mineral surfaces via protonation and metal–ligand complexation, being effective for ionic clay ores, where the REE are ionically bound (Banerjee et al., 2021; Gergoric et al., 2018; Ji et al., 2022; Liu et al., 2025; Pan et al., 2022; Petraglia et al., 2025; Zhao et al., 2025c). Unfortunately, crystalline ores, such as monazite and bastnasite, are more resistant to organic acids (Abdulvaliyev et al., 2024; Lazo et al., 2017). In this case, pre-treatments are usually required, such as mechanochemical activation, roasting, and electrokinetic-assisted leaching (Banerjee et al., 2021; Jensen et al., 2007; Karaca, 2025; Ray et al., 2025; Rezaei et al., 2022).

This approach has several advantages, such as non- or low-toxicity, biodegradability, less corrosivity, low environmental impact, and easy

refining after leaching by liquid–liquid extraction, which is the most common method applied industrially after leaching to purify REE concentrates (Almohasin et al., 2023; Amusa et al., 2026). Lab-scale tests show that several different organic acids can be applied, under different operational conditions, to achieve high REE extraction efficiency, as shown in Table 9. Citric-acid leaching can reach up to 90% REE recovery under optimised conditions (2 mol/L, 343 K, 240 min) (Ray et al., 2025). Acetic acid applied to REE leaching from e-waste magnets system shows high selectivity by dissolving the REE and not leaching the iron present in the source material, enabling downstream purification (Petraglia et al., 2025). However, organic acids usually have slower reaction rates than inorganic acids. Therefore, to extract the same amount, organic acids require a larger process footprint (e.g. larger vessels) than inorganic acids. The moisture content in ores can also directly interfere with the extraction efficiency, as some organic acids are not fully soluble in the aqueous phase (Song et al., 2022). In this case, smaller carbonic chains (< 5C – carbon atoms per chain), with higher polarity, are preferable, such as acetic (2C), oxalic (2C), lactic (3C), and tartaric (4C).

Organic acids leach rare-earth elements (REEs) through two coupled mechanisms: proton donation and ligand complexation. Proton attack initiates the disruption of surface functional groups and weakly bound REE species, whereas carboxylate ligands stabilise REE³⁺ ions in solution through the formation of strong metal–organic complexes (Banerjee et al., 2021; Liu et al., 2025). Because protonation of the mineral surface can be comparatively slow, this step frequently governs the overall reaction rate, making mass-transfer optimisation essential for enhanced extraction (Liu et al., 2025; Ray et al., 2025). Operational parameters such as temperature, agitation, and the liquid–solid (L/S) ratio exert strong control over boundary-layer diffusion and the transport of REE–ligand complexes (Banerjee et al., 2021; Gergoric et al., 2018; Ji et al., 2022; Liu et al., 2025; Petraglia et al., 2025; Ray et al., 2025). Temperature plays an important role. For instance, citric acid leaching of red mud increased from 36% at 25°C to 67% at 70°C because faster pore diffusion, higher proton activity, and more favourable complexation kinetics accelerate extraction (Ray et al., 2025).

The L/S ratio also significantly influences leaching by modifying slurry rheology, particle accessibility, and reagent availability (Banerjee et al., 2021). Lower solid loadings generally improve REE dissolution — in coal ash, they raised extraction from roughly 40–50% to over 60% with organic acids — while stronger agitation enhances mass transfer and surface renewal (Banerjee et al., 2021). Agitation intensity further affects leaching efficiency by improving external mass transfer and continuously renewing the reactive surface (Gergoric et al., 2018). This effect was shown for Nd, Pr, and Dy in NdFeB magnet waste, where increased stirring speed markedly enhanced REE dissolution during organic-acid leaching (Gergoric et al., 2018). Together, these findings emphasise that REE leaching by organic acids is governed not only by chemical affinity and ligand strength but also by proton availability, hydrodynamic conditions, and the efficiency of solid–liquid interactions. A mechanistic understanding that integrates both chemical and mass-transfer phenomena is therefore essential for designing high-performance, low-acid extraction systems, particularly for materials with heterogeneous mineralogy or complex surface chemistries.

The leaching mechanism of REE³⁺ through organic acids is divided into two main steps: protonation, where REE³⁺ ions are liberated from the solid, and complexation, where the REE are dissociated with carboxylate ligand in the solution and chelated (Banerjee et al., 2021; Petraglia et al., 2025). The kinetics of the system can be driven by both steps depending on the acid pKa and the type of REE (LREE or HREE). Organic acids with lower pKa, such as oxalic acid (pKa of 1.2), at low pH, the protonation is the dominant step with H⁺ ions attacking the surface sites (≡SO–REE³⁺), forming ≡SOH and releasing REE³⁺ in the solution. Subsequently, carboxylate anions produced by acid dissociation chelate the cation to yield an inner-sphere REE-organic complex (Petraglia et al., 2025; Ray et al., 2025). In this case, the larger and less charge-dense LREE³⁺ are more easily proton-desorbed and hydrated, leading to

Table 9
Summary of organic acid leaching approaches for rare earth element (REE) extraction.

Ore type / feed	Leaching reagent(s)	REE analysed	Operational conditions	Leaching efficiency (%) ¹	Ref
Calcined coal refuse	Citric acid (0.5–2 M)	La, Ce, Nd, Y	90°C; pH 2–4; 30–120 min	42–70 (La > Ce > Nd > Y)	(Ji et al., 2022)
Coal fly ash (ionic exchange phase)	Citric acid (0.1–0.5 M)	La, Ce, Nd (+ transition metals)	25°C; pH ≈ 5.0; continuous column leaching (8 h)	56–60	(Zhang et al., 2025)
E-waste magnets	Acetic acid (0.5 M)	Nd, Dy, Fe	60°C; pH 4.5; 180 min	65	(Petraglia et al., 2025)
Ion-adsorption clay	Tartaric acid (5%)	La, Ce, Nd, Sm	90°C; pH 1.8; 60 min	65 (LREE), 19 (HREE)	(Banerjee et al., 2021)
Ion-adsorption clay	Oxalic acid (0.1–1 M)	La, Ce, Nd, Y (+ Fe, Al for selectivity)	25–50°C; pH 2–4; 240 min	55–78 (REE); < 25 (Fe, Al)	(Zhao et al., 2025c)
Ion-adsorption REE clay	Citric / Lactic / Oxalic (0.1 M)	Y, Dy, Er, Yb; La, Ce, Nd	25°C; pH 4–5; 180 min	65–75 (HREE), < 55 (LREE)	(Zhao et al., 2025b)
Leach liquor treatment	Formo-phenolic-resin adsorption after citric acid leachate	La, Ce, Nd (total REE)	25°C; pH ≈ 3.5	90–95	(Lelong et al., 2025)
Mobile-phone magnets	Citric acid (1 M)	Nd, Pr, Dy, Tb	80°C; pH ≈ 3.0; 120 min	70–85	(Stein et al., 2022)
NdFeB magnet powder	Mixtures of citric acid + lactic acid (0.5 M each)	Nd, Pr, Dy	70°C; pH ≈ 3.5; 60 min	> 80	(Belfqueh et al., 2023)
NdFeB magnet waste	Acetic acid (1 M)	Nd, Dy	70°C; pH 3.5–4.0; 180 min	58 (Nd), 43 (Dy)	(Gergoric et al., 2018)
NdFeB magnet residues	Citric acid + H ₂ O ₂ (0.5 + 0.2 M)	Nd, Pr	70°C; pH 3.2; 60 min	93	(Makarova et al., 2020)
NdFeB magnet scrap	Lactic acid (1 M)	Nd, Pr, Dy	80°C; pH ≈ 2.5; 90 min	68	(Gergoric et al., 2018)
Phosphate rock	Mixed carboxylic acids (lactic + malic + citric)	La, Ce, Nd	90°C; pH ≈ 2.0; 60 min	68–73	(Abdulvaliyev et al., 2024)
Red mud (industrial residue)	Citric acid (0.2–1 M)	La, Ce, Nd, Pr, Sm	80°C; pH 2–4; 60–180 min	48–76	(Ray et al., 2025)
Red mud	Acetic acid (0.5–2 M)	La, Ce, Nd, Pr	90°C; pH ≈ 3.5; 120 min	57	(Ray et al., 2025)

¹ Overall, unless highlighted.

higher dissolution rates. Banerjee et al. (2021), for example, achieved 65% of LREE leaching and only 19% of HREE by using tartaric acid (5%, 90°C, and pH of 1.8). In the presence of weak acids and higher pKa, such as acetic acid (pKa of 4.8) and mild pH (4 to 5) the process becomes driven by the complexation step and HREEs are more easily leached than LREEs due to the stronger inner-sphere complexes formed between smaller radii and more charge-dense REE³⁺ ions and the carboxylate groups of the multidentate ligands, resulting in more stable chelation (Zhao et al., 2025c).

Thermodynamic properties also vary due to the joint structure: acid strength and ligand structure. Leaching by strong acids, with greater proton activity tends to be endothermic, and diffusion controlled. Citric and oxalic acids (pKa of 3.1 and 1.2, respectively) produce REE-O/REE-OH bonds effectively, and the reactions are mildly endothermic ($\Delta H \approx +10$ to 25 kJ/mol, $\Delta S \approx 50$ to 85 J/mol.K). At high temperatures (>70°C), they tend to be spontaneous ($\Delta G < 0$). Experimentally, the efficiency rises from 60% to 90% by increasing the temperature from 25 to 70°C, validating the thermodynamic approach. Moreover, the activation energy ($E_a \approx 25$ –35 kJ/mol) is in concordance with the requirements of the shrinking-core diffusion model, which describes a process in which a porous product layer forms around an unreacted solid core, and the overall rate is controlled not by the surface reaction but by the diffusion of ions through this outer layer. This behaviour is characteristic of systems where proton attack is rapid, but mass transfer through the reacted layer limits the overall kinetics, consistent with experimental observations (Banerjee et al., 2021; Gergoric et al., 2018; Ray et al., 2025).

In contrast, leaching by weaker acids, which relies on a complexation step, tends to be exothermic and entropy-driven. Acetic and lactic acids (pKa of 4.8 and 3.9, respectively) do not generate enough proton activity for strong mineral attack, thus the kinetic is driven by the ligand complexation. Because weaker organic acids do not provide the high proton activity or reaction enthalpy characteristic of proton-driven dissolution by strong mineral acids or stronger carboxylic acids (e.g., citric and oxalic acid), the system does not reach the same energetic regime associated with mineral protonation. Consequently, the enthalpy

tends to be lower (ΔH : –8 to + 6 kJ/mol) and the entropy higher (ΔS : 40–70 J/mol.K) (Liang et al., 2024). Due to the entropic contribution, the system is spontaneous but not strongly exothermic (ΔG : –14 to –16 kJ/mol at 298 K), however, at high temperatures, the spontaneous reaction is easily feasible (Gergoric et al., 2018; Zhao et al., 2025c).

The costs of organic acids are higher than those of inorganic acids; however, the investment in equipment is lower, as the system does not require corrosion protection. Any waste produced is also less harmful and biodegradable, consequently reducing costs of treatment and disposal. Due to being less hazardous compared to conventional inorganic acids, the investment in personal protective equipment, specialised labour and environmental damage mitigation and recovery is also less (Abdulvaliyev et al., 2024; Ray et al., 2025; Zhao et al., 2025c). The leaching by oxalic acid, for example, tend to be cheaper than sulfuric acid after 100 cycles when accounting for makeup costs (Rahmatullah et al., 2025). Citric-acid processes avoid expensive acid-resistant linings and neutralisation plants, cutting capital and operational expenditures for small-to-medium operations, LCA-based evaluations show reduced environmental cost per kilogram for REE extracted when biodegradability and effluent neutrality are considered (Zhao et al., 2025c).

3.3. Synthesis and outlook for eco-friendly leaching of Queensland REE ores

The diversity of Queensland's REE ore types, including non-ionic residual clay-hosted deposits, heavy mineral sands, phosphorite-hosted apatite ores, skarn/IOCG systems, and legacy tailings, necessitates differentiated hydrometallurgical approaches. Surface-adsorbed and weakly bound REEs in clay-rich profiles (e.g. Hughenden) respond efficiently to mild leaching agents, particularly ammonium salts, organic acids, DESs, and ILs, enabling selective desorption without disruption of the mineral lattice (Basu and Banerjee, 2023; Knorsch et al., 2025; Moldoveanu and Papangelakis, 2016; 2021; Spellman, 2022). These ores present the fastest transition toward low-impact extraction because their mineralogical configuration requires minimal

energy input, limited chemical intensity, and no high-temperature activation. Table 10 shows that bioleaching, organic-acid leaching, DES, and ILs are particularly well suited to clay-hosted, surface-adsorbed REE deposits, offering lower-impact extraction options that fit well with circular-economy principles and the evolving regulatory landscape in Australia.

In contrast, deposits where REE are structurally incorporated into phosphate, silicate, or oxide lattices, including heavy mineral sands of Cape York (monazite-xenotime), Georgina Basin phosphorites (carbonate-fluorapatite), and Mary Kathleen-type skarn/IOCG systems, require more intensive hydrometallurgical strategies (Hughes and Munro, 1965; Willin, 2022). These ores demand pre-treatment steps like calcination, alkaline cracking, or oxidative roasting to unlock lattice-bound REE (Chakhmouradian and Wall, 2012; Emsbo et al., 2015; Krishnamurthy and Gupta, 2015). Once structural barriers are removed, greener solvents, including DESs, ILs, and organic acids, can be integrated downstream, reducing reliance on strong mineral acids traditionally used for monazite/xenotime or allanite breakdown (Alguacil and Robla, 2023; Belfqueh et al., 2023; Liu et al., 2025; Quijada-Maldonado and Romero, 2021; Turanov et al., 2018). Queensland's phosphorite-hosted REE represent a promising intermediate case: their apatite matrix dissolves more readily, allowing organic acids and bioleaching to achieve economically meaningful recoveries under softer conditions (Cloud, 1987; Emsbo et al., 2016; McArthur and Walsh, 1984). This mineralogical spectrum, summarised in Table 11, frames Queensland as a unique natural laboratory where both, low-intensity and high-intensity hydrometallurgical, approaches are found.

Looking forward, a hybrid “ore-specific green processing

Table 10

Comparative assessment of green extraction technologies for rare earth element (REE) recovery from surface-adsorbed and lattice-bound deposits, highlighting their advantages, limitations, and potential processing roles.

Green Method	Best for Surface-Adsorbed REE	Best for Lattice-Bound REE	Main Role in Processing
Bioleaching	Produces organic acids that mobilize REE Best used for initial leaching of low-grade ores	Can help break down the lattice Process is slow and limited in efficiency	Early-stage leaching for low-grade ores Sustainable recovery
Deep Eutectic Solvents	Highly effective and selective Ideal for replacing ammonium salts or strong acids in clays	Promising results after pre-treatment (e.g. roasting, grinding) Process intensification to dissolve tightly bound REE	Low environmental impact
Electrokinetic mining (EKM)	Enhances ion-exchange extraction by mobilizing REE with an electric field Efficient for clays	Helps penetration of acids or DES into lattice minerals Requires strong electric field and pre-treatment	Leaching intensification and efficiency improvement
Ionic Liquids	Can directly leach REE from clays High selectivity Low environmental footprint Costs more than DES	Effective only after pre-treatment Highly selective leaching or downstream separation	Selective separation
Organic Acid Leaching	Works directly and very effectively for ion-exchange recovery of REE Mild acidity environment	Can be applied after pre-treatment to slowly dissolve REE Requires high temperature or extended time	Mild conditions Eco-friendly leaching alternative to strong acids

framework” emerges as the most realistic development route for the state. Clay-hosted REE can adopt fully green leaching regimes (DES, IL, organic acids, bioleaching, EKM), while lattice-bound REE can incorporate green reagents primarily after pre-treatment. Electrokinetic mining (EKM) is a novel technology that can enhance desorption in clays and improve reagent penetration in denser rocks. Meanwhile, Queensland's extensive tailings, already finely milled, represent the lowest-impact feedstock for green leaching, requiring minimal beneficiation and enabling rapid adoption of DES/IL approaches (van der Ent et al., 2020). Taken together, this suite of technologies positions Queensland to develop an environmentally responsible REE extraction sector where hydrometallurgical routes are tailored to ore mineralogy, chemical bonding environment, and the degree of pre-treatment required.

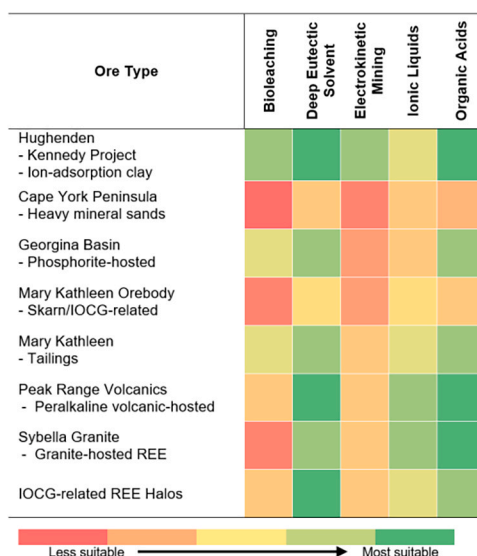
4. Refining

The separation of REE after the leaching step is crucial and although different methods can be applied, ultimately the choice is driven by the previous process/solvent used during leaching. Solvent extraction is the most common method; however, ion exchange, precipitation, adsorption, EKM, and membrane processes have been utilised. To reach high purity, typically $\geq 99\%$ for individual oxides and often $\geq 99.9\%$ for magnet-grade Nd_2O_3 , Pr_6O_{11} , Dy_2O_3 and Tb_4O_7 , and separate HREE and LREE it requires a multistage hydrometallurgical process based on ion stability, hydration, solubility and ionic radii (McNulty et al., 2022). Currently, liquid-liquid solvent extraction (SX/LEE), using organophosphorus extractants (e.g. D_2EHPA , P_2O_4 /Cyanex 272, TBP) remains the most common method of REE refining applied industrially. Greener solvents have emerged to replace the original solvents due to the higher biodegradability, less waste, volatility and toxicity (Kim et al., 2025). Generally, the operation goes through counter-current mixer-settler cascades to progressively fractionate LREE from HREE (Kim et al., 2025). Currently, Queensland has a pilot-scale clay-hosted and phosphorite beneficiation that integrates an liquid-liquid extraction (LLE) unit. However, even when reaching high separation efficiency, the LLE has limitation such as solvent loss and high chemical demand (Delaval et al., 2024).

Ion-exchange techniques can be considered as a complementary after SX/LEE to reach higher purity levels or for dilute complex secondary streams (El Ouardi et al., 2023). Ionic resins and clays are the optimal solid ion exchange materials. Solution-based ion-exchange systems can also be employed; however, they typically require additional downstream separation steps (e.g., evaporation, precipitation, or solvent exchange) to efficiently recover the REE-loaded phase. The advantages include the high selectivity, processability, and environmental friendliness. However, the drawbacks are that the kinetics tend to be low, the resins can foul, and further regeneration costs are high. Chemicals based on sulfonic, phosphonic or chelating resin active groups ($-\text{SO}_3\text{H}$, $-\text{PO}_3\text{H}_2$, $-\text{COOH}$) usually have high selectivity, being able to separate different REE (light and heavy) and minimise iron co-extraction. Usually, HREE display higher separation efficiency due to their higher charge density. Ion exchange by oxalate, carbonate and phosphate is driven by pH and can be run in a one-step reaction as done from NdFeB slurries via phosphoric media without mobilising the Fe, consequently improving the purification (He et al., 2022). Resins containing chelating groups (iminodiacetate, formophenolic) show high REE recovery from citric and oxalic leaching (Delaval et al., 2024). Researchers are developing continuous flow column systems that integrate electrochemical stripping to improve efficiency and reduce waste; adsorption has also been explored (Delaval et al., 2024). Similarly, adsorption has been considered. In this case, the mechanism focuses on chemical surface complexation and is driven by coordination/chemisorption and entropy, while the ion exchange core is the physical replacement of counterions driven by electrostatic attraction (primarily outer-sphere Coulombic interactions between the negatively charged adsorbent surface and hydrated REE^{3+} ions) (Li et al., 2023; Payne et al., 2013; Shen et al., 2024).

Table 11

Comparative heat map of green extraction technologies for representative Queensland REE deposits based on mineralogical characteristics and expected processing performance.



The selectivity tends to be higher for HREE than LREE. [Lelong et al. \(2025\)](#) reported that a formophenolic-like resin achieved about 85% adsorption for Dy^{3+} and Y^{3+} at pH 4.5, while retaining only ~ 65% for La^{3+} and Ce^{3+} ([Lelong et al., 2025](#)). The shift is due to the higher charge-density and smaller ionic radii of HREE that result in faster and greater thermodynamic stability compared to LREE. Other refining processes focused on greener downstream treatment have emerged, including ILs, DESs, and EKM, which can be applied as selective refining steps following leaching and offer reduced environmental impact while supporting Australia's low-footprint approach to REE processing ([Anne-Antoine Otron et al., 2025](#); [Delaval et al., 2024](#)).

Membrane-based refining offers a low-footprint and solvent-saving approach to REE refining after leaching by greener solvent. Some of the most promising are the supported liquid membranes (SLM), and polymer-inclusion membranes (PIM) impregnated with extractants (e.g. Cyanex 272 and organophosphorus) ([Delaval et al., 2024](#)). Australian research partnerships (Northern Minerals and the University of Melbourne) are developing polymeric and metal-organic framework (MOF) membranes for REE refining. Considering the Queensland context, the use of membranes aligns with sustainable downstream processing, complementing solvent extraction and adsorption to minimise waste and energy demand. However, some challenges remain, such as fouling, chemical stability, and scalability.

5. Purification

By this stage a high-purity (>99%) metal oxides are obtained. To achieve this grade, the most common process is by multistage solvent extraction with organophosphorus reagents (e.g. D_2EHPA , Cyanex 272, TBP) ([Kim et al., 2025](#)). A typical REE separation plant may require hundreds to thousands of mixer-settler stages, generating large volumes of spent aqueous raffinate and organic residue; reported waste streams range from 5–20 m^3 of acidic effluent per tonne of TREO produced ([Chen, 2011](#); [Hermassi et al., 2022](#)). Despite its effectiveness, the process is time-consuming, solvent-intensive, and produces substantial secondary waste. Currently, China is well-positioned to further develop this process at low cost. To proceed with this step in Australia, novel methods focused on sustainability must be explored. The use of microfluidic systems is a promising avenue as they promote highly efficient mass transfer allied to different purification methods (e.g. liquid-liquid

extraction ion-exchange, and adsorption). The microscale systems have higher efficiency, faster kinetics, enhanced selectivity, lower solvent consumption, and lesser waste generation when compared to the industrial scale. This is because the mass transfer is improved by reducing the system size ([Abbasi et al., 2018](#); [Welter et al., 2022](#)). [Abbasi et al. \(2018\)](#) developed a parallel-flow microfluidic chip for Gd(III) extraction using MDEHPA, achieving 96% purification within 13.5 s at pH 2.5 and 2.9 vol% extractant, a more than tenfold improvement in mass-transfer efficiency compared to conventional mixers ([Abbasi et al., 2018](#)). Scaling up this process is possible by operating multiple parallel reactors and implementing multi-stage separations on one platform ([Saez et al., 2016](#)). For purification, microfluidic solvent extraction can be sequentially coupled with on-chip stripping or crystallisation modules, to progressively enrich specific REE, such as Nd, Dy, and Y. These approaches align with Australia's sustainability goals, enabling decentralised, low-waste refining for high-purity REE recovery ([Abbasi et al., 2018](#); [Saez et al., 2016](#)).

6. Future Perspectives

Australia is well positioned to contribute to the growing global demand for REE, and Queensland, in particular, offers a combination of shallow deposits, diverse mineralogy, and established mining expertise. However, the reliance of conventional processing routes on large volumes of strong acids and corrosive reagents presents significant regulatory, environmental, and social challenges in the Australian context. Rather than making these methods impossible, these constraints are likely to limit their long-term acceptability and economic viability. This creates a clear incentive to develop alternative extraction routes that can meet both environmental expectations and commercial requirements.

Within this context, green hydrometallurgical approaches such as bioleaching, organic acids, DESs, ILs, and electrokinetic systems represent a growing technological toolkit. The review shows that these methods are not universally applicable, but that their effectiveness depends strongly on mineralogy and ore type. For clay-hosted deposits, several studies have already demonstrated efficient recovery using mild reagents and controlled leaching sequences, suggesting a relatively short pathway from laboratory results to pilot-scale operations. By contrast, crystalline REE minerals remain more challenging, and their treatment will likely require hybrid approaches that combine pretreatment with

selective green leaching or electrokinetic methods.

Looking ahead, progress in Queensland will depend less on identifying a single “best” technology and more on developing ore-specific, integrated processing strategies. Several research and development priorities emerge from the comparative analysis presented in this review. First, pilot-scale validation of bioleaching and DES-based processes for clay-hosted and tailings-derived REE resources should be a near-term focus, as these systems already show promising recoveries under mild conditions. Second, hybrid flowsheets that combine mechanical, thermal, or chemical pretreatment with DES or electrokinetic extraction should be investigated for lattice-bound ores. Third, greater attention should be given to solvent recycling, reagent regeneration, and process intensification to ensure that green technologies remain economically competitive at scale.

Technology readiness also needs to be considered more explicitly. Bioleaching and DES-based processes are approaching pilot-scale demonstration for certain feedstocks, while ILs and electrokinetic systems are still at earlier stages of development or require further integration with other processes. Bridging this gap will require coordinated efforts in pilot testing, long-term stability studies, and techno-economic assessments under realistic operating conditions. Beyond the technological dimension, the success of a Queensland REE industry will depend on how effectively research, regulation, and industry collaborate to build an integrated domestic value chain. National strategies already emphasise the importance of local processing capacity, and Queensland’s existing mining and metallurgical infrastructure provides a practical foundation for this transition.

Beyond technological development, the long-term viability of energy-intensive green extraction routes in Queensland is closely tied to the state’s ongoing energy transition. Currently, Queensland’s electricity grid relies predominantly on coal and natural gas, which undermines the environmental case for processes with high power demands (Wang et al., 2025a; [Understand the electricity supply system | Homes and housing | Queensland Government, 2025](#)). However, the state’s solar and wind endowment, especially across the North West Minerals Province, provides a strong foundation for decarbonising mineral processing operations. Meaningful industrial precedent already exists within Queensland’s metals sector. Sun Metals’ zinc refinery in Townsville — the second largest single-site electricity consumer in Queensland — commissioned a 125 MW solar farm supplying approximately 22% of its operational energy requirements, and has committed to 100% renewable electricity by 2040, establishing that energy-intensive hydrometallurgical operations can be decarbonised at industrial scale (Sun Metals, 2020; RE100, 2020). In northwest Queensland, the Dugald River zinc mine, located in proximity to several prospective REE deposits in the Mount Isa region, began sourcing approximately one third of its electricity from the Dugald River Solar Farm, reducing operational carbon emissions by 33% and demonstrating the feasibility of renewable-powered mining in the same geographic corridor as Queensland’s REE resources (Proactive Investors, 2025). At a broader infrastructure level, the A\$5 billion CopperString 2032 transmission project — currently under construction and scheduled for grid connection by 2031 — will link the North West Minerals Province to the National Electricity Market, unlocking up to 6 GW of renewable energy capacity and providing the transmission backbone necessary to supply low-carbon electricity to future critical minerals operations across the region (Powerlink Queensland, 2024; SFA Oxford, 2025). Taken together, these developments suggest that the energy constraint currently limiting the environmental performance of EKM and other power-dependent extraction routes is not a permanent barrier, but rather a transitional challenge that Queensland’s evolving energy infrastructure is positioned to resolve. Integrating renewable energy planning explicitly into the design and siting of future REE processing facilities would therefore represent a decisive step toward genuinely sustainable extraction in the region.

In this sense, the future of REE extraction in the region is not defined

by a single breakthrough technology, but by the gradual integration of ore-specific green processes, pilot-scale validation, and local refining capability. If these elements are developed in parallel, Queensland could move beyond being a promising resource base to becoming a reference model for environmentally responsible REE extraction, demonstrating how technological innovation, policy alignment, and regional industry can evolve together.

7. Conclusion

Queensland contains a wide variety of REE-bearing deposits. These include clay-hosted systems, phosphorites, heavy-mineral sands, granitic deposits, IOCG-related mineralisation, and historical mine tailings. Many of these resources occur close to the surface, creating favourable conditions for lower-cost extraction and providing an important opportunity for the expansion of Australia’s critical minerals sector.

This review highlights that the mineralogical characteristics of each deposit strongly control the selection of the most suitable extraction route. Conventional hydrometallurgical methods (e.g. strong inorganic acids and alkalis) remain effective, particularly for lattice-bound REE minerals. However, they are commonly associated with high chemical consumption and significant environmental impacts. In contrast, emerging green technologies such as bioleaching, DESs, ILs, and electrokinetic methods show strong potential to reduce environmental risks. These approaches can also maintain technically viable extraction efficiencies.

Among the approaches evaluated, bioleaching and DES systems appear especially promising for several Queensland ore types, particularly clay-hosted deposits and REE-enriched tailings, whereas more complex crystalline ores will likely require hybrid processing routes that combine conventional and emerging technologies to achieve efficient and sustainable recovery.

Although no single technology can currently address all REE deposit types, the combination of Queensland’s geological diversity, established mining expertise, and growing focus on sustainable resource development provides a strong foundation for the future growth of a regional REE industry. Advancing greener extraction and refining strategies will be essential for reducing environmental impacts. These developments will also strengthen Australia’s role in secure and diversified global REE supply chains.

CRedit authorship contribution statement

R.A. Welter: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **A. McCoy-West:** Writing – review & editing. **K. Shahbaz:** Writing – review & editing. **I. Sanislav:** Supervision, Conceptualization. **H. McCoy-West:** Writing – review & editing. **G. Vamvounis:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Abbasi, A., Rahbar-Kelishami, A., Ghasemi, M.J., 2018. Development of a microfluidic-chip system based on parallel flow for intensified Gd(III) extraction from nitrate

- media using cationic extractant. *J. Rare Earths* 36, 1198–1204. <https://doi.org/10.1016/j.jre.2018.03.024>.
- Abbott, A.P., Capper, G., Davies, D.L., McKenzie, K.J., Obi, S.U., 2006. Solubility of metal oxides in deep eutectic solvents based on choline chloride. *J. Chem. Eng. Data* 51, 1280–1282. <https://doi.org/10.1021/je060038c>.
- Abdulvaliyev, R., Utlarukova, A., Mukangaliyeva, A., Likhova, N., Kassymzhanov, K., 2024. Comparative analysis of acid leaching for the efficient recovery of lanthanum and cerium from phosphate. *Separations* 2024 (11), 288. <https://doi.org/10.3390/separations11100288>.
- Acar, Y.B., Alshawabkeh, A.N., 2002. Principles of electrokinetic remediation. *Environ. Sci. Technol.* 27, 2638–2647. <https://doi.org/10.1021/es00049a002>.
- Afridi, J., Wirzal, M.D.H., Foong, C.Y., Azmi Bustam, M., Abd Halim, N.S., Insyirah, N., Abdul Manaf, A.S., Mohd Hizam, S., Firdaus, M.A., Irfan Khan, M., Warsi Khan, H., Usman, M., 2024. Extraction of rare earth elements from ion adsorption clay using bio-based ionic liquid via COSMO-RS: computational and experimental validation. *J. Rare Earths* 43, 2276–2284. <https://doi.org/10.1016/j.jre.2024.11.002>.
- Alguacil, F.J., 2024. Utilizing deep eutectic solvents in the recycle, recovery, purification and miscellaneous uses of rare earth elements. *Molecules* 29 (6), 1356. <https://doi.org/10.3390/molecules29061356>.
- Alguacil, F.J., Robla, J.I., 2023. Recent work on the recovery of rare earths using ionic liquids and deep eutectic solvents. *Minerals* 13 (10), 1288. <https://doi.org/10.3390/min13101288>.
- Alguacil, F.J., Robla, J.I., Rodriguez Largo, O., 2024. Recent uses of ionic liquids in the recovery and utilization of rare earth elements. *Minerals* 14, 734. <https://doi.org/10.3390/min14070734>.
- Almohasin, J.A., Balag, J., Miral, V.G., Moreno, R.V., Tongco, L.J., Lopez, E.C.R., 2023. Green solvents for liquid–liquid extraction: recent advances and future trends. *Eng. Proc.* 56, 174. <https://doi.org/10.3390/asec2023-16278>.
- Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, R.E., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. *Environ. Sci. Technol.* 46, 3406–3414. <https://doi.org/10.1021/es203518d>.
- Amal, S., Laura, S.C., Jokin, H.B., Javier, N.M.F., 2021. Extraction of rare earth elements with deep eutectic solvents. *EP3596241B1*.
- Amirah, A., 2024. Morocco: a key player in global battery manufacturing thanks to its phosphates. accessed 6.15.25 Invest-Time. <https://invest-time.com/en/morocco-a-key-player-in-global-battery-manufacturing-thanks-to-its-phosphates/>.
- Amusa, H.K., Anwer, S., Hamzat, A.K., Adeyemi, I.A., Giwa, A., Ali, J.K., AlNashef, I.M., Alhseinat, E., 2026. Advances in metal recovery from e-waste: green solvent assessments with ionic liquids and deep eutectic solvents. *Sustainable Chemistry for the Environment* 13, 100307. <https://doi.org/10.1016/j.mineng.2025.109322>.
- Anenburg, M., Broom-Fendley, S., Chen, W., 2021. Formation of rare earth deposits in carbonatites. *Elements* 17, 327–332. <https://doi.org/10.2138/gselements.17.5.327>.
- Anne-Antoine Otron, A.M., Tran, L.H., Blais, J.F., 2025. Sustainable extraction and purification of REE and other metals from unsorted battery waste. *Miner. Eng.* 228, 109322. <https://doi.org/10.1016/j.scenv.2025.100307>.
- Arienzo, M., Ferrara, L., Trifuoggi, M., Toscanesi, M., 2022. Advances in the fate of rare earth elements, REE, in transitional environments: coasts and estuaries. *Water* 14, 401. <https://doi.org/10.3390/w14030401>.
- Artushenko, O., Rojano, W.S., Nazarkovsky, M., Azevedo, M.F.M.F., Saint Pierre, T.D., Kai, J., Zaitsev, V., 2024. Recovery of rare earth elements from waste phosphors using phosphonic acid-functionalized silica adsorbent. *Sep. Purif. Technol.* 330, 125525. <https://doi.org/10.1016/j.seppur.2023.125525>.
- Azimi, G., 2025. Technological advancements in rare earth elements recovery from ionic clays: a comprehensive review. *Hydrometall.* 231, 106414. <https://doi.org/10.1016/j.hydromet.2024.106414>.
- Balaram, V., 2019. Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geosci. Front.* 10, 1285–1303. <https://doi.org/10.1016/j.gsf.2018.12.005>.
- Balaram, V., 2023. Advances in analytical techniques and applications in exploration, mining, extraction, and metallurgical studies of rare earth elements. *Minerals* 13, 1031. <https://doi.org/10.3390/min13081031>.
- Banerjee, R., Mohanty, A., Chakravarty, S., Chakladar, S., Biswas, P., 2021. A single-step process to leach out rare earth elements from coal ash using organic carboxylic acids. *Hydrometall.* 201, 105575. <https://doi.org/10.1016/j.hydromet.2021.105575>.
- Barazi, S.A., Anonychuk, A., Aoki, T., Biggs, J., Bourg, S., Conforti, V., Cox, C., Danino-Perroard, R., Debruyne, S., Eckert, S., Hamilton, C., Handley, P., Harada, T., Hanzawa, M., Hebestreit, C., 2025. Global critical minerals outlook 2025.
- Barmettler, F., Castelberg, C., Fabbri, C., Brandl, H., 2016. Microbial mobilization of rare earth elements (REE) from mineral solids—a mini review. *AIMS Microbiol.* 2, 190–204. <https://doi.org/10.3934/microbiol>.
- Barrueto, Y., Hernández, P., Jiménez, Y.P., Morales, J., 2022. Properties and application of ionic liquids in leaching base/precious metals from e-waste. *A Review. Hydrometallurgy* 212, 105895. <https://doi.org/10.1016/j.hydromet.2022.105895>.
- Basu, B., Banerjee, B., 2023. Rare earth elements: processing, catalytic applications and environmental impact. *Walter De Gruyter GmbH, Berlin*. <https://doi.org/10.1515/9783110788082>.
- Bea, F., 1996. Residence of REE, Y, Th and U in granites and crustal protoliths; implications for the chemistry of crustal melts. *J. Petrol.* 37, 521–552. <https://doi.org/10.1093/ptrology/37.3.521>.
- Beckton, J., Hatcher, R., 2011. ASX/Media Announcement.
- Belfqueh, S., Seron, A., Chapron, S., Arrachart, G., Menad, N., 2023. Evaluating organic acids as alternative leaching reagents for rare earth elements recovery from NdFeB magnets. *J. Rare Earths* 41, 621–631. <https://doi.org/10.1016/j.jre>.
- Bie, C., Wu, S., Sun, X., 2024. The fractional extraction for sustainable recovery of rare earth and thorium in radioactive waste with oxoacetate functionalized ionic liquid. *Sep. Purif. Technol.* 350, 127898. <https://doi.org/10.1016/j.seppur.2024.127898>.
- Binnemans, K., Jones, P.T., Müller, T., Yurramendi, L., 2018. Rare earths and the balance problem: how to deal with changing markets. *J. Sust. Met.* 4, 126–146. <https://doi.org/10.1007/s40831-018-0162-8>.
- Bosecker, K., 1997. Bioleaching: metal solubilization by microorganisms. *FEMS Microbiol. Rev.* 20, 591–604. <https://doi.org/10.1111/j.1574->
- Bradley, B., Read, N., 2023. Extensive rare earth elements (REE) intersected in surface clays at Kennedy project. Queensland, West Perth.
- Bradley, B., Read, N., 2024. Kennedy REE project - Maiden 150mt inferred mineral resource for the Kennedy ionic clay-hosted REE project, Queensland.
- Branch, P., Humphries, P., 2012. Queensland phosphate deposits and associated rare earth element potential. *Geological Survey of Queensland, Brisbane, Australia*.
- Bridge, G., 2004. Contested terrain: Mining and the environment. *Annu. Rev. Env. Resour.* 29, 205–259. <https://doi.org/10.1146/annurev.energy.28.011503.163434>.
- Brisson, V.L., Zhuang, W.Q., Alvarez-Cohen, L., 2016. Bioleaching of rare earth elements from monazite sand. *Biotechnol. Bioeng.* 113, 339–348. <https://doi.org/10.1002/bit.25823>.
- Brown, R.M., Mirkouei, A., Reed, D., Thompson, V., 2023. Current nature-based biological practices for rare earth elements extraction and recovery: bioleaching and biosorption. *Renew. Sustain. Energy Rev.* 173, 113099. <https://doi.org/10.1016/j.rser.2022.113099>.
- Carlesi, C., Cortes, E., Dibernardi, G., Morales, J., Muñoz, E., 2016. Ionic liquids as additives for acid leaching of copper from sulfidic ores. *Hydrometall.* 161, 29–33. <https://doi.org/10.1016/j.hydromet>.
- Carretas, J.M., Ferreira, L.M., Santos, P.M.P., Gomes, S.S., Araújo, M.F., Maria, L., Leal, J.P., 2023. Tentative approaches for extraction of lanthanides from wastewater with low metal concentration. *Membranes* 13, 467. <https://doi.org/10.3390/membranes13050467>.
- Chakhmouradian, A.R., Wall, F., 2012. Rare earth elements: minerals, mines, magnets (and more). *Elements* 8, 333–340. <https://doi.org/10.2113/gselements.8.5.333>.
- Chakhmouradian, A.R., Zaitsev, A.N., 2012. Rare earth mineralization in Igneous Rocks: sources and processes. *Elements* 8 (5), 347–353. <https://doi.org/10.2113/gselements.8.5.347>.
- Chandler, R., Spandler, C., 2020. The igneous petrogenesis and rare metal potential of the peralkaline volcanic complex of the southern peak range, Central Queensland, Australia. *Lithos* 358–359, 105386. <https://doi.org/10.1016/j.lithos.2020.105386>.
- Chao, E., Back, J.M., Minkin, J.A., Tatsumoto, M., Junwen, W., Conrad, J.E., McKee, E. H., Zonglin, H., Qingrun, M., Shengguang, H., 1997. Sedimentary carbonate-hosted giant Bayan Obo REE-Fe-Nb ore deposit of Inner Mongolia, China: a cornerstone example for giant polymetallic ore deposits of hydrothermal origin. *Bulletin* 2143. <https://doi.org/10.3133/b2143>.
- Chen, Z., 2011. Global rare earth resources and scenarios of future rare earth industry. *J. Rare Earths* 29, 1–6. [https://doi.org/10.1016/s1002-0721\(10\)60401-2](https://doi.org/10.1016/s1002-0721(10)60401-2).
- Chen, P., Ilton, E.S., Wang, Z., Rosso, K.M., Zhang, X., 2024a. Global rare earth element resources: a concise review. *Appl. Geochem.* 175, 106158. <https://doi.org/10.1016/j.apgeochem.2024.106158>.
- Chen, W., Wang, P., Meng, F., Pehlken, A., Wang, Q.C., Chen, W.Q., 2024b. Reshaping heavy rare earth supply chains amidst China's stringent environmental regulations. *Fundam. Res.* 5, 505. <https://doi.org/10.1016/j.fmr>.
- Chinkaka, E., Klinger, J.M., Davis, K.F., Bianco, F., 2023. Unexpected expansion of rare-earth element mining activities in the Myanmar–China border region. *Remote Sens.* 15 (18), 4597. <https://doi.org/10.3390/rs15184597>.
- Chlahbi, S., Belem, T., Elghali, A., Rochdane, S., Zerouali, E., Inabi, O., Benzaoua, M., 2023. Geological and geomechanical characterization of phosphate mine waste rock in view of their potential civil applications: a case study of the Benguerir mine site, Morocco. *Minerals* 13 (10), 1291. <https://doi.org/10.3390/min13101291>.
- Christenson, E.A., Schijf, J., 2011. Stability of YREE complexes with the trihydroxamate siderophore desferrioxamine b at seawater ionic strength. *Geochim. Cosmochim. Acta* 75, 7047–7062. <https://doi.org/10.1016/j.gca.2011.09.022>.
- Cicconi, M.R., Le Losq, C., Henderson, G.S., Neuville, D.R., 2021. The redox behavior of rare earth elements. In: *In: Magma Redox Geochemistry*. Wiley Blackwell, pp. 381–398. <https://doi.org/10.1002/978111947>
- Cloud, P., 1987. Phosphorite sedimentation: phosphate deposits of the world. *Science* (1979). 236, 1125–6. <https://doi.org/10.1126/science.236.4805.1125-a>.
- Connelly, N.G., 2005. *Nomenclature of inorganic chemistry. IUPAC recommendations*.
- Corner, L., 2025. Electrokinetic mining enables efficient and eco-friendly REE recovery. *AzoMining*. Available at: <https://www.azomining.com/News.aspx?newsID=18242>.
- Costelloe, M., 2003. *Environmental review of the Mary Kathleen uranium mine*. James Cook University, Townsville.
- Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. *J. Hazard. Mater.* 158 (2–3), 228–256. <https://doi.org/10.1016/j.jhazmat>.
- Daafi, Y., Chakir, A., Jourani, E., Ouabba, S.M., 2014. Geology and mine planning of phosphate deposits: Benguerir deposit Gantour Basin – Morocco. *Procedia Eng.* 83, 70–75. <https://doi.org/10.1016/j.proeng>.
- Dai, Y., Li, Y., Hu, W., Tao, Q., Liu, Z., 2023. Functionalized ionic liquids based on DODGA with enhanced Eu(III)/U(VI) separation efficiency in highly acidic environment. *J. Mol. Liq.* 387, 122557. <https://doi.org/10.1016/j.molliq.2023.122557>.
- Davris, P., Balomenos, E., Pania, D., Paspaliaris, I., 2016. Selective leaching of rare earth elements from bauxite residue (red mud), using a functionalized hydrophobic ionic liquid. *Hydrometall.* 164, 125–135. <https://doi.org/10.1016/j.hydromet>.
- Dean, J.A., Lange, N., Adolph, 1998. *Lange's handbook of chemistry*, 15th ed. McGraw-Hill.

- Dehkordi, M.M., Nodeh, Z.P., Dehkordi, K.S., Salmanvandi, H., Khorjestan, R.R., Ghaffarzadeh, M., 2024. Soil, air, and water pollution from mining and industrial activities: sources of pollution, environmental impacts, and prevention and control methods. *Results Eng.* 23, 102729. <https://doi.org/10.1016/j.rineng.2024.102729>.
- Delaval, B., Goessler, C., Duong, P., Castro, N.G., Galea, B., Maloney, G., 2024. From minerals to materials - supplementary report: rare earths. Canberra.
- Delzoppo, L., 2013. Urquhart Point Mineral Sands Project proposed by Oresome Australia Pty Ltd - Environmental Impact Statement (EIS) Report under the Environmental Protection Act 1994.
- Dong, Y., Zan, J., Lin, H., 2023. Bioleaching of heavy metals from metal tailings utilizing bacteria and fungi: mechanisms, strengthen measures, and development prospect. *J. Environ. Manage.* 344, 118511. <https://doi.org/10.1016/j.jenvman.2023.118511>.
- Do-Thanh, C.L., Luo, H., Dai, S., 2023. A perspective on task-specific ionic liquids for the separation of rare earth elements. *RSC Sustainability* 1 (5), 1168–1176. <https://doi.org/10.1039/d3su00007a>.
- Drew, L.J., Qingrun, M., Weijun, S., 1990. The Bayan Obo iron-rare-earth-niobium deposits, inner Mongolia, China. *Lithos* 26, 43–65. [https://doi.org/10.1016/0024-4937\(90\)90040-8](https://doi.org/10.1016/0024-4937(90)90040-8).
- Dusengemungu, L., Kasali, G., Gwanama, C., Mubemba, B., 2021. Overview of fungal bioleaching of metals. *Environ. Adv.* 5, 100083. <https://doi.org/10.1016/j.envadv.2021.100083>.
- Dushyantha, N., Nanayakkara, C.J., Kuruppu, G.N., 2024. Advancement in electrokinetic processes for efficient critical metal extraction: unveiling the potential of electrokinetic in-situ leaching (EK-ISL) in mining and mineral processing. *Miner. Eng.* 213, 108744. <https://doi.org/10.1016/j.mineng.2024.108744>.
- Dutkiewicz, A., Landgrebe, T.C.W., Rey, P.F., 2015. Origin of silica and fingerprinting of Australian sedimentary opals. *Gondw. Res.* 27, 786–795. <https://doi.org/10.1016/j.gr.2013.10.013>.
- El Ouardi, Y., Virolainen, S., Massima Moutele, E.S., Laatikainen, M., Repo, E., Laatikainen, K., 2023. The recent progress of ion exchange for the separation of rare earths from secondary resources – a review. *Hydrometall.* 218, 106047. <https://doi.org/10.1016/j.hydromet.2023.106047>.
- Emsbo, P., McLaughlin, P.I., Breit, G.N., du Bray, E.A., Koenig, A.E., 2015. Rare earth elements in sedimentary phosphate deposits: solution to the global REE crisis? *Gondw. Res.* 27 (2), 776–785. <https://doi.org/10.1016/j.gr.2014.10.008>.
- Emsbo, P., McLaughlin, P.I., du Bray, E.A., Anderson, E.D., Vandenbroucke, T., Zielinski, R.A., 2016. Rare earth elements in sedimentary phosphorite deposits: a global assessment, in: Verplanck, P.L., Hitzman, M.W. (Eds.), *Rare Earth and Critical Elements in Ore Deposits*, Rev. Econ. Geol. GeoScienceWorld, pp. 101–113. Doi: 10.5382/rev.18.05.
- Entezari-Zarandi, A., Larachi, F., 2019. Selective dissolution of rare-earth element carbonates in deep eutectic solvents. *J. Rare Earths* 37, 528–533. <https://doi.org/10.1016/j.jre.2018.07.015>.
- Ewart, A., 1982. Petrogenesis of the tertiary anorogenic volcanic series of southern Queensland, Australia, in the light of trace element geochemistry and o, Sr and Pb isotopes. *J. Petrol.* 23, 344–382. <https://doi.org/10.1093/petrology/23.3.344>.
- Falconnet, P., 1985. The economics of rare earths. *J. Less-Common Met.* 111, 9–15. [https://doi.org/10.1016/0022-5088\(85\)90163-8](https://doi.org/10.1016/0022-5088(85)90163-8).
- Farjana, S.H., Huda, N., Mahmud, M.A.P., Saidur, R., 2019. A review on the impact of mining and mineral processing industries through life cycle assessment. *J. Clean. Prod.* 231, 1200–1217. <https://doi.org/10.1016/j.jclepro.2019.05.264>.
- Feng, L., Long, W., Li, B., Li, T., Zhang, Z., Wang, X., Li, H., 2025. Microfluidic strategy for rapid and efficient extraction of scandium ions from red mud. *Sep. Purif. Technol.* 375 (5), 133710. <https://doi.org/10.1016/j.seppur.2025.133710>.
- Ferreira, C., Sarragaça, M., 2024. A comprehensive review on deep eutectic solvents and its use to extract bioactive compounds of pharmaceutical interest. *Pharmaceuticals* 17, 124. <https://doi.org/10.3390/ph17010124>.
- Föllmi, K.B., Föllmi, K.B., 1996. The phosphorus cycle, phosphogenesis and marine phosphate-rich deposits. *Earth Sci. Rev.* 40 (1–2), 55–124. [https://doi.org/10.1016/0012-8252\(95\)00049-6](https://doi.org/10.1016/0012-8252(95)00049-6).
- Gadd, G.M., 2007. Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. *Mycol. Res.* 111, 3–49. <https://doi.org/10.1016/j.mycres.2007.01.001>.
- Gergoric, M., Ravaux, C., Steenari, B.-M., Espgren, F., Retegan, T., 2018. Leaching and recovery of rare-earth elements from neodymium magnet waste using organic acids. *Metals* 8, 721. <https://doi.org/10.3390/met8090721>.
- Golev, A., 2025. Rare earths in focus: powering energy transition. accessed 9.4.25 Queensland Government. <https://geoscience.data.qld.gov.au/blog/rare-earths-focus-powering-energy-transition>.
- Goodenough, K.M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E. A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D.G., Shaw, R.A., Thrane, K., Keulen, N., 2016. Europe's rare earth element resource potential: an overview of REE metallogenetic provinces and their geodynamic setting. *Ore Geol. Rev.* 72, 838–856. <https://doi.org/10.1016/j.oregeorev.2015.09.019>.
- Guidugli, L.F., Reza, T., 2025. Systematic evaluation of stearic acid -based hydrophobic deep eutectic solvents on the extraction of selected light and heavy rare earth elements from water. *J. Ionic Liq.* 5 (2), 100176. <https://doi.org/10.1016/j.jil.2025.100176>.
- Hammarstrom, J.M., Seal II, R.R., Meier, A.L., Kornfeld, J.M., 2017. Environmental considerations related to mining of nonfuel minerals. In: *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*. U.S. Geol. Surv. Prof. Pap. 1802-B. Doi: 10.3133/pp1802B.
- Han, Y.H., Cui, X.W., Zhang, Y., Zhang, H., Chen, Z., 2025. Environmental impacts of rare earth elements mining and strategies for sustainable management: a comprehensive review. *J. Hazard. Mater.* 500, 140400. <https://doi.org/10.1016/j.jhazmat.2025.140400>.
- Hansen, B.B., Spittle, S., Chen, B., Poe, D., Zhang, Y., Klein, J.M., Horton, A., Adhikari, L., Zelovich, T., Doherty, B.W., Gurkan, B., Maginn, E.J., Ragauskas, A., Dadmun, M., Zawodzinski, T.A., Baker, G.A., Tuckerman, M.E., Savinell, R.F., Sangoro, J.R., 2020. Deep eutectic solvents: a review of fundamentals and applications. *Chem. Rev.* 121, 1232–1285. <https://doi.org/10.1021/acs.chemrev.0c00385>.
- Haque, N., Hughes, A., Lim, S., Vernon, C., 2014. Rare earth elements: Overview of mining, mineralogy, uses, sustainability and environmental impact. *Resources* 3 (4), 614–635. <https://doi.org/10.3390/resources3040614>.
- Harmon, R.S., Russo, R.E., Hark, R.R., 2013. Applications of laser-induced breakdown spectroscopy for geochemical and environmental analysis: a comprehensive review. *Spectrochim. Acta Part B at. Spectrosc.* 87, 11–26. <https://doi.org/10.1016/j.sab.2013.05.017>.
- Haxel, G.B., Hedrick, J.B., Orris, G.J., 2022. Rare earth elements — critical resources for high technology.
- He, L., Xu, Q., Li, W., Dong, Q., Sun, W., 2022. One-step separation and recovery of rare earth and iron from NdFeB slurry via phosphoric acid leaching. *J. Rare Earths* 40, 338–344. <https://doi.org/10.1016/j.jre.2021.01.003>.
- He, N., Zhang, C., Meng, X., Shi, Q., Shen, L., Zhao, H., 2025a. Bioleaching rare earth elements from bastnaesite with isolated functional bacterium: an eco-friendly alternative strategy. *Bioresour. Technol.* 432, 132680. <https://doi.org/10.1016/j.biortech.2025.132680>.
- He, Y., Ma, L., Li, X., Liu, X., Liang, X., Zhu, J., He, H., 2025b. Microbial-mediated bastnaesite dissolution as a viable source of clay-adsorbed rare earth elements in the regolith-hosted deposits. *Geochim. Cosmochim. Acta* 394, 43–52. <https://doi.org/10.1016/j.gca.2025.01.013>.
- Hermassi, M., Granados, M., Valderrama, C., Ayora, C., Cortina, J.L., 2022. Recovery of rare earth elements from acidic mine waters: an unknown secondary resource. *Sci. Total Environ.* 810, 152258. <https://doi.org/10.1016/j.scitotenv.2021.152258>.
- Hidayat, M., 2025. Madagascar rare earths supply chain: strategic alternative. *Discovery Alert*. URL <https://discoveryalert.com.au/madagascar-rare-earths-supply-chain-2025/> (accessed 11.28.25).
- Hitchman, A., 2018. Australian resources review: mineral sand 2017. Australian Resources Review: Mineral Sand 2017. <https://doi.org/10.11636/9781925297706>.
- Hoatson, D.M., Jaireth, S., Miezitis, Y., 2011. The major rare-earth-element deposits of Australia: geological setting, exploration, and resources. *Geoscience Australia* 204.
- Hoshino, M., Sanematsu, K., Watanabe, Y., 2016. REE mineralogy and resources, in: handbook on the physics and chemistry of rare earths. Elsevier B.V., pp. 129–291. Doi: 10.1016/bs.hpcr.2016.03.006.
- Huang, X.W., Long, Z.Q., Wang, L.S., Feng, Z.Y., 2015. Technology development for rare earth cleaner hydrometallurgy in China. *Rare Met.* 34, 215–222. <https://doi.org/10.1007/s12598-015-0473-x>.
- Hughes, F.E., Munro, D.L., 1965. Uranium ore deposit at Mary Kathleen. In: McAndrew, J. (Ed.), *Geology of Australian Ore Deposits*. 8th Commonwealth Mining and Metallurgical Congress, Australasian Institute of Mining and Metallurgy, Melbourne, pp. 256–263.
- Hughes, J.M., Rakovan, J., 2002. The crystal structure of apatite, Ca₅(PO₄)₃(F,OH,Cl). *Rev. Mineral. Geochem.* 48, 1–12. <https://doi.org/10.2138/rmg.2002.48.1>.
- Hughes, I.D., Däne, M., Ernst, A., Hergert, W., Lüders, M., Poulter, J., Staunton, J.B., Svane, A., Szotek, Z., Temmerman, W.M., 2007. Lanthanide contraction and magnetism in the heavy rare earth elements. *Nature* 446, 650–653. <https://doi.org/10.1038/nature05668>.
- Hughes, A., Britt, A.F., Pheeney, J., Summerfield, D., Senior, A., Hitchman, A.P., Cross, A. J., Sexton, M., Colclough, H., Hill, J., 2023. Australia's identified mineral resources 2022. *Geoscience Australia*.
- Huleatt, M., 2019. Australian Resource Reviews: Rare Earth Elements. <https://doi.org/10.11636/9781925848441>.
- Huston, D., 2024. Global rare earth element deposits - a compilation. Commonwealth of Australia - Geoscience Australia. <https://doi.org/10.26186/148953>.
- Ibad, S.M., Tsegab, H., Siddiqui, N.A., Adam, M., Mishra, S., Ridha, S., Ahmed, N., Azmi, A., 2024. The upstream rare earth resources of Malaysia: insight into geology, geochemistry, and hydrometallurgical approaches. *Geosci. Front.* 15 (6), 101899. <https://doi.org/10.1016/j.gsf.2024.101899>.
- IEA (2020), *World Energy Outlook 2020*, IEA, Paris <https://www.iea.org/reports/world-energy-outlook-2020>. (accessed: 10.01.2025).
- Jackon, R., Emery, B., 2024. Ark mines ltd. - rare earth elements, <https://arkmines.com/> (accessed: 09.09.2025).
- Jaireth, S., Hoatson, D.M., Miezitis, Y., 2014. Geological setting and resources of the major rare-earth-element deposits in Australia. *Ore Geol. Rev.* 62, 72–128. <https://doi.org/10.1016/j.oregeorev.2014.02.008>.
- Jensen, P.E., Ahning, B.K., Ottosen, L.M., 2007. Organic acid enhanced electrodiolytic extraction of lead from contaminated soil fines in suspension. *J. Chem. Technol. Biotechnol.* 82, 920–928. <https://doi.org/10.1002/jctb.1762;pagegroup:string:publication>.
- Jha, M.K., Kumari, A., Panda, R., Kumar, J.R., Yoo, K., Lee, J.Y., 2016. Review on hydrometallurgical recovery of rare earth metals. *Hydrometall.* 165, 2–26. <https://doi.org/10.1016/j.hydromet.2016.01.035>.
- Ji, B., Li, Q., Zhang, W., 2022. Leaching recovery of rare earth elements from the calcination product of a coal coarse refuse using organic acids. *J. Rare Earths* 40, 318–327. <https://doi.org/10.1016/j.jre.2020.11.021>.
- Johnson, D.B., 2014. Biomining — biotechnologies for extracting and recovering metals from ores and waste materials. *Curr. Opin. Biotechnol.* 30, 24–31. <https://doi.org/10.1016/j.copbio.2014.04.008>.

- Jones, S., Santini, J.M., 2023. Mechanisms of bioleaching: iron and sulfur oxidation by acidophilic microorganisms. *Essays Biochem.* 67, 685. <https://doi.org/10.1042/ebc20220257>.
- Joshi, K., Magdoui, S., Brar, S.K., 2025. Bioleaching for the recovery of rare earth elements from industrial waste: a sustainable approach. *Resour. Conserv. Recycl.* 215, 108129. <https://doi.org/10.1016/j.resconrec.2025.108129>.
- Kang, S., Ling, B., Liang, X., Wang, G., Xu, J., Xu, Y., Zhu, R., Wei, J., Zhu, J., He, H., 2024. Recovery of rare earth elements from ion-adsorption deposits using electrokinetic technology: the soil conductivity mechanism study. *Minerals* 14, 491. <https://doi.org/10.3390/min14050491>.
- Kaplan, S.S., Kurtulan, C.C., Gurmen, S., Orhan, G., Sonmez, M.S., 2025. Influence of calcination conditions on deep eutectic solvents (DES) leaching efficiency of light rare earth elements in bastnaesite ore. *Miner. Eng.* 220, 109087. <https://doi.org/10.1016/j.mineng.2024.109087>.
- Karaca, O., 2025. Citric acid-assisted electrokinetic remediation of arsenic and metal-rich acidic mine pond sediments. *Toxics* 13 (11), 1000. <https://doi.org/10.3390/toxics13111000>.
- Khalid, H.M., Santos, R.M., 2025. Deep eutectic solvents and ionic liquids in hydrometallurgical recovery of metals - a review of recent advances and challenges. *Hydrometall.* 238, 106571. <https://doi.org/10.1016/j.hydromet.2025.106571>.
- Kim, J., Choi, J., Lee, S., 2025. A review of rare earth elements recovery from bastnaesite ore: from beneficiation to metallurgical processing. *J. Sustain. Metall.* 11, 773–798. <https://doi.org/10.1007/s40831-025-01019-0/tables/10>.
- Knorsch, M., Gazley, M., Ince, M., Kartal, M., Trunfull, E., Lilly, K., Piechocka, A., Lu, Y., Cooke, B., Kelaart, C., 2025. Characterisation of clay-hosted rare-earth element deposits in Australia: mineralogy, geochemistry and metallurgy. *Aust. J. Earth Sci.* 72 (8), 1005–1024. <https://doi.org/10.1080/08120099.2025.2570934>.
- Kolar, E., Cattoor, R.P.R., Kriel, F.H., Sedev, R., Middlemas, S., Klier, E., Hatch, G., Priest, C., 2016. Microfluidic solvent extraction of rare earth elements from a mixed oxide concentrate leach solution using Cyanex® 572. *Chem. Eng. Sci.* 148, 212–218. <https://doi.org/10.1016/j.ces.2016.04.009>.
- Kozhevnikova, A.V., Zinov'eva, I.V., Milevskii, N.A., Zakhodyaeva, Y.A., Voshkin, A.A., 2023. Complex extraction of rare earth elements from nitrate solutions with a tri-n-octylamine-octanoic acid bifunctional ionic liquid. *J. Mol. Liq.* 390, 123073. <https://doi.org/10.1016/j.molliq.2023.123073>.
- Krishnamurthy, N., Gupta, C.K., 2015. *Extractive Metallurgy of Rare Earths*, 2nd ed. CRC Press, Boca Raton, FL. Doi: 10.1201/b19055.
- Kynicky, J., Smith, M.P., Xu, C., 2012. Diversity of rare earth deposits: the key example of China. *Elements* 8, 361–367. <https://doi.org/10.2113/gselements.8.5.361>.
- Lakshmanan, V.L., 1992. Emerging technologies in hydrometallurgy. *Miner. Process. Extr. Metall. Rev.* 8, 219–228. <https://doi.org/10.1080/08827509208952688>.
- Lazo, D.E., Dyer, L.G., Alorro, R.D., Browner, R., 2017. Treatment of monazite by organic acids I: solution conversion of rare earths. *Hydrometall.* 174, 202–209. <https://doi.org/10.1016/j.hydromet.2017.10.003>.
- Lazzarini, P., 2024. Queensland mining industry heads back to the future to improve safety | Queensland Resources Council. URL <https://www.qrc.org.au/Queensland-mining-industry-heads-back-to-the-future-to-improve-safety/> (accessed 8.12.25).
- Lelong, E., Couturier, J., Levard, C., Pellet-Rostaing, S., Arrachart, G., 2025. Extraction of rare earth elements from organic acid leachate using formo-phenolic-like resins. *Recycling* 10, 165. <https://doi.org/10.3390/recycling10040165/s1/>.
- Lelong, E., Couturier, J., Levard, C., Pellet-Rostaing, S., Arrachart, G., 2025. Extraction of rare earth elements from organic acid leachate using formo-phenolic-like resins. *Recycling* 10, 165. <https://doi.org/10.3390/recycling10040165>.
- Liang, S., Meng, Q., Liu, Z., Cai, H., Liu, H., Rong, M., Yang, L., 2024. Scalable and facile fabrication of sulfonic-acid-functionalized porous hypercrosslinked polymers for efficient recovery of rare earth elements from tailing wastewater. *Chem. Eng. J.* 499, 155850. <https://doi.org/10.1016/j.cej.2024.155850>.
- Li, H., Eksteen, J., Oraby, E., 2018. Hydrometallurgical recovery of metals from waste printed circuit boards (wpcbs): current status and perspectives – a review. *Resour. Conserv. Recycl.* 139, 122–139. <https://doi.org/10.1016/j.resconrec.2018.08.007>.
- Li, M.Y.H., Zhou, M.-F., Williams-Jones, A.E., 2019. The genesis of regolith-hosted heavy rare earth element deposits: insights from the world-class Zudong deposit in Jiangxi province, South China. *Econ. Geol.* 114, 541–568. <https://doi.org/10.5382/econgeo.4642>.
- Li, F., Xiao, Z., Zeng, J., Chen, J., Sun, X., 2020. Recovery of REEs from leaching liquor of ion-adsorbed-type rare earths ores using ionic liquid based on cooking oil. *Hydrometallurgy* 196, 105449. <https://doi.org/10.1016/j.hydromet.2020.105449>.
- Li, X., Li, W., Gao, Y., Tian, G., 2022. Effect of mechanical activation on the leaching process of rare earth metal yttrium in deep eutectic solvents. *Applied Sciences* 2022, 12(16), 8253; Doi: 10.3390/app12168253.
- Li, B., Shi, X., Li, C., Hua, Q., Li, X., Yan, Q., 2023. Theoretical investigation of outer-sphere adsorption of hydrated yttrium ion on the basal surfaces of kaolinite: a density functional study. *Chem. Geol.* 641. <https://doi.org/10.1016/j.chemgeo.2023.121769>.
- Ling, J.K.U., Hadinoto, K., 2022. Deep eutectic solvent as green solvent in extraction of biological macromolecules: a review. *Int. J. Mol. Sci.* 2022, 23(6), 3381; Doi: 10.3390/ijms23063381.
- Lisitsin, V., Valetich, M., 2022. Geological Survey of Queensland - Rare earth elements in phosphorite deposits of the Georgina Basin, North-West Queensland.
- Liu, S.L., Fan, H.R., Liu, X., Meng, J., Butcher, A.R., Yann, L., Yang, K.F., Li, X.C., 2023. Global rare earth elements projects: New developments and supply chains. *Ore Geol. Rev.* 157, 105428. <https://doi.org/10.1016/j.oregeorev.2023.105428>.
- Liu, Z., Yang, F., Sun, Z., Chi, Q., Li, Y., 2024. Efficient selective leaching of ytterbium and lutetium oxides by new hydrophobic deep eutectic solvents. *Sep. Purif. Technol.* 343, 127097. <https://doi.org/10.1016/j.seppur.2024.127097>.
- Liu, P., Wang, X., Zhang, W., 2025. Impact of organic acids on extraction of rare earth elements: Mechanisms and optimization. *J. Rare Earths* 44 (1), 299–310. <https://doi.org/10.1016/j.jre.2025.02.012>.
- Lomba, L., García, C.B., Ribate, M.P., Giner, B., Zuriaga, E., 2021. Applications of deep eutectic solvents related to health, synthesis, and extraction of natural based chemicals. *Applied Sciences* 2021, 11(21), 10156; Doi: 10.3390/app112110156.
- Lottermoser, B.G., Ashley, P.M., 2005. Tailings dam seepage at the rehabilitated Mary Kathleen uranium mine. Australia. *J. Geochem. Explor.* 85 (3), 119–137. <https://doi.org/10.1016/j.gexplo.2005.01.001>.
- Lucas, J., 2015. Rare earths: science, technology, production and use. Elsevier. <https://doi.org/10.1016/c2012-0-02577-x>.
- Maes, S., Zhuang, W.Q., Rabaey, K., Alvarez-Cohen, L., Hennebel, T., 2017. Concomitant leaching and electrochemical extraction of rare earth elements from monazite. *Environ. Sci. Technol.* 51, 1654–1661. <https://doi.org/10.1021/acs.est.6b03675>.
- Ma, J., Li, S., Wang, J., Jiang, S., Panchal, B., Sun, Y., 2023. Bioleaching rare earth elements from coal fly ash by *Aspergillus niger*. *Fuel* 354, 129387. <https://doi.org/10.1016/j.fuel.2023.129387>.
- Ma, R., Li, J., Zhang, X., Jia, P., Liu, Z., Wu, J., Feng, F., Xin, W., 2024. Decomposition of monazite in Bayan Obo rare earth ore by roasting of Na₂CO₃ pellets. *J. Rare Earths* 42, 1969–1978. <https://doi.org/10.1016/j.jre.2023.09.014>.
- Makarova, I., Ryl, J., Sun, Z., Kurilo, I., Górnicka, K., Laatikainen, M., Repo, E., 2020. One-step recovery of REE oxalates in electro-leaching of spent NdFeB magnets. *Sep. Purif. Technol.* 251, 117362. <https://doi.org/10.1016/j.seppur.2020.117362>.
- Mancheri, N.A., 2015. World trade in rare earths, chinese export restrictions, and implications. *Resour. Policy* 46, 262–271. <https://doi.org/10.1016/j.resourpol.2015.10.009>.
- Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J., Tukker, A., 2019. Effect of chinese policies on rare earth supply chain resilience. *Resour. Conserv. Recycl.* 142, 101–112. <https://doi.org/10.1016/j.resconrec.2018.11.017>.
- Mandaokar, A., 2023. Rare earth metals market research report information by type (cerium, dysprosium, erbium, europium, neodymium, holmium, lanthanum, lutetium, and others), by application (metallurgy, batteries, magnets, glass & ceramics, polishing agents, and others), and by region - global forecast to 2032. Market Research Future. URL <https://www.marketresearchfuture.com/reports/rare-earth-metal-market-2261> (accessed 6.5.25).
- Marcus, Y., 1991. Thermodynamics of solvation of ions. Part 5.—Gibbs free energy of hydration at 298.15 K. *J. Chem. Soc. Faraday Trans. 87*, 2995–2999. <https://doi.org/10.1039/FT9918702995>.
- Marsden, S. (2024). Myanmar's rare earth boom | Global Witness. (2024) Retrieved November 28, 2025, from <https://globalwitness.org/en/campaigns/transition-minerals/fuelling-the-future-poisoning-the-present-myanmars-rare-earth-boom/> (accessed 10.10.25).
- Martin, M.I., García-Díaz, I., López, F.A., 2023. Properties and perspective of using deep eutectic solvents for hydrometallurgy metal recovery. *Miner. Eng.* 203, 108306. <https://doi.org/10.1016/j.mineng.2023.108306>.
- McArthur, J.M., Walsh, J.N., 1984. Rare-earth geochemistry of phosphorites. *Chem. Geol.* 47, 191–220. [https://doi.org/10.1016/0009-2541\(84\)90126-8](https://doi.org/10.1016/0009-2541(84)90126-8).
- McConnell, D., 1973. Apatite: Its crystal chemistry, mineralogy, utilization, and geologic and biologic occurrences, 1st ed. Springer. Doi: 10.1007/978-3-7091-8314-4.
- McCoy-West, A.J., Bennett, V.C., O'Neill, H.S.C., Hermann, J., Puchtel, I.S., 2015. The interplay between melting, refertilization and carbonate metasomatism in off-cratonic lithospheric mantle under Zealandia: an integrated major, trace and platinum group element study. *J. Petrol.* 56, 563–604. <https://doi.org/10.1093/petrology/egv011>.
- McNulty, T., Hazen, N., Park, S., 2022. Processing the ores of rare-earth elements. *MRS Bull.* 47, 258–266. <https://doi.org/10.1557/s43577-022-00288-4/figures/3> (accessed 7.8.25).
- Meehan, P., Lawn, D.S., 2024. The rare earth mining process in Myanmar: from extraction to export rare earth mining in the kachin state. University of Warwick, Myanmar, p. 22.
- Moldoveanu, G.A., Papangelakis, V.G., 2016. An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays. *Miner. Eng.* 89, 123–136.
- Moldoveanu, G.A., Papangelakis, V.G., 2021. Chelation-assisted ion-exchange leaching of rare earths from clay minerals. *Metals* 11 (8), 1265. <https://doi.org/10.3390/met11081265>.
- Muddanna, M.H., Baral, S.S., 2021. Bioleaching of rare earth elements from spent fluid catalytic cracking catalyst using *Acidithiobacillus ferrooxidans*. *J. Environ. Chem. Eng.* 9 (1), 104848. <https://doi.org/10.1016/j.jece.2020.104848>.
- National Minerals Information Center, 2024. Mineral commodity summaries. <https://doi.org/10.3133/mcs2024>.
- National Minerals Information Center, 2025. Mineral commodity summaries 2025. Reston, VA. <https://doi.org/10.3133/mcs2025>.
- Nkrumah, P.N., Erskine, P.D., Erskine, J.D., van der Ent, A., 2021. Rare earth elements (REE) in soils and plants of a uranium-REE mine site and exploration target in Central Queensland, Australia. *Plant Soil* 464, 375–389. <https://doi.org/10.1007/s11104-021-04956-3>.
- Owusu-Fordjour, E.Y., Yang, X., 2023. Bioleaching of rare earth elements challenges and opportunities: a critical review. *J. Environ. Chem. Eng.* 11, 110413. <https://doi.org/10.1016/j.jece.2023.110413>.
- Pan, Y., Fleet, M.E., 2002. Compositions of the apatite-group minerals: substitution mechanisms and controlling factors. *Rev. Mineral. Geochem.* 48, 13–49. <https://doi.org/10.2138/rmg.2002.48.2>.
- Panda, P., Mishra, S., 2024. Effect of process variables on the extraction of Y(III) from nitrate medium utilizing ionic liquid [THAH]⁺[DEHP]⁻. *Mater. Today Proc.* 102, 97–106. <https://doi.org/10.1016/j.matpr.2023.03.411>.

- Pan, J., Zhao, X., Zhou, C., Yang, F., Ji, W., 2022. Study on solvent extraction of rare earth elements from leaching solution of coal fly ash by P_2O_4 . *Minerals* 2022, 12(12), 1547. Doi: 10.3390/min12121547.
- Parhi, P.K., Behera, S.S., Mandal, D., Das, D., Mohapatra, R.K., 2020. Fundamental principle and practices of solvent extraction (SX) and supported liquid membrane (SLM) process for extraction and separation of rare earth metal(s), in: *Rare-Earth Metal Recovery for Green Technologies: Methods and Applications*. Springer, Cham, pp. 57–85. Doi: 10.1007/978-3-030-38106-6_4.
- Payne, T.E., Brendler, V., Ochs, M., Baeyens, B., Brown, P.L., Davis, J.A., Ekberg, C., Kulik, D.A., Lutzenkirchen, J., Missana, T., Tachi, Y., Van Loon, L.R., Altmann, S., 2013. Guidelines for thermodynamic sorption modelling in the context of radioactive waste disposal. *Environ. Model. Softw.* 42, 143–156. <https://doi.org/10.1016/j.envsoft.2013.01.002>.
- Pelaez, M., Nolan, N.T., Pillai, S.C., Seery, M.K., Falaras, P., Kontos, A.G., Dunlop, P.S.M., Hamilton, J.W.J., Byrne, J.A., O'Shea, K., Entezari, M.H., Dionysiou, D.D., 2012. A review on the visible light assisted titanium dioxide photocatalysts for environmental applications. *Appl. Catal. B* 125, 331–349. <https://doi.org/10.1016/j.apcatb.2012.05.036>.
- Perna, F.M., Vitale, P., Capriati, V., 2020. Deep eutectic solvents and their applications as green solvents. *Curr. Opin. Green Sustain. Chem.* 21, 27–33. <https://doi.org/10.1016/j.cogsc.2019.09.004>.
- Petraglia, F.F.N., Martins, T.A.G., Hashimoto, H., Tenório, J.A.S., Espinosa, D.C.R., 2025. Acetic acid leaching of rare earth elements from e-waste magnets: process optimization and kinetic evaluation. *Waste Manag.* 205, 115001. <https://doi.org/10.1016/j.wasman.2025.115001>.
- Pieckowski, M., Ołędzka, I., Bączek, T., Kowalski, P., 2025. Deep eutectic solvents in capillary electromigration techniques—a review of recent advancements. *Molecules* 30 (18), 3674. <https://doi.org/10.3390/molecules30183674>.
- Pires, C.M.G., Ponte, H.A., Grassi, M.T., Ponte, M.J.J.S., Ribeiro, A.B., 2023. Extracting light rare earth elements by applying electric field assisted mining technique. *Miner. Eng.* 203, 108354. <https://doi.org/10.1016/j.mineng.2023.108354>.
- Pistilli, M., 2024. Top 10 phosphate countries by production (updated 2024). *Investing News*. accessed 6.14.25 Network. <https://investingnews.com/daily/resource-investing/agriculture-investing/phosphate-investing/top-phosphate-countries-by-product/on/>.
- Poulet, T., Parbhakar-Fox, A., Jackson, L., Degeling, H., 2017. Emerging strategic minerals in Queensland.
- Powerlink Queensland, 2024. CopperString 2032. Queensland Government. Available at: <https://mining.com.au/queensland-government-to-bring-copperstring-to-life/>. Accessed on: 13/06/2026.
- Prabhune, A., Dey, R., 2023. Green and sustainable solvents of the future: deep eutectic solvents. *J. Mol. Liq.* 379, 121676. <https://doi.org/10.1016/j.molliq.2023.121676>.
- Proactive Investors, 2025. Solar and wind to drive sustainable mining at Queensland zinc mine. Available at: <https://www.proactiveinvestors.co.uk/companies/news/1063751/solar-and-wind-to-drive-sustainable-mining-at-queensland-zinc-mine-1063751.html>. Accessed on: 13/06/2026.
- Prodius, D., Klocke, M., Smetana, V., Alammari, T., Garcia, M.P., Windus, T.L., Nlebedim, I.C., Mudring, A.V., 2020. Rationally designed rare earth separation by selective oxalate solubilization. *Chem. Commun.* 56, 11386–11389. <https://doi.org/10.1039/D0CC02270E>.
- Prusty, S., Pradhan, S., Mishra, S., 2022. Amine/carboxylic acid based bifunctional ionic liquids as extractants for Nd(III), Sm(III) and Eu(III) from aqueous solution containing EDTA. *Chem. Sel.* 7, e202202334. <https://doi.org/10.1002/slect.202202334>.
- Qu, Y., Lian, B., 2013. Bioleaching of rare earth and radioactive elements from red mud using penicillium tricolor RM-10. *Bioresour. Technol.* 136, 16–23. <https://doi.org/10.1016/j.biortech.2013.03.070>.
- Queensland Government, 2025. Queensland Critical Minerals Prospectus. Department of Natural Resources and Mines, Manufacturing and Regional and Rural Development, Queensland Government, Brisbane, Australia. Available at: Queensland Critical Minerals Prospectus PDF (accessed 2025).
- Queensland Department of State Development, 2023. What are critical minerals and why are we mining them in Queensland? Queensland Government. Available at: <https://www.statedevelopment.qld.gov.au/news-and-events/what-are-critical-minerals-a-nd-why-are-we-mining-them-in-queensland>. Accessed on: 13/06/2026.
- Quijada-Maldonado, E., Romero, J., 2021. Solvent extraction of rare-earth elements with ionic liquids: toward a selective and sustainable extraction of these valuable elements. *Curr. Opin. Green Sustain. Chem.* 27, 100428. <https://doi.org/10.1016/j.cogsc.2020.100428>.
- Rahmatullah, F.A., Permatasari, F.A., Iskandar, F., 2025. Techno-economic analysis of organic acid-based hydrometallurgical recycling of NCM cathodes. *J. Environ. Chem. Eng.* 13, 118304. <https://doi.org/10.1016/j.jece.2025.118304>.
- Rasoulnia, P., Barthen, R., Lakaniemi, A.M., 2021. A critical review of bioleaching of rare earth elements: the mechanisms and effect of process parameters. *Crit. Rev. Environ. Sci. Technol.* 51, 378–427. <https://doi.org/10.1080/1064>.
- Rawlings, D.E., Johnson, D.B., 2007. The microbiology of biomining: development and optimization of mineral-oxidizing microbial consortia. *Microbiology (N.Y)* 153, 315–324. <https://doi.org/10.1099/mic.0.2006/001206-0>.
- Rawlings, D.E., Silver, S., 1995. Mining with microbes. *Nat. Biotechnol.* 13, 773–778. <https://doi.org/10.1038/nbt0895-773>.
- Ray, A.R., Tripathy, B.C., Mishra, S., 2025. Investigation on process optimization and kinetics for leaching of rare earth elements from red mud using citric acid. *Scientific Reports* 2025 15:1, 36533-. Doi: 10.1038/s41598-025-17134-7.
- REI100, 2020. QLD's biggest zinc refinery joins REI100 – Sun Metals commits to use 100% renewable electricity. Climate Group. Available at: <https://www.there100.org/our-work/press/qlds-biggest-zinc-refinery-joins-re100-sun-metals-commits-use-100-renewable>. Accessed on 13/06/2026.
- Reed, D.W., Fujita, Y., Daubaras, D.L., Jiao, Y., Thompson, V.S., 2016. Bioleaching of rare earth elements from waste phosphors and cracking catalysts. *Hydrometallurgy* 166, 34–40. <https://doi.org/10.1016/j.hydromet.2016.08.006>.
- Ren, W.X., Li, P.J., Geng, Y., Li, X.J., 2009. Biological leaching of heavy metals from a contaminated soil by *Aspergillus niger*. *J. Hazard. Mater.* 167, 164–169. <https://doi.org/10.1016/j.jhazmat.2008.12.104>.
- Rezaei, H., Ziaedin Shafaei, S., Abdollahi, H., Shahidi, A., Ghassa, S., 2022. A sustainable method for germanium, vanadium and lithium extraction from coal fly ash: sodium salts roasting and organic acids leaching. *Fuel* 312, 122844. <https://doi.org/10.1016/j.fuel.2021.122844>.
- Rohner, P., 2023. GBM Resources Limited - Annual Report, <https://www.listcorp.com/asx/gbm/gbm-resources-limited/news/2023-annual-report-2947312.html> (accessed 11.12.25).
- Rohrwerder, T., Gehrke, T., Kinzler, K., Sand, W., 2003. Bioleaching review part a: progress in bioleaching: fundamentals and mechanisms of bacterial metal sulfide oxidation. *Appl. Microbiol. Biotechnol.* 63, 239–248. <https://doi.org/10.1007/s00253-003-1448-7>.
- Rudnick, R.L., Gao, S., 2003. In: Holland, H.D., Turekian, K.K. (Eds.), *Treatise on Geochemistry*, 3. Elsevier, Amsterdam, pp. 1–64.
- Saez, J., Etxebarria, J., Antónana-Diez, M., Benito-Lopez, F., 2016. On-demand generation and removal of alginate biocompatible microvalves for flow control in microfluidics. *Sens. Actuators B Chem.* 234, 1–7. <https://doi.org/10.1016/j.snb.2016.04.140>.
- Sakr, A.K., Praneeth, S., Dardona, M., Kakaris Porter, D., Tummala, C.M., Roy, P.K., Dittrich, T.M., 2025. Potential for eco-friendly recovery of rare earth elements from fly ash using carboxylic acids: a comparative study with mineral acids and environmental risk assessment for sustainable fly ash reuse. *Chem. Eng. J.* 503, 158355. <https://doi.org/10.1016/j.cej.2024.158355>.
- Santana, H.S., Lopes, M.G.M., Silva, J.L., Taranto, O.P., 2018. Application of microfluidics in process intensification. *Int. J. Chem. React. Eng.* 16 (12). <https://doi.org/10.1515/ijcre-2018-0038>.
- Sarker, S.K., Yadav, S., Haque, N., Pramanik, B.K., 2025. Impact of alkali roasting and leaching conditions on the recovery of rare earth elements from iron-rich mine tailings: a study using deep eutectic solvents. *Process Saf. Environ. Prot.* 199, 107259. <https://doi.org/10.1016/j.psep.2025.107259>.
- Sarkodie, E.K., Jiang, L., Li, K., Yang, J., Guo, Z., Shi, J., Deng, Y., Liu, H., Jiang, H., Liang, Y., Yin, H., Liu, X., 2022. A review on the bioleaching of toxic metal(loid)s from contaminated soil: insight into the mechanism of action and the role of influencing factors. *Front. Microbiol.* 13, 104. <https://doi.org/10.3389/fmicb.2022.1049277>.
- SFA Oxford, 2025. Queensland's critical minerals and energy transition. SFA (Oxford) Ltd. Available at: <https://www.sfa-oxford.com/lithox/critical-minerals-policy-legislation/all-countries/australia/australia-critical-minerals-energy-transition/queensland/>. Accessed on: 13/06/2026.
- Shakiba, G., Saneie, R., Abdollahi, H., Ebrahimi, E., Rezaei, A., Mohammadkhani, M., 2023. Application of deep eutectic solvents (DESs) as a green lixiviant for extraction of rare earth elements from caustic-treated monazite concentrate. *J. Environ. Chem. Eng.* 11 (5), 110777. <https://doi.org/10.1016/j.jece.2023.110777>.
- Shannon, R.D., 1976. Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. *Acta Cryst.* A32, 751–767. <https://doi.org/10.1107/s0567739476001551>.
- Sharma, A., Sharma, R., Thakur, R.C., Singh, L., 2023. An overview of deep eutectic solvents: Alternative for organic electrolytes, aqueous systems & ionic liquids for electrochemical energy storage. *J. Energy Chem.* 82, 592–626. <https://doi.org/10.1016/j.jechem.2023.03.039>.
- Shen, L., Yu, X., Zhou, H., Wang, J., Zhao, H., Qiu, G., Chen, Z., 2024. Optimization and mechanism studies for the biosorption of rare earth ions by *yarrowia lipolytica*. *Environ. Sci. Pollut. Res.* 31, 52118–52131. <https://doi.org/10.1007/s11356-024-34660-5>.
- Shi, S., Pan, J., Dong, B., Zhou, W., Zhou, C., 2023. Bioleaching of rare earth elements: perspectives from mineral characteristics and microbial species. *Minerals* 2023, 13 (9), 1186. Doi: 10.3390/min13091186.
- Shiksha, S., 2025. Surface vs subsurface mining: methods and applications. *Sustainability Shiksha*. URL <https://sustainability.shiksha/ecosystem-natural-resources/surface-vs-subsurface-mining-methods/> (accessed 11.26.25).
- Shuping, C., Zhihan, Z., Dong, W., Wenjing, Z., Tao, Q., Zhi, W., Wanhai, X., Yong, L., Guobiao, L., 2025. Selective leaching and recovery of rare earth from NdFeB waste through a superior selective and stable deep eutectic solvent. *Sep. Purif. Technol.* 353, 128498. <https://doi.org/10.1016/j.seppur.2024.128498>.
- Smith, E.L., Abbott, A.P., Ryder, K.S., 2014. Deep eutectic solvents (DESs) and their applications. *Chem. Rev.* 114 (21), 11060–11082. <https://doi.org/10.1021/cr300162p>.
- Sobri, N.A.M., Harun, N., Yunus, M.Y.M., 2024. A review of the ion exchange leaching method for extracting rare earth elements from ion adsorption clay. *Chem. Eng. Res. Des.* 208, 94–114. <https://doi.org/10.1016/j.cherd.2024.06.023>.
- Song, D., Wang, T., Liu, Z., Zhao, S., Quan, J., Li, G., Zhu, H., Huang, J., He, W., 2022. Characteristic comparison of leaching valuable metals from spent power li-ion batteries for vehicles using the inorganic and organic acid system. *J. Environ. Chem. Eng.* 10 (1), 107102. <https://doi.org/10.1016/j.jece.2021.107102>.
- Spellman, F.R., 2022. The science of rare earth elements: concepts and applications, 1st ed. CRC Press, Boca Raton. Doi: 10.1201/9781003350811.
- Stein, R.T., Kasper, A.C., Veit, H.M., 2022. Recovery of rare earth elements present in mobile phone magnets with the use of organic acids. *Minerals* 12, 668. <https://doi.org/10.3390/min12060668>.

- Stronck, N.A., Niedermann, S., 2016. Atmospheric contamination of the primary Ne and Ar signal in mid-ocean ridge basalts and its implications for ocean crust formation. *Geochim. Cosmochim. Acta* 172, 306–321. <https://doi.org/10.1016/j.gca.2015.09.016>.
- Sun Metals, 2020. Renewables. Sun Metals Corporation. Available at: <https://www.sunmetals.com.au/sustainability/renewables/> 13/06/2026.
- Sybella – REO Discovery Northwest QLD | Red Metal Ltd, 2025. URL https://redmetal.com.au/project_by_province/sybella-northwest-qld/ (accessed 12.3.25).
- Tilp, A.H., Akl, H.M., Kandil, A.E.H.T., Cheira, M.F., Gado, H.S., Salah, B.A., 2024. Extraction of La, Ce and Nd using an ionic liquid and its application to rare earth leachate derived from phosphogypsum. *J. Rare Earths*. <https://doi.org/10.1016/j.jre.2024.07.005>.
- Turanov, A.N., Karandashev, V.K., Yarkevich, A.N., 2018. Extraction of rare-earth elements from hydrochloric acid by carbamoyl methyl phosphine oxides in the presence of ionic liquids. *Russ. J. Inorg. Chem.* 63, 406–413. <https://doi.org/10.1134/s0036023618030221>.
- U.S. Geological Survey, 2025. *Mineral Commodity Summaries 2025: Rare Earths*. U.S. Geological Survey, Reston, Virginia.
- UFOP, 2016. Report on Global Market Supply 2016/2017: European and World Demand for Biomass for the Purpose of Biofuel Production in Relation to Supply in the Food and Feedstuff Markets. Union zur Förderung von Oel- und Proteinpflanzen e.V. (UFOP), Berlin, Germany.
- UFOP, 2020. Report on Global Market Supply 2019/2020. Union zur Förderung von Oel- und Proteinpflanzen e.V. (UFOP), Berlin, Germany. Available at: UFOP Report on Global Market Supply 2019/2020 (accessed 08 June 2025).
- Understand the electricity supply system | Homes and housing | Queensland Government, 2025. URL <https://www.qld.gov.au/housing/buying-owning-home/energy-water-home/electricity/electricity-prices/understand-electricity-system> (accessed 11.4.25).
- Valenta, R., Gow, P., Connors, K., 2021. Queensland new economy minerals compilation - rare earth elements. Brisbane.
- Valenta, R.K., Erskine, P.D., Gow, P., 2021. Queensland rare earth element occurrences and resource potential. *Queensland Geological Record*. Geological Survey of Queensland.
- van der Ent, A., Erskine, P.D., Gow, P., Valenta, R.K., 2020. Toward closing a loophole: Recovering rare earth elements from uranium metallurgical process tailings. *JOM* 73, 39–53. <https://doi.org/10.1007/s11837-020-04451-7>.
- Van Gosen, B.S., Fey, D.L., Shah, A.K., Verplanck, P.L., Hoefen, T.M., 2014. Deposit model for heavy-mineral sands in coastal environments. *Sci. Investig. Rep.* 2010–5070. <https://doi.org/10.3133/sir20105070>.
- Van Gosen, B.S., Verplanck, P.L., Long, K.R., Gambogi, J., and Seal, R., 2014b, The rare-earth elements: Vital to modern technologies and lifestyles: U.S. Geol. Surv. Fact Sheet 2014-3078, Doi: 10.3133/fs20143078.
- Van Gosen, B.S., Verplanck, P.L., Emsbo, P., 2019. Rare earth element mineral deposits in the United States. *Circular* 1454, 1–16. <https://doi.org/10.3133/cir1454>.
- Vaughan, J., Tungpalan, K., Parbhakar-Fox, A., Fu, W., Gagen, E.J., Nkrumah, P.N., Southam, G., van der Ent, A., Erskine, P.D., Gow, P., Valenta, R., 2021. Toward closing a Loophole: recovering rare earth elements from uranium metallurgical process tailings. *JOM* 73, 39–53. <https://doi.org/10.1007/s11837-020-04451-7>.
- Vaughan, J., Guan, Y., Loureiro Gontijo, V.L., Sultana, U., 2024. Mary Kathleen tailings derived rare earth concentrate via double salt precipitation and caustic conversion. In: *Proc. South. Afr. Rare Earths 2nd Int. Symp.*, Southern African Institute of Mining and Metallurgy, pp. 87–96.
- Vera, M., Schippers, A., Hedrich, S., Sand, W., 2022. Progress in bioleaching: fundamentals and mechanisms of microbial metal sulfide oxidation – part a. *Appl. Microbiol. Biotechnol.* 106, 6933–6952. <https://doi.org/10.1007/s00253-022-12168-7>.
- Virkutyte, J., Sillanpää, M., Latostenmaa, P., 2002. Electrokinetic soil remediation — critical overview. *Sci. Total Environ.* 289, 97–121. [https://doi.org/10.1016/s0048-9697\(01\)01027-0](https://doi.org/10.1016/s0048-9697(01)01027-0).
- Voncken, J.H.L., 2016. *The Rare Earth Elements: An Introduction*. SpringerBriefs in Earth Sciences. Springer, Cham. Doi: 10.1007/978-3-319-26809-5.
- von Gnielinski, F.E., 2015. Queensland Minerals: A summary of major mineral resources, mines and projects.
- Wang, Z., Xu, D., Chi, G., Shao, Y., Lai, J., Deng, T., Guo, F., Wang, Z., Dong, G., Ning, J., Zou, S., 2017. Mineralogical and isotopic constraints on the genesis of the jingchong Co–Cu polymetallic ore deposit in Northeastern Hunan Province. *South China. Ore Geol. Rev.* 88, 638–654. <https://doi.org/10.1016/j.oregeorev.2017.02.011>.
- Wang, G., Xu, J., Ran, L., Zhu, R., Ling, B., Liang, X., Kang, S., Wang, Y., Wei, J., Ma, L., Zhuang, Y., Zhu, J., He, H., 2023. A green and efficient technology to recover rare earth elements from weathering crusts. *Nat. Sustain.* 6, 81–92. <https://doi.org/10.1038/s41893-022-00989-3>.
- Wang, G., Liang, X., Zhu, J., He, H., 2024. The use of electrokinetics promises a sustainable mining future. *Innovation* 5, 100615. <https://doi.org/10.1016/j.xinn.2024.100615>.
- Wang, G., Liang, X., Ling, B., Xu, J., Ran, L., Wei, J., Zhu, R., Zhu, J., He, H., 2025a. Recovery of rare earth elements from weathering crust soils using electrokinetic mining technology. *J. Rare Earths* 43, 1548–1558. <https://doi.org/10.1016/j.jre.2024.06.007>.
- Wang, G., Zhu, J., Liang, X., Ling, B., Xu, J., Yang, Y., Kang, S., Tan, W., Xu, Y., Zou, X., Ran, L., Wei, J., He, H., 2025b. Industrial-scale sustainable rare earth mining enabled by electrokinetics. *Nat. Sustain.* 8, 182–189. <https://doi.org/10.1038/s41893-024-01501-9>.
- Wang, M., Li, J., Liu, H., Huang, S., Liu, X., Liu, Y., Awais, M., Wang, J., 2025c. Rare earth element extraction from ionic rare earth ores by two typical acidogenic microorganisms, *Aspergillus niger* and *acidithiobacillus ferrooxidans*. *Int. J. Mol. Sci.* 26 (5), 1986. <https://doi.org/10.3390/ijms26051986>.
- Warner, K., 2025. Electrokinetic tech hits 95% REE recovery - metal tech news. URL <https://www.metaltchnews.com/story/2025/01/29/tech-bytes/electrokinetic-tech-hits-95-percent-ree-recovery/>.
- Watts, H., Fisher, T., 2021. Leaching the unleachable mineral: rare earth dissolution from monazite ore in condensed phosphoric acid. *Minerals* 11, 931. <https://doi.org/10.3390/min11090931>.
- Welter, R.A., Jr., J.S., de Souza, M., Lopes, M., Taranto, O., Santana, H., 2022. Are microreactors the future of biodiesel synthesis?, in: *The future of biodiesel*. pp. 47–82.
- Williams-Jones, A.E., Migdisov, A.A., Samson, I.M., 2012. Hydrothermal mobilisation of the rare earth elements - a tale of “cerium” and “yttria. *Elements* 8, 355–360. <https://doi.org/10.2113/gselements.8.5.355>.
- Willin, C., 2022. All eyes on North-West Queensland’s Georgina Basin to ease global fertiliser shortages. accessed 6.15.25 ABC News. <https://www.rockphosphate.co.nz/news/2022/7/21/industry-article-abc-news-all-eyes-on-north-west-queensland-georgina-basin-to-ease-global-fertiliser-shortages>.
- Worlanyo, A.S., Jiangfeng, L., 2021. Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: a review. *J. Environ. Manage.* 279, 111623. <https://doi.org/10.1016/j.jenvman.2020.111623>.
- Wstawski, S., Emmons-Burzyńska, M., Rzelewska-Piekut, M., Skrzypczak, A., Regel-Rosocka, M., 2021. Studies on copper(II) leaching from e-waste with hydrogen sulfate ionic liquids: effect of hydrogen peroxide. *Hydrometallurgy* 205, 105730. <https://doi.org/10.1016/j.hydromet.2021.105730>.
- Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. *Res. Pol.* 38, 384–394. <https://doi.org/10.1016/j.resourpol.2013.05.005>.
- Wu, S., Wang, L., Zhao, L., Zhang, P., El-Shall, H., Moudgil, B., Huang, X., Zhang, L., 2018. Recovery of rare earth elements from phosphate rock by hydrometallurgical processes – a critical review. *Chem. Eng. J.* 335, 774–800. <https://doi.org/10.1016/j.cej.2017.10.143>.
- Xu, J., Wang, G., Ling, B., Kang, S., Yang, Y., Liang, X., Wei, J., Xu, Y., Zhu, J., He, H., 2025. Electrokinetic transport mechanisms of rare earth elements in ion-adsorption deposits: an integrated model approach. *Environ. Technol. Innov.* 39, 104276. <https://doi.org/10.1016/j.eti.2025.104276>.
- Yang, X.J., Lin, A., Li, X.L., Wu, Y., Zhou, W., Chen, Z., 2013. China’s ion-adsorption rare earth resources, mining consequences and preservation. *Environ. Dev.* 8, 131–136. <https://doi.org/10.1016/j.envdev.2013.03.006>.
- Yaraghi, A., Ariffin, K., Baharun, N., 2019. A short review on REE recovery from ion-adsorption clays. *Asp. Min. Miner. Sci.* 2 (5), 1–3. <https://doi.org/10.31031/AMMS.2019.02.000550>.
- Zante, G., Boltova, M., 2020. Review on hydrometallurgical recovery of metals with deep eutectic solvents. *Sustain. Chem. I* (3), 238–255. <https://doi.org/10.3390/suschem1030016>.
- Zhang, L., Dong, H., Liu, Y., Bian, L., Wang, X., Zhou, Z., Huang, Y., 2018. Bioleaching of rare earth elements from bastnaesite-bearing rock by actinobacteria. *Chem. Geol.* 483, 544–557. <https://doi.org/10.1016/j.chemgeo.2018.03.023>.
- Zhang, J., Zhang, X., Su, X., Du, H., Lu, Y., Zhang, Q., 2024. Rare earth extraction from phosphogypsum by *Aspergillus niger* culture broth. *Molecules* 2024, 29(6), 1266, Doi: 10.3390/molecules29061266.
- Zhao, C., Yang, B., Hu, S., Wang, J., Liu, Y., Qiu, G., 2025a. Bioleaching and mechanism of ion-adsorption type rare earth ores and tailings using *acidithiobacillus ferrooxidans*. *Hydrometallurgy* 236, 106495. <https://doi.org/10.1016/j.hydromet.2025.106495>.
- Zhao, M., Teng, Z., Ma, X., Jiang, X., Zhang, H., Yang, Y., Li, T., 2025b. Insight into leaching rare earth from ion-adsorption type rare earth ores with citric acid: Performance, kinetic analysis and differentiation leaching. *J. Rare Earths* 43, 591–602. <https://doi.org/10.1016/j.jre.2024.02.005>.
- Zhao, M., Zhang, H., Han, H., Jiang, X., Yang, Y., Li, T., 2025c. Differential leaching mechanisms and ecological impact of organic acids on ion-adsorption type rare earth ores. *Sep. Purif. Technol.* 362, 131701. <https://doi.org/10.1016/j.seppur.2025.131701>.
- Zhou, Y., Xue, X., Yang, H., Song, S., Huang, X., 2020. Novel harmless utilization of Bayan Obo tailings: Separation and recovery of iron and rare earth. *Ind. Eng. Chem. Res.* 59, 13682–13695. <https://doi.org/10.1021/acs.iecr.0c01438>.
- Zhu, K., 2024. Visualizing global rare earth metals production (1995–2023). accessed 6.5.25 Visual Capitalist. <https://www.visualcapitalist.com/visualizing-global-rare-earth-metals-production-1995-2023/>.