COUNCIL FOR
CRITICAL MINERALS
DEVELOPMENT
IN THE GLOBAL SOUTH

Duke NICHOLAS INSTITUTE *for* ENERGY, ENVIRONMENT & SUSTAINABILITY

SUSTAINABLE ENERGY FOR ALL
ENERGY. CLIMATE. DEVELOPMENT.

Report

Beneath the Bottleneck

An R&D and Technology Readiness Review of Lithium and Rare Earth Processing

Aashish Yadav, Sandeep Pai, and Jennifer Broadhurst

Nicholas Institute for Energy, Environment & Sustainability nicholasinstitute.duke.edu

Authors and Affiliations

Aashish Yadav, Duke University
Sandeep Pai, Nicholas Institute for Energy, Environment & Sustainability, Duke University
Jennifer Broadhurst, University of Cape Town

Acknowledgments

The authors would like to thank peer reviewers whose thoughtful and constructive feedback substantially improved this report. We are grateful to Abhinav Sengupta (Council on Energy, Environment and Water), Abhishek Saxena (India Climate Collaborative), Rishi Kishore (GIZ India), Edwin Wuadom Warden (SEforAll), and Divyam Nagpal (SEforAll) for their careful review of our drafts and their valuable comments on the analysis and its presentation.

Citation

Yadav, A., S. Pai, and J. Broadhurst. 2026. *Beneath the Bottleneck: An R&D and Technology Readiness Review of Lithium and Rare Earth Processing*. NI 26-14. Durham, NC: Nicholas Institute for Energy, Environment & Sustainability, Duke University. https://nicholasinstitute.duke.edu/publications/beneath-bottleneck-technology-readiness-review-lithium-rare-earth-processing.

Cover image courtesy Coordenação-Geral de Observação da Terra

Council for Critical Minerals Development in the Global South

The Council for Critical Minerals Development in the Global South was established as a collaborative platform that supports governments to design and implement evidence-based policies that enable critical mineral resources to drive sustainable industrialisation, economic diversification, and more equitable participation in regional and global supply chains.

Nicholas Institute for Energy, Environment & Sustainability

The Nicholas Institute for Energy, Environment & Sustainability at Duke University accelerates solutions to critical energy and environmental challenges, advancing a more resilient and sustainable world. The Nicholas Institute conducts and supports actionable research and undertakes sustained engagement with policymakers, businesses, and communities—in addition to delivering transformative educational experiences to empower future leaders. The Nicholas Institute's work is aligned with the Duke Climate Commitment, which unites the university's education, research, operations, and external engagement missions to address climate challenges.

Sustainable Energy For All

Sustainable Energy for All has a global mandate to accelerate progress on the energy transition in emerging and developing countries. Hosted by UNOPS, SE For All works at the intersection of energy, climate and development, partnering with governments and organizations worldwide to end energy poverty, double energy efficiency, significantly expand renewable energy and combat climate change.

Contact

Nicholas Institute | Duke University | P.O. Box 90467 | Durham, NC 27708
1201 Pennsylvania Avenue NW | Suite 500 | Washington, DC 20004
919.613.1305 | nicholasinstitute@duke.edu

CONTENTS

Executive Summary ____ **1**
- For Companies ____ 1
- For Governments ____ 2

Introduction ____ **3**

Methods and Scoping ____ **7**

Results ____ **8**
- Lithium from Brines ____ 9
- Lithium from Hard-Rock Ores (Spodumene) ____ 15
- Rare Earth Elements Production ____ 20

Key R&D Opportunities Across the Value Chain ____ **29**

Discussion ____ **30**

Conclusion ____ **30**

References ____ **32**

EXECUTIVE SUMMARY

Meeting climate targets requires an eightfold rise in lithium demand and a doubling of magnet rare earth demand by 2040 (IEA 2023). The binding constraint is not getting the resources out of the ground, but the midstream processing stages, where China controls 60% to 70% of lithium conversion and more than 85% of rare earth separation. Many Global South countries and companies within them are trying to expand their processing capability. Yet, many of these actors lack understanding of the latest research, development, and innovation in critical mineral processing.

This first-of-its-kind report maps the production baseline and active research and development (R&D) across the lithium and rare earth value chains (four processing routes in total), assigns technology readiness levels (TRLs)[1] to each technology. It distills the following recommendations for companies and governments seeking to build processing capacity:

For Companies

Companies making strategic decisions about where to invest in critical mineral processing should concentrate on five priorities that emerge directly from our assessment:

1. **Capture value at the processing chokepoint.** Mining a lithium deposit or rare earth resource without securing downstream conversion, separation, or refining capacity leaves most of the margin and strategic leverage with whoever controls the midstream. Because these value chains are concentrated rather than truly global, chokepoint participation is best treated as an entry point toward broader integration across adjacent stages of the chain, not as an end state. This requires identifying and committing to specific processing partnerships or in-country conversion investments at the project development stage, well before financial close.

2. **Target the pilot-to-demonstration stage.** The most commercially credible innovations across the lithium and rare earth chains—direct lithium extraction (DLE), lower-temperature spodumene roasting, and continuous rare earth ion exchange—currently sit at TRLs 5 to 7. These are the stages where capital availability, not technical uncertainty, is the main constraint. Financing instruments differ by stage: pilot plants need equity and grant capital, while demonstration and first commercial units need offtake commitments and debt guarantees. Companies able to invest in equity, offtake commitments, or co-development partnerships at this stage will secure better technology access and pricing than those that wait for TRLs 8 to 9.

3. **In lithium via brine route, invest in new technologies beyond the traditional evaporation ponds.** Conventional brine evaporation recovers only 30% to 50% of lithium over a 12- to 24-month cycle and is exposed to regulatory and water-use constraints. DLE technologies, at the commercial stage in China (Sunresin) and Argentina (aluminum-adsorption at Rio Tinto's Fénix operation; Eramet's Centenario plant) and at the pilot stage elsewhere (Lilac Solutions, EnergyX, Summit Nanotech), can recover more than 90% of lithium in hours. However, DLE performance is strongly brine-chemistry dependent and most flowsheets still require

1 Technology readiness levels are a standardized scale developed to measure the maturity of a new technology. They range from scale 1 (scientific research) to 9 (fully operational) (see Figure 4).

downstream concentration. Many recent projects are adopting hybrid DLE-plus-pond configurations. New entrants should evaluate DLE against site-specific brine chemistry and water constraints rather than building pond-only infrastructure by default.

4. **In the lithium via hard-rock spodumene route, prioritize the energy and carbon cost of conversion.** Calcination at 1,000°C to 1,100°C is both the largest cost driver and the most energy-intensive step in hard-rock processing. The kiln accounts for roughly half of refinery process energy and is the dominant source of Scope 1 emissions (Abdullah et al. 2024).[2] Lower-temperature sulfate and chloride roasting routes operate at markedly lower temperatures and credibly offer lower energy and reagent intensity while also accepting lower-grade feeds and tailings that conventional acid roasting cannot process. Mangrove Lithium's membrane electrolysis for direct lithium chloride–to–lithium hydroxide (LiCl-to-LiOH) conversion is a complementary step that reduces soda ash and lime consumption at the back end of the chain. These lower-temperature routes sit at TRL 6 to 7 and represent among the most actionable decarbonization levers available to companies.

5. **In rare earths, treat separation and recycling as important priorities.** Separation remains the most concentrated and technically demanding stage of the rare earth chain—more than 85% of global separation capacity sits in China. Companies should evaluate REEtec's proprietary solvent-free separation process (TRL 7, Norway), which avoids the organic solvents used in conventional solvent extraction (SX) (company-reported), as the most credible near-term alternative for new separation capacity outside China. In parallel, NdFeB magnet recycling via hydrogen processing (for example, by HyProMag (UK, first commercial production June 2025) and Cyclic Materials (Canada, TRL 6 to 7), is becoming a commercially relevant feedstock source. Recycling is a medium-term rather than near-term supply lever, however: feedstock remains constrained until first-generation electric vehicle (EV) and wind-turbine magnets reach end-of-life in volume around 2030.

For Governments

Governments taking strategic decisions for securing critical mineral value chains should concentrate on four priorities:

1. **Fund the commercialization valley, not only laboratory experiments.** Government programs in the United States (DOE Critical Materials 2023), European Union, Australia, and Canada have directed significant funding toward both early-stage research grants and supporting mature facilities. Governments can offer loans, pilot plant subsidies, and government-backed offtake agreements to catalyze creation of critical mineral value chains. Australia's Critical Minerals Facility is moving in this direction, but the scale and speed of deployment needs to increase materially to keep pace with the rate at which promising technologies are reaching TRL 6 to 7 (see Box 1).

2. **Build a shared international evaluation framework for critical mineral processing R&D.** We identified active R&D in at least eight contexts: Australia, Canada, China, Japan, Norway, the United Kingdom, the United States, and several

2 Scope 1 emissions are direct greenhouse gas emissions associated with fuel combustion in boilers, furnaces, and vehicles that are controlled or owned by an organization (EPA 2026).

Latin American project sites. There are no publicly available TRL definitions, shared registries, or coordinated mechanisms for directing capital toward the most advanced technologies. The result is significant duplication of effort. With support by governments, the IEA Critical Minerals Council or other global councils can create a public registry of critical mineral processing R&D technologies. Such a registry would cover technology status, TRL evidence, and pilot results rather than proprietary process knowledge, so participating countries gain coordination benefits without surrendering competitive or strategic advantage.

3. **Pair supply-side funding with demand-side commitments.** The most effective recent interventions have been demand instruments rather than grants: guaranteed price floors (for example, the 2025 United States Department of Defense arrangement with MP Materials, which set a floor price for domestically produced NdPr), strategic stockpiles, and magnet or content requirements in EV and defense procurement. Supply-side grants without a demand signal are precisely what leaves TRL level 6 to 7 firms stranded in the commercialization valley.

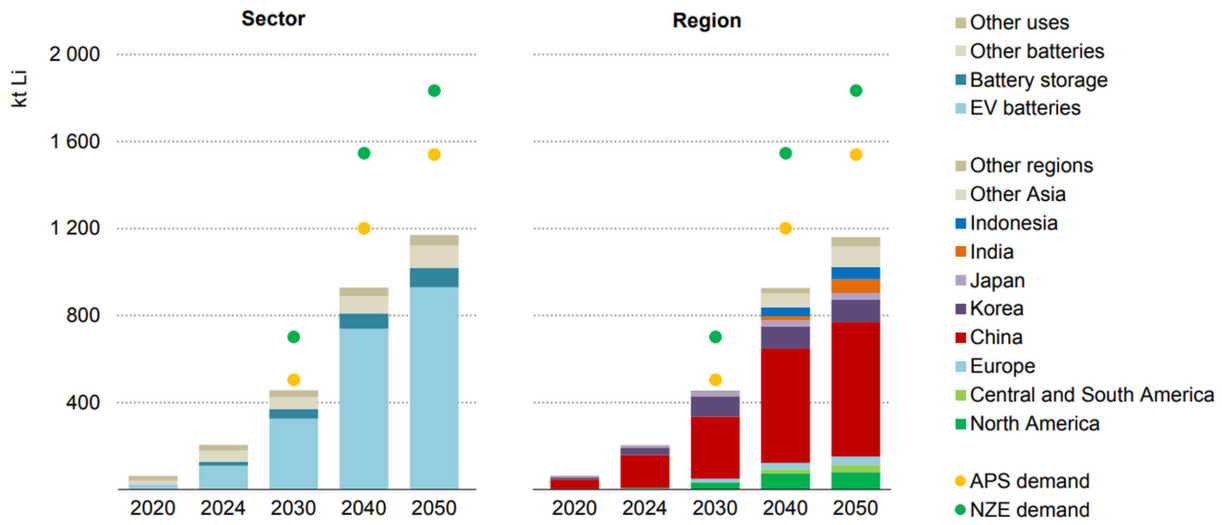
4. **For emerging economies, support deliberate technology transfer.** Several of the most commercially promising technologies, such as DLE, sulfate roasting, sensor-based ore sorting, and NdFeB recycling, could lower the capital and skill barriers compared to conventional processing plants. Governments in resource-rich emerging economies should negotiate technology transfer provisions and domestic processing mandates as part of mining agreements from the outset, rather than seeking to add them after production has begun. Bilateral and regional trade agreements can serve as enforcement vehicles for these provisions: technology-transfer and local-processing clauses embedded in free-trade agreements are more durable than project-level agreements, particularly where the counterparties are state-owned enterprises.

INTRODUCTION

Meeting the 1.5°C climate target established under the Paris Agreement requires a rapid deployment of clean energy technologies across the global economy (UNCC 2021). Integrated assessment models and net zero pathways developed by the Intergovernmental Panel on Climate Change and the International Energy Agency (IEA) consistently show that stabilizing warming at 1.5°C demands near-complete decarbonization of the power sector by 2050, alongside deep electrification of transport, industry, and buildings (IPCC 2018, IEA 2021). In practical terms, this transition entails massive additions of solar photovoltaics, onshore and offshore wind turbines, and battery electric vehicles (EVs), as well as the grid storage and transmission infrastructure needed to support them.

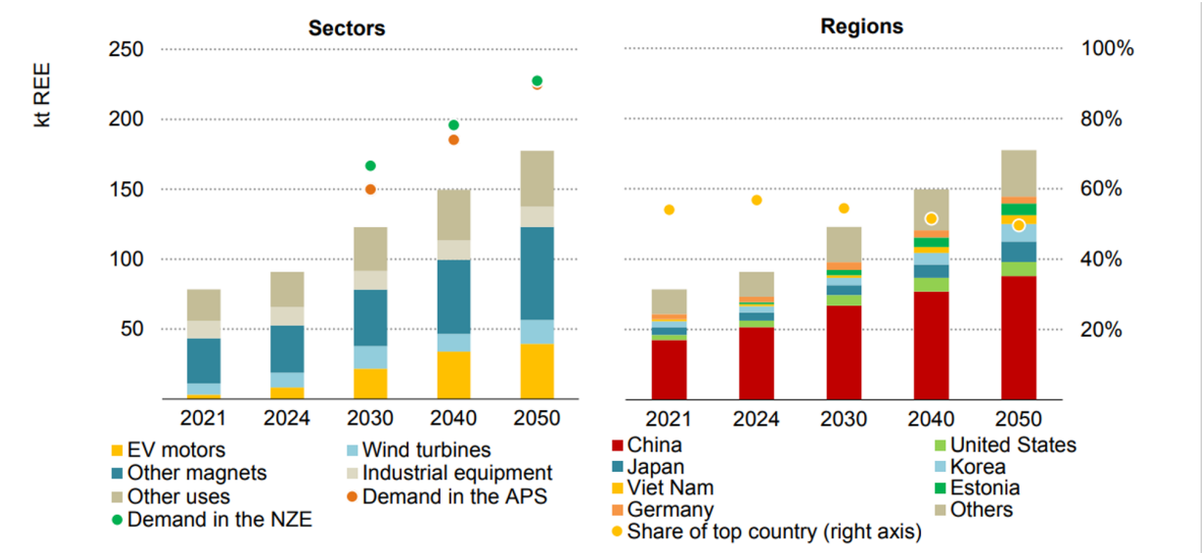
A defining characteristic of these clean energy technologies is that they are significantly more material-intensive than the fossil-fuel systems they replace (Giurco et al. 2019; Hund et al. 2023). Several clean energy technologies such as wind turbines, EVs, or grid-scale batteries require large quantities of critical minerals including lithium, cobalt, nickel, copper, and the rare earth elements (REEs). The IEA projects that, under a net-zero scenario, demand for lithium alone could grow by a factor of eight to nine by 2040 relative to 2020 levels, while demand for rare earth elements used in permanent magnets is expected to roughly double or more over the same period (IEA 2023). Meeting these projections will require not only

Figure 1. Global lithium demand outlook by sector and region in the IEA's Stated Policies Scenario (STEPS)



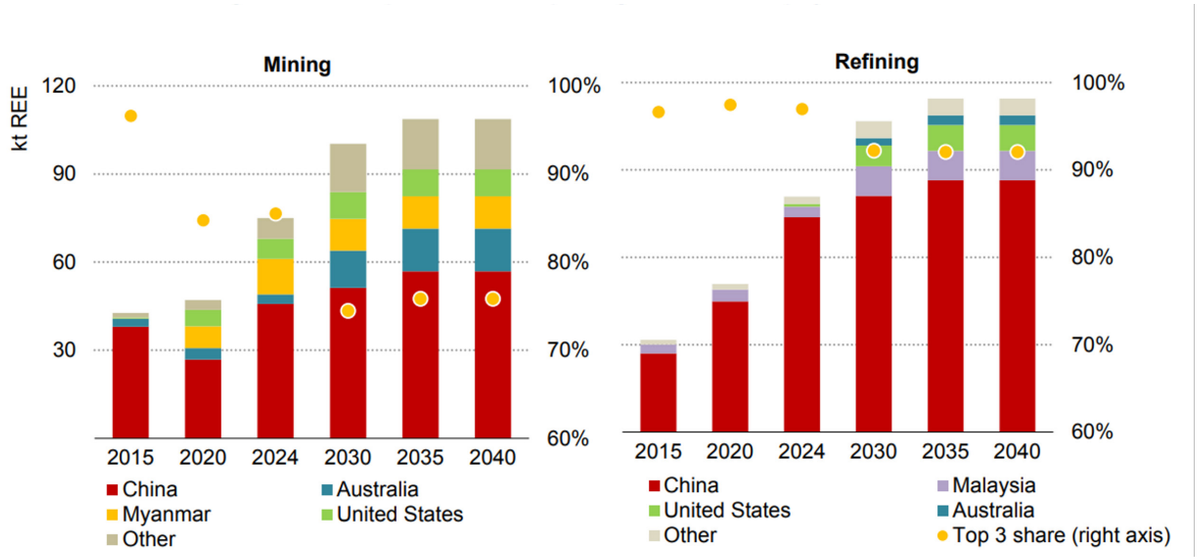
Source: IEA 2025
Note: APS = Announced Pledges Scenario and the NZE = Net Zero Emissions by 2050 Scenario (part of STEPS)

Figure 2. Outlook for the demand of magnet rare earth elements by sector and region in the STEPS



Source: IEA 2025
Note: APS = Announced Pledges Scenario and the NZE = Net Zero Emissions by 2050 Scenario (part of STEPS)

Figure 3. Magnet rare earths production from operating and announced projects in the base case



Source: IEA 2025

expanding mining operations, but also scaling up beneficiation, processing, and refining capacity at every stage of the critical mineral value chain.

The value chains of several of these minerals are geographically concentrated and structurally constrained. Currently, the critical mineral value chain is heavily concentrated in China, which controls most of the global processing and refining capacity for both lithium and rare earth elements. China accounts for roughly 60% to 70% of global lithium chemical conversion capacity and, for rare earths, roughly two-thirds of mined output but an even larger share of separation and refining (85% to 90%) and magnet production (close to 90%) (IEA 2023, USGS 2025).

Outside China, only a few commercial-scale facilities can process lithium-bearing ores or concentrates into battery-grade chemicals or separate individual rare earth oxides at the purity levels required for permanent magnet manufacturing. The consequence is that, even where mining assets exist, such as in Africa, the value-adding processing steps that determine final product quality and economics remain almost entirely China-dependent.

This imbalance has generated substantial interest in research and development (R&D) and innovation aimed at processing and beneficiation of critical minerals outside China. Governments in the Global South (such as India) and the Global North (like the United States), have launched critical mineral strategies that explicitly target domestic processing capacity, accompanied by funding programs, loan guarantees, and offtake agreements designed to accelerate commercial deployment (see Box 1).

Based on this policy push, a growing ecosystem of university laboratories, established mining and chemical companies, and well-capitalized startups are actively developing processing and beneficiation technologies in many countries. A number of technical reviews cover the geology, processing, and production of these minerals (e.g., Petrakis et al. [2025]; Ta-

desse et al. [2019]; Khalil et al. [2022]), but these tend to focus on a single commodity, ore type, or step in the value chain, or address policy and supply chain strategy at a high level without engaging with process-level detail. To our knowledge, no prior review combines process-level detail with a comparable cross-route technology readiness level (TRL) and commercialization assessment across both the lithium and rare earth value chains.

We address this gap by providing a systematic and succinct overview of current and emerging technologies across the entire value chain of two critical mineral families: lithium (sourced from both brine and hard-rock spodumene deposits) and rare earth elements (sourced from hard-rock ores and ion-adsorption clays). Our focus on lithium and rare earth elements reflects both their strategic importance and their processing complexity.

This report focuses on production from primary sources. A wide body of R&D also addresses the recovery of these metals from secondary sources such as mine residues, industrial by-products, and end-of-life products, but this is outside our scope except where a recycling technology is already commercially relevant to the primary supply chain (see the section on key R&D opportunities).

We ask the following research questions:

1. What is the current state of R&D and innovation across lithium and rare earth element processing chains, and which technologies have the most credible pathways to commercial deployment?
2. Which processing technologies are most promising for emerging economies to embrace?

We answer these questions by evaluating each processing route in turn. For each route, we describe the current industrial baseline step by step, document the known cost structure, characterize the most technically credible R&D opportunities at each processing stage, and assign TRL assessments based on available evidence.

Box 1: Policy Example—Australia's Critical Minerals Facility

Australia's government-backed Critical Minerals Facility illustrates the policy levers available to resource-rich countries. Its flagship commitment, an AUS$1.25 billion concessional loan to Iluka Resources in 2022, enabled construction of the Eneabba rare earth refinery in Western Australia, Australia's first fully integrated rare earths refinery (Iluka Resources 2022). The instrument matters as much as the amount: concessional debt with long tenor filled a financing gap that commercial lenders would not, without requiring the government to pick technology winners directly. Comparable mechanisms exist in Canada (Strategic Innovation Fund) and the United States (DOE Loan Programs Office). For Global South policymakers, the transferable lesson is to pair concessional finance with offtake support at the demonstration-to-commercial transition, where private capital is scarcest.

The remainder of this paper is structured as follows. The next section describes the methodology used to scope and conduct this review. Then, authors present results for each processing route: lithium from brines, lithium from hard-rock ores, and rare earth element production from hard-rock and ion-adsorption sources. We then summarize the key R&D opportunities across the value chain, and the final sections discuss the broader implications of our work. Readers may navigate selectively: policymakers and investors may focus on the executive summary, the producer and cost subsections of the results section, and the sections on key opportunities through the discussion, while readers seeking process-level detail will find step-by-step descriptions with R&D notes throughout the results section.

METHODS AND SCOPING

The study was conducted in two stages. In the first stage, we reviewed academic and industry literature. Based on this review, we came up with details of the process of critical mineral production and R&D opportunities. This involved identifying R&D across the various steps involved in the production of critical minerals.

For the academic literature, we searched Google Scholar, Scopus, and Web of Science using combinations of search phrases including "lithium extraction," "spodumene processing," "lithium brine recovery," "direct lithium extraction," "rare earth separation," "solvent extraction rare earths," "ion-adsorption clay," and "NdFeB magnet recycling," screening peer-reviewed work published between 2014 and 2026. Next, we complemented this with industry sources such as annual reports and investor presentations from major producers (SQM, Albemarle, Lynas Rare Earths, MP Materials, Pilbara Minerals), technical reports from the IEA, US Geological Survey, the European Commission SCRREEN2 project, and the US Department of Energy Critical Materials Assessment to corroborate technology deployment claims.

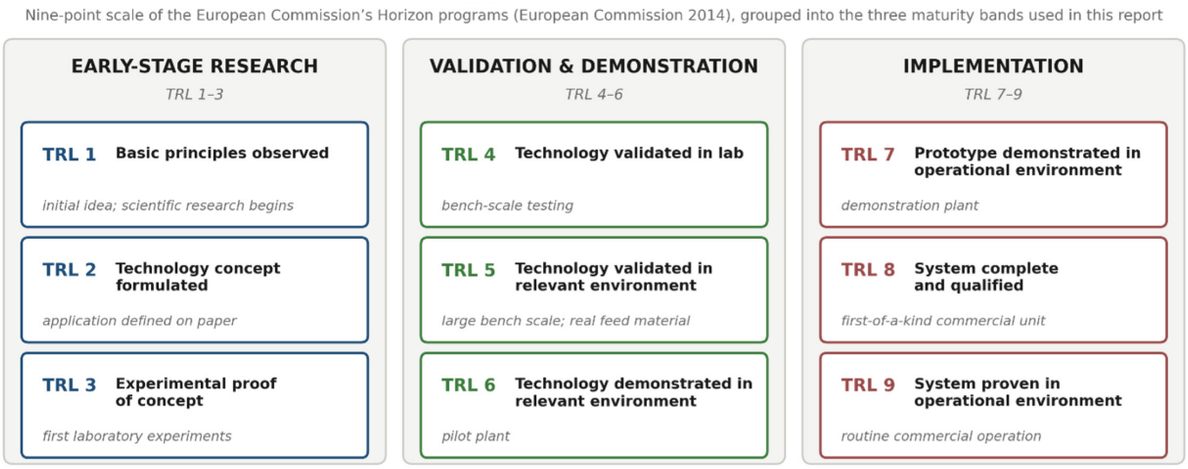
Terminology in this field is used inconsistently, particularly for rare earths, so we apply the following definitions throughout:

- *Beneficiation* refers to the physical concentration of mined ore (crushing, sorting, flotation, gravity and magnetic separation)
- *Processing* refers to the chemical conversion of concentrates into intermediate products (roasting, leaching, precipitation, solvent extraction)
- *Refining* refers to final purification into battery-grade chemicals, separated oxides, metals, or alloys.

This paper focuses on beneficiation and processing.

Technology readiness levels follow the nine-point scale used by the European Commission's Horizon programs (European Commission 2014). For interpretation, we group them into three bands: early-stage research (TRL 1–3), validation and demonstration (TRL 4–6), and implementation (TRL 7–9). Where sources conflict—for example, a company press release claiming TRL 6 while peer-reviewed work supports TRL 4—we assign the more conservative value and label company-reported claims as such. Assignments were made by the authors based on documented pilot- or commercial-scale evidence and cross-checked against published TRL statements where available. Technologies highlighted in the section on key R&D

Figure 4. Technology readiness levels (TRLs)



opportunities were selected where (a) an identifiable developer or research group is active, (b) pilot- or commercial-scale results are documented or company-reported, and (c) the technology addresses a cost, energy, or environmental constraint identified in the results.

We limited the work to lithium and rare earth elements because both face the most acute processing bottlenecks, and because their production routes differ substantially in chemistry, capital intensity, and technology maturity. Other critical minerals such as copper, cobalt, nickel, and graphite were excluded to scope this work. All tonnages in this report are metric tonnes (t); tpa denotes tonnes per annum.

Graphite deserves a specific note: anode-grade spherical and synthetic graphite is arguably the most China-concentrated battery midstream of all (more than 90% of spherical graphite capacity), and it is a processing rather than mining bottleneck exactly like the chains reviewed here. However, it was excluded because its processing chain (purification, spheroidization, coating) differs fundamentally from the hydrometallurgical routes covered in this paper. It is therefore the most obvious extension of this work.

Within lithium, we cover production from evaporative brine processing (concentrated in the Lithium Triangle[3] and China's salt lakes) and from hard-rock spodumene (dominated by Australia), which together account for approximately 85% to 90% of global lithium chemical production (USGS 2025). Within rare earth elements, we cover production from hard-rock ores (bastnäsite and monazite) and from in situ leaching of ion-adsorption clay deposits in southern China (the primary source of heavy rare earths [Krishnamurthy and Gupta 2016]), tracing the full chain from beneficiation and ore cracking through solvent extraction to individual rare earth oxides.

3 A region of the Andes Mountains that spans the borders of Bolivia, Chile, and Argentina.

RESULTS

In this section, we discuss lithium and rare earth production routes and highlight key R&D opportunities for each.

Lithium from Brines

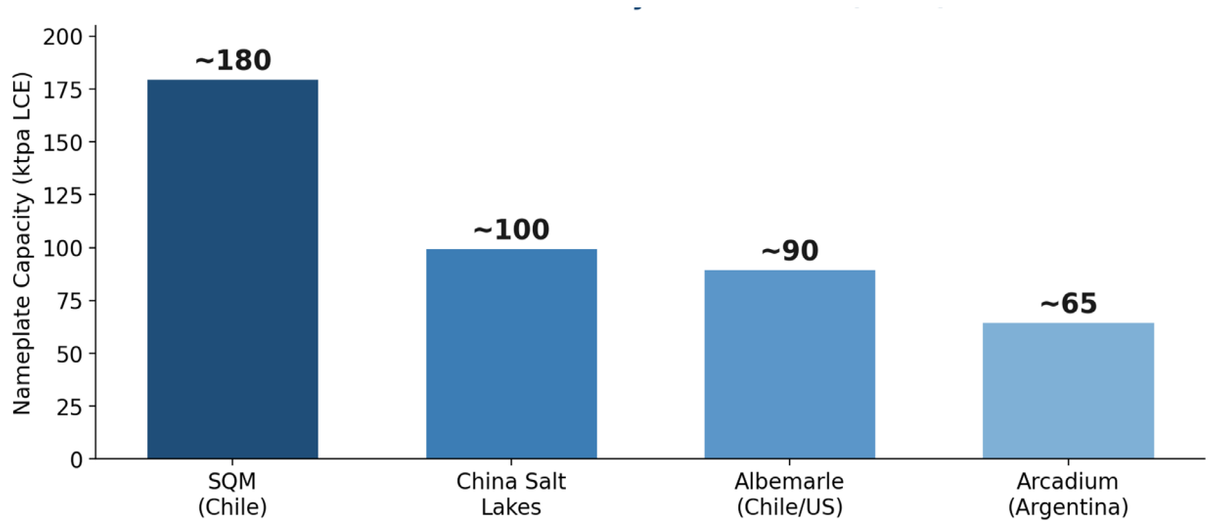
Global lithium demand is surging, with EVs and renewable energy storage accounting for approximately 87% of demand in 2024 (IEA 2025). This trend is likely to continue, with lithium demand for clean energy technologies projected to rise more than fivefold between 2025 and 2040 (IEA 2025).

In response, global lithium production has seen explosive growth, scaling from 37,000 tonnes of mined product in 2015 to roughly 290,000 tonnes in 2025 (USGS 2026). While exploration and development are underway in many countries (including Argentina, Bolivia, Zimbabwe, the United States, and Canada), approximately 72% of raw lithium production is currently concentrated in three countries: Australia (roughly 32%), China (roughly 21%), and Chile (roughly 19%) (USGS 2026). Advanced processing and refining, particularly of ore concentrates, is even more concentrated, with roughly 70% of lithium processing capacity residing in China (IEA 2023). While unconventional sources such as oilfield and geothermal brines are increasingly being explored, lithium is predominantly obtained from two primary natural sources: hard-rock lithium ores (65% to 70% of production, see the section in the results on lithium from hard-rock ores) and salt-lake brines (25% to 35% of production) (S&P 2025).

Who Produces and Where

Brine-based lithium production accounts for roughly 25% to 35% of global lithium output (USGS 2025, IEA 2023). The industry is concentrated in the Lithium Triangle of South America—Chile, Argentina, and Bolivia—where large-scale underground salt-flat aquifers

Figure 5. Lithium brine producers by nameplate capacity, 2024



Sources: USGS (2025), SQM (2024), Albemarle (2024), Stausholm (2024).

(also called salar aquifers, the brine reservoirs that sit beneath dry salt-flat surfaces) contain lithium-rich brines (Munk et al. 2016; López Steinmetz and Salvi 2021). Chile's Salar de Atacama has brine concentrations reaching ~1,800 mg/L lithium, among the highest in the world (Flexer et al. 2018). Argentina's Salar de Olaroz and Hombre Muerto are also significant. China's Qinghai and Tibetan salt lakes contribute additional volume, though their high magnesium-to-lithium ratios make processing more challenging (Yersaiynova et al. 2026).

The major producers are SQM (~180,000 tpa LCE[4] nameplate capacity, Chile; [SQM 2024a, b]), Albemarle (~85,000 tpa LCE in Chile plus ~5,000 tpa LCE at Silver Peak, Nevada—the only active US brine operation [Albemarle Corporation 2024), and Arcadium Lithium (now part of Rio Tinto) operating in Argentina with ~65,000 tpa LCE combined (Stausholm 2024). Chinese salt lake operators, including Qinghai Salt Lake Industry and Zangge Mining, add an estimated ~100,000 tpa LCE (USGS 2025).

Within brine output, conventional evaporation still accounts for well over half of production, while direct lithium extraction (DLE)-based operations contributed about 11% of lithium production from brines in 2024 (Razmjou 2024). Eramet's Centenario plant in Argentina, the first Western greenfield DLE operation at commercial scale, produced its first lithium carbonate in 2024 (Eramet 2024b).

The Process

Lithium is recovered from brines via two routes: conventional solar evaporation, which still dominates output, and DLE, a family of technologies that extract lithium directly from brine without multi-month evaporation.

Conventional Evaporation

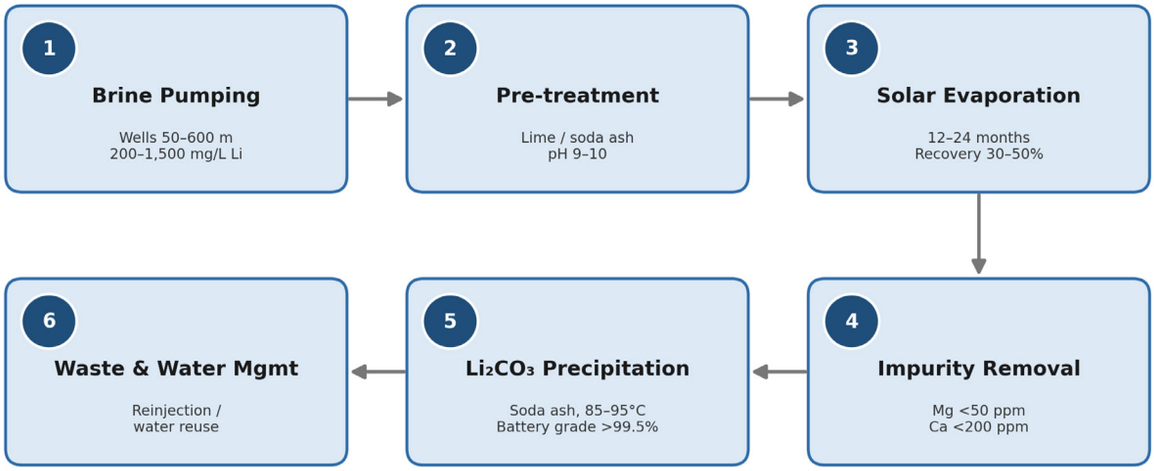
Lithium production from brine is currently dominated by the traditional evaporation process. This process consists of six main steps, shown in Figure 6. We describe each step and identify key R&D opportunities, providing TRL where evidence allows.

Brine Pumping: The process starts with wells drilled 50 to 600 m into the salar aquifer (the underground brine layer beneath the salt flat). The pumped brine is a complex salt solution, mostly sodium, potassium, magnesium, calcium, and boron, with lithium typically making up only 200 to 1,500 ppm (Flexer et al. 2018; Munk et al. 2016). This brine is piped to the surface and directed into the first evaporation ponds.

> **R&D:** Sensors used here are mostly conductivity probes, ion-selective electrodes for lithium and magnesium, and downhole pressure transducers, technologies borrowed from oil and gas well monitoring. The benefit for pumping is that operators can see in real time which wells are still pulling high-grade brine and which have started drawing more diluted fluid from the edges of the aquifer, so under-performing wells can be slowed or rotated before they degrade plant feed quality. SQM and Albemarle have published on these tools (SQM 2024a; Albemarle Corporation 2024) and satellite interferometric radar that can detect centimeter-scale ground subsidence is used to track over-extraction as a proxy for aquifer health (Munk et al. 2016). Industry adoption is currently slow because the sensors need frequent recalibration in the saline, high-temperature pond environment, but the cost case improves as battery-grade specifications tighten (TRL 7-8).

4 Tonnes per annum of lithium carbonate equivalent.

Figure 6. Simplified flow of conventional (evaporative) brine lithium processing



Adapted from Yersaiynova et al. (2026) and Flexer et al. (2018)

Pretreatment: Before reaching the main ponds, the brine is conditioned. Lime or soda ash is added to raise the pH to around 9 to 10 and begin removing problematic impurities like boron (particularly high in Salar de Atacama brines at >400 mg/L) and magnesium (Meshram et al. 2014). Suspended solids are settled or filtered out.

> **R&D:** N-methylglucamine (NMG) chelating resins are well-established for boron removal in seawater desalination. Recent work has adapted them to lithium-brine pretreatment, commonly in tandem with titanium-type lithium-ion sieves, with reported boron uptake of roughly 1–2 mmol/g of resin and high selectivity over the brine's major ions, including lithium (Lu et al. 2023; TRL 5–6, mostly lab and bench scale). The benefit over the incumbent boron solvent-extraction circuit (a kerosene diluent with an aliphatic-diol/octanol-type extractant) is a smaller physical plant footprint and lower reagent cost. Careful automated lime-dosing control is likewise important during pretreatment to limit coprecipitation of lithium with magnesium hydroxide, a loss that can reach several percent of plant output if dosing overshoots (Wilkomirksy 1999).

Solar Evaporation: This is the heart of the evaporative route—the step that gives the process its name, sets its 12- to 24-month timeline, and serves as a key bottleneck. The brine is spread across enormous pond arrays. SQM's Atacama system covers roughly 17 km2, equivalent to about 2,400 football pitches. The desert sun does the work of evaporating water. Over 12 to 24 months, the brine passes through multiple pond stages. First, common salt (NaCl) crystallizes out. Then potassium salts like sylvite and carnallite precipitate (these are harvested as potash byproducts, an important revenue stream). Gradually, the lithium concentration climbs from parts-per-million to about 4% to 6% lithium chloride (Flexer et al. 2018; Yersaiynova et al. 2026). The magnesium-to-lithium ratio of the original brine is critical at this stage. Atacama's ~6:1 ratio is manageable, while Uyuni's ~20:1 ratio means too much lithium gets trapped in magnesium salt crystals. Overall, lithium recovery from

the pond system is only 30% to 50%, which is one of the biggest weaknesses of this method. This headline figure should be read as overall recovery to final product: it combines lithium lost to salt entrainment in the ponds (trapped in halite, sylvite, and magnesium salt crystals) with downstream plant losses; recovery within the chemical plant itself (the next step, impurity removal) is considerably higher.

> **R&D:** Reducing evaporative losses and compressing the multi-month pond timeline is an active research direction, motivated by the low recovery of conventional ponds—typically on the order of 40%, with the remainder lost to entrainment and incomplete extraction (Flexer et al. 2018). One approach pursued at the laboratory and early-pilot stage is capillary "string" evaporation, in which porous fibers concentrate and crystallize salts along their length. Developers of this technology report an evaporation rate roughly 20 times that of a conventional pond and an estimated reduction in land area exceeding 90% (Chen et al. 2023). The technique has since moved from bench prototypes to field deployment through a pilot partnership with SQM in South America (Poore 2025). These accelerated-evaporation methods remain well short of full-scale substitution for existing pond arrays (TRL 4–5, authors' assessment).

Impurity Removal (Plant): The concentrated brine enters a chemical processing plant where remaining magnesium, calcium, sulfate, and boron are removed through targeted precipitation and filtration. Hydrated lime ($Ca(OH)_2$) precipitates magnesium as magnesium hydroxide and removes sulfate as gypsum, while soda ash (Na_2CO_3) precipitates calcium as calcium carbonate; residual boron is removed by solvent extraction or ion exchange (Meshram et al. 2014; An et al. 2012). The target is a clean lithium chloride solution with Mg < 50 ppm and Ca < 200 ppm.

> **R&D:** Nanofiltration membranes for magnesium/lithium separation are advancing from commercial pretreatment use toward higher-selectivity, lithium-specific designs (TRL 5–7; M.S. et al. 2024). Sunresin (China) has commercialized adsorption-based direct lithium extraction across several Qinghai salt-lake operations (including Jintai, Zangge, and Minmetals) using its proprietary aluminum-hydroxide-based adsorbent, with nine commercial contracts totaling ~73,000 tpa of capacity by 2022 (Sunresin 2022). Electrochemical magnesium removal (electrodialysis) remains at laboratory-to-pilot stage (TRL 4–5, authors' assessment; Chen et al. 2018; Sun et al. 2020). The expected commercial benefit is a reduction in lime and soda ash consumption — reagents are the single largest operating-cost component in brine processing, at roughly one-third of total cash cost and dominated by soda ash and lime (S&P Global 2019) and a tighter magnesium specification for downstream battery-grade conversion.

Lithium Carbonate Precipitation: Soda ash is added to the purified brine at 85°C to 95°C. Lithium carbonate precipitates as a white solid, which is centrifuged, washed, and dried. Technical-grade product runs ~99.0% to 99.2% purity; battery grade (>99.5%) requires an additional redissolution and reprecipitation step. Some producers convert the carbonate further to lithium hydroxide via causticization with lime. For example, Albemarle produces lithium hydroxide at its Kemerton plant in Western Australia, which is needed for high-nickel lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) cathode chemistries (Albemarle Corporation 2024).

R&D: Mangrove Lithium (Vancouver, Canada) is piloting a membrane electrolysis route that converts lithium chloride directly to lithium hydroxide, bypassing the carbonate intermediate and producing recyclable hydrochloric acid as the main byproduct (TRL 6, company-reported; Mangrove Lithium 2026a, b). The company reports lower refining energy use and operating cost versus the conventional carbonate-then-causticization route. Novalith (Sydney, Australia) uses pressurized carbon dioxide in place of sulfuric acid and soda ash to produce battery-grade lithium carbonate directly from ore, avoiding bulk-reagent consumption; the process is at pilot scale, producing several tonnes per annum, with engineering underway on a first commercial plant (TRL 5–6, authors' assessment; Novalith 2023; CEFC 2023). Both routes target the same problem: cutting reagent consumption - soda ash and lime are the single largest reagent cost in conventional brine processing (S&P Global 2019) and shortening the multistep purification needed to achieve battery grade.

Waste and Water Management: The depleted brine is either reinjected into the salar or evaporated to dryness. Water use is a major socioenvironmental concern—net water losses from the evaporitic process are estimated at roughly 100 to 800 m^3 per tonne of LCE, with the concentrated-brine production stage dominating the water footprint (Palacios et al. 2026; Marinova et al. 2024). SQM's Atacama operations face regulatory caps under their agreement with CORFO (Corporación de Fomento de la Producción, the Chilean state development agency that holds the Atacama mining leases). The new SQM-Codelco partnership (from 2025) partly addresses government concerns about resource stewardship (SQM 2024a). Carbon dioxide emissions are comparatively low (~2,900 kg CO_2-eq/t LCE) because the process relies largely on solar evaporation. This equates to roughly one-seventh of the footprint of Australian spodumene converted in China (Lagos et al. 2024).

R&D: Closed-loop brine reinjection and water-recovery pilots are being pursued by SQM and Albemarle at Atacama. SQM has publicly targeted at least a 50% reduction in brine extraction, aiming to halve its water use by 2031 (SQM 2023). The most disruptive water-saving option remains DLE combined with brine recirculation, which avoids the large open evaporation ponds. Life-cycle assessments confirm materially lower freshwater consumption than conventional evaporation, though the magnitude is site- and energy-source-dependent and claims of very large reductions are not yet independently verified at commercial scale (Mousavinezhad et al. 2024).

Direct Lithium Extraction

DLE technologies offer an alternative route for recovering lithium from brines, including low-lithium sources such as geothermal and oilfield brines. This route can potentially overcome many limitations of the traditional evaporation approach, such as low lithium recoveries, 12- to 24-month retention periods, and strong dependence on region-specific weather conditions (Razmjou 2024; Khalil et al. 2022). DLE methods use adsorption, ion exchange, solvent extraction, membranes, or electrochemical methods to pull lithium directly from brine in hours rather than months, with target recovery above 90% and substantially lower land and water footprints (Farahbakhsh et al. 2024).

DLE is not new. The aluminum-based adsorption method has operated commercially for more than two decades at the Fénix operation at Salar del Hombre Muerto in Argentina (now part of Rio Tinto; the operation was developed by FMC/Livent), and at several Chinese salt lake operations, including those run by Sunresin and Zangge Mining. In 2024, DLE

accounted for about 11% of lithium production from brines (Razmjou 2024). Investment has accelerated sharply since 2020: a 2023 Deloitte assessment identified roughly 38 technology developers and 57 lithium projects using or planning DLE (Deloitte 2023).

The DLE landscape is best understood by technology family and maturity.

- Aluminum-based adsorption is the most advanced and dominant approach (TRL 8–9). It is economical, proven at commercial scale, and able to extract lithium from diverse brines, including those with low lithium concentrations and high magnesium-to-lithium ratios (Razmjou 2024).
- Ion-exchange methods are gaining increasing attention (TRL 7–8; for example, Lilac Solutions' Kachi demonstration in Argentina), with manganese (lithium manganese oxide [LMO])- and titanium-based sorbents reported to offer superior lithium selectivity compared to aluminum sorbents (Razmjou 2024).
- Solvent-extraction DLE has reached pilot scale (~TRL 7; for example, Adionics, France), and a demonstration plant by Qinghai Chaidamu Xinghua Lithium Salt Co. in China has been reported, bringing that route to roughly TRL 8 (Razmjou 2024).
- Membrane technologies, particularly nanofiltration and electrodialysis, are at an earlier stage (TRL 4-5) but could disrupt adsorption- and solvent-based methods because they avoid direct contact between brine and product and suit modular deployment.
- More novel approaches (TRL below 4) include electrochemical or battery-based DLE and advanced membranes such as polymeric and liquid-liquid membranes (Razmjou 2024).

The commercial landscape is moving quickly. Sunresin (China) operates large-scale commercial plants in Qinghai. Eramet's Centenario (Argentina) was commissioned in 2024 as one of the first Western commercial-scale DLE plants (Eramet 2024b). Standard Lithium has run a demonstration plant in Arkansas since 2020 and is developing a commercial project with Equinor. POSCO commissioned the first phase of its Sal de Oro plant at Hombre Muerto in 2024. Vulcan Energy is developing integrated geothermal-brine DLE in Germany's Upper Rhine Valley (demonstration stage). Lilac Solutions (USA), EnergyX (pilot in Bolivia), Summit Nanotech (Canada, piloting in Chile), and Koch Technology Solutions are advancing toward commercial deployment. (Deloitte 2023; Razmjou 2024; Eramet 2024b)

On economics, DLE operating costs are broadly comparable to evaporation, while capital costs are higher (estimated at $45,000 to $80,000 per tonne of annual LCE capacity) due to the technology and infrastructure requirements. Over time, DLE may achieve better cost-benefit ratios through its higher lithium recovery (Razmjou 2024).

Three caveats matter for new entrants. First, DLE performance is strongly brine-chemistry dependent (magnesium-to-lithium ratio, sulfate, boron). Second, most commercial flowsheets still require a downstream concentration step, and freshwater and reagent demands can be significant. Third, in practice, many 2024–2025 projects are adopting hybrid DLE-plus-pond configurations, and for very high-grade, low-magnesium, high-evaporation salars such as Atacama, conventional ponds remain the lowest-cost route (Razmjou 2024; Khalil et al. 2022).

Cost Structure

Brine evaporation is generally the lowest-cost lithium production route, with operating costs (the cost of operating the plant once built) typically ranging from $3,000 to $6,000 per tonne LCE, compared to $5,000 to $8,000 or more for hard-rock spodumene processing (Yersaiynova et al. 2026; Gao et al. 2023). Capital costs are also lower because the main infrastructure is earthwork ponds rather than chemical plants. However, these costs vary significantly by location: Atacama operations benefit from high lithium grades and intense solar evaporation, while sites with high magnesium-to-lithium ratios (like Bolivia's Uyuni at ~20:1 or China's Qinghai at >30:1) can push costs toward the upper end or even make traditional evaporation uneconomic (Flexer et al. 2018). The biggest cost drivers are lime and soda ash reagents, pond construction and maintenance, and energy for the downstream chemical plant. For DLE-specific capital and operating costs, see the section describing DLE immediately preceding this one.

Lithium from Hard-Rock Ores (Spodumene)

Hard-rock lithium is hosted in pegmatites, which are coarse-grained igneous rocks. The major lithium-bearing pegmatite occurrences are in Australia, China, the United States, and Canada. Within these pegmatites, lithium occurs in various mineral forms, including aluminosilicate minerals such as spodumene, lepidolite, and petalite. The most commercially important is spodumene ($LiAlSi_2O_6$), which accounts for around 90% of lithium production from nonbrine sources as a result of its relatively high lithium content, abundance, and relative ease of processing (Tadesse et al. 2019; Petrakis et al. 2025). Lepidolite and zinnwaldite are lower-grade, fluorine-bearing alternatives; China has nonetheless scaled lepidolite conversion significantly in Jiangxi province despite higher costs and fluorine-bearing waste streams, and lepidolite supplied a meaningful share of Chinese output in 2023 (Gao et al. 2023).

Who Produces and Where

Hard-rock spodumene accounts for the majority share of global lithium production, roughly 55% to 65% in 2024 (USGS 2025), having overtaken brine as Australian production scaled up over the past decade. Australia is by far the dominant hard-rock based lithium producer. The Greenbushes mine in Western Australia (operated by Talison Lithium, a joint venture between Albemarle 49% and a Tianqi/IGO partnership at 51%) is the world's largest spodumene operation at ~1.6 Mtpa concentrate (Tianqi Lithium 2024; IGO Limited 2024). Pilbara Minerals runs the Pilgangoora Lithium-Tantalum Project at ~1,000 ktpa[5] SC6 [a 6% Li_2O concentrate, the standard traded product] after its P1000 expansion (Pilbara Minerals 2024). Mineral Resources operates the Mt. Marion mine as a 50/50 joint venture with Ganfeng Lithium and holds a 50% stake in the Wodgina mine in a joint venture with Albemarle. Both mines produce spodumene concentrate for export; Albemarle separately converts spodumene to lithium hydroxide at its wholly-owned Kemerton plant, which was placed into care and maintenance in early 2026 (Mineral Resources 2024; Albemarle Corporation 2024).

Most concentrate is shipped to China for chemical conversion, where companies such as Tianqi, Ganfeng, and Yahua dominate the lithium hydroxide and carbonate market. Outside China, conversion capacity is being built at Tianqi/IGO's Kwinana plant in Western Austra-

5 Kilotons (metric tons) per annum.

lia (24,000 tpa LiOH, the first production line ["Train 1"] operating below nameplate, and construction of the second line halted in January 2025) and Albemarle's integrated facility at Wodgina. Brazil's Sigma Lithium (Grota do Cirilo) and Canada's Nemaska Lithium are emerging non-Australian producers (USGS 2025).

Africa has also emerged rapidly on the mining side. Zimbabwe became a top-five global spodumene source in 2023–2024 through the Bikita (Sinomine), Arcadia (Huayou Cobalt), and Sabi Star (Chengxin) operations. These are largely Chinese-owned and ship concentrate to China for conversion (USGS 2025), representing a direct illustration of the value-chain dependence discussed in the introduction. Mali's Goulamina project adds further African capacity.

The Process

The conventional commercial process for producing battery-grade lithium products from spodumene comprises two overarching stages: mining and mineral processing to produce a raw product in the form of a concentrate containing roughly 6% to 7% lithium oxide, and refining to extract the lithium from the concentrate and generate a pure lithium chemical. The ore-to-product value chain can be divided into six steps (Figure 7):

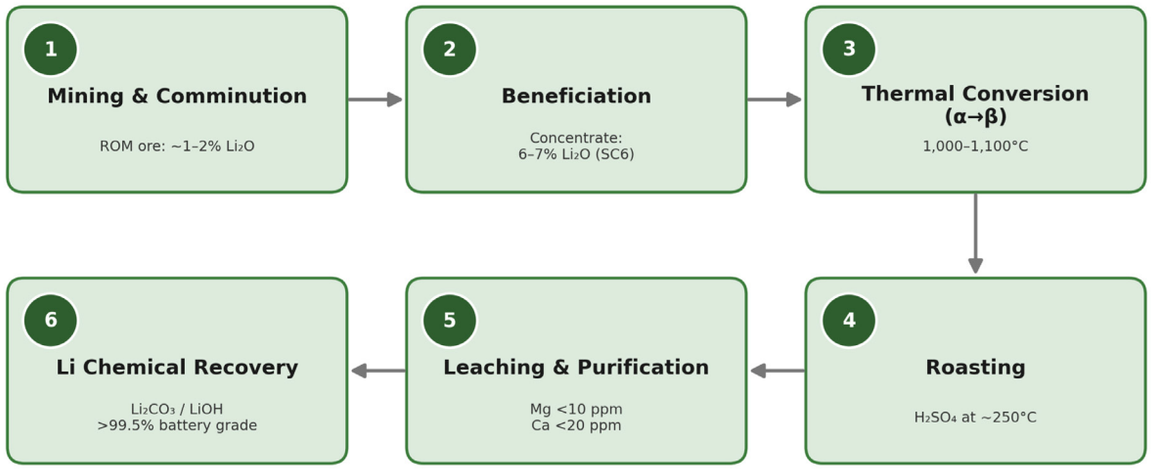
1. Mining and comminution to extract, liberate, and reduce the size of the lithium-bearing mineral
2. Beneficiation to physically separate lithium minerals from the gangue and generate a concentrate
3. Thermal conversion to transform stable alpha-spodumene into the more reactive beta-spodumene phase
4. Roasting to convert the spodumene to water-soluble lithium salts
5. Leaching and purification to generate a pure lithium salt solution
6. Lithium chemical recovery.

Mining and Comminution: Spodumene-bearing pegmatites are extracted by conventional open-pit mines (Greenbushes, Pilgangoora) or underground methods. Run-of-mine ore typically contains ~1% to 2% lithium oxide. The ore is crushed in multiple stages and ground to 150–600 μm to liberate the spodumene from gangue minerals like quartz, feldspar, and mica.

> **R&D:** Sensor-based ore sorting using X-ray transmission (XRT) and X-ray fluorescence (XRF) detectors is now being deployed at several lithium operations including Pilgangoora and Wodgina (TOMRA and Steinert systems, TRL 8–9). The benefit is energy savings of 15% to 25% in downstream grinding because sorted ore can reject 20% to 30% of low-grade rock before the mill (Tabelin et al. 2021). High-pressure grinding rolls (HPGR) are gradually replacing semi-autogenous (SAG) mills for the same reason: HPGR runs at roughly half the specific energy consumption of conventional SAG circuits, with benefits scaling at high throughput.

Beneficiation: Froth flotation is the most widely used technique for the beneficiation of spodumene. Typically, flotation is conducted with fatty acids, such as oleic acid/sodium

Figure 7. Simplified flow of hard-rock (spodumene) lithium processing via the sulfuric acid route



Adapted from Yersaiynova et al. (2026), Karrech et al. (2020), and Petrakis et al. (2025).

oleate, oxidized paraffin soap, or naphthenic acid soap (Tadesse et al. 2019). Dense media separation (DMS) is commonly used as a preconcentration technique to reject coarse gangue prior to flotation. In DMS, particles are sorted by sinking or floating in a high-density fluid, exploiting spodumene's relatively high specific gravity to produce a coarse concentrate.

Magnetic separation is also frequently applied as a preconcentration technique for the removal of iron-bearing minerals, such as amphibole and tourmaline, which cannot be achieved by DMS and flotation (Tadesse et al. 2019; Petrakis et al. 2025). The combined output is a 6% to 7% Li2O concentrate (called SC6 in industry shorthand), the standard raw product traded internationally (Karrech et al. 2020).

R&D: Novel collectors and depressants for fine-particle spodumene flotation are an active area of academic research. This research is motivated by the poor performance of conventional fatty-acid (sodium oleate) systems on fine fractions, where recoveries often fall well below 50% (Cook and Gibson 2023). Next-generation reagents including modified hydroxamates and chelating collectors have shown substantially higher spodumene recovery and selectivity in bench-scale microflotation tests. For example, a β-amino-hydroxamate collector recovered about 90% of spodumene versus roughly 57% for sodium oleate under the same conditions (Qi et al. 2024). Complementary work on coarse-particle beneficiation of Pilgangoora ore has demonstrated theoretical spodumene recoveries above 90% with efficient gangue rejection at coarse grind sizes (Opoku et al. 2025). These approaches remain largely at laboratory and pilot scale (TRL 4–6). The expected commercial benefit is a modest uplift in lithium recovery from existing reserves, on the order of several percentage points. At a large Western Australian operation, this could translate to additional LCE output without new mining (authors' estimate).

Thermal Conversion (Calcination): Natural alpha-spodumene is chemically very stable and does not react with acids under practical leaching conditions. To make the lithium accessible, the concentrate is roasted at 1,000°C to 1,100°C in a rotary kiln, which converts it to the beta phase (a rearranged, more open crystal structure of the same mineral, formed when alpha-spodumene is heated past about 1,000°C). This expanded crystal structure can be attacked by acid to release the lithium in the next step. This decrepitation step typically takes 30 to 60 minutes (Gao et al. 2023).

> **R&D:** Microwave-assisted decrepitation has been studied at laboratory scale as a route to cut the energy and time of the α-to-β conversion (TRL 3–4). Bench studies report order-of-magnitude reductions in heating energy and time relative to conventional furnaces while achieving lithium recoveries comparable to conventional calcination (~97%). However, scale-up to a continuous rotary kiln has not been demonstrated (Salakjani et al. 2021; Peltosaari,et al. 2015). Separately, electrically heated (indirect) rotary kilns are now commercially offered for spodumene conversion and are being evaluated to lower the carbon footprint of the high-temperature roast. This phase is the single largest energy consumer in hard-rock lithium refining — accounting for roughly half of process energy use (Abdullah et al. 2024). No full-scale commercial deployment of electrified or hydrogen-fired decrepitation kilns has yet been implemented.

Roasting: More than 50 years after it was first commercialized, the sulfuric acid roasting process remains the most widely used route for extracting lithium from ores (Petrakis et al. 2025). In this process, the beta-spodumene concentrate is mixed with concentrated sulfuric acid and roasted at ~250°C. The reaction converts the lithium into water-soluble lithium sulfate (Li2SO4), while aluminum and silicon remain as insolubles. This is the dominant industrial route, used at virtually every Chinese converter and at Kwinana (Australia) (Yersaiynova et al. 2026).

> **R&D:** Research is mainly concerned with applying alternative media for roasting calcined or uncalcined concentrates. These include alkalis (sodium hydroxide or lime), other acids (hydrochloric or hydrofluoric acid), or salts such as limestone, sodium carbonate, and sulfates (potassium, sodium, and calcium sulfate) (Petrakis et al. 2025; Rioyo et al. 2020). Reported laboratory recoveries are high across several routes—for example, sodium-carbonate roasting with hydroxide leaching (~96%), mechanical-activation/sodium-sulfate roasting (~92%), and fluoride roasting (93–98%, though with environmental concerns). Lithium Australia's SiLeach and LieNA processes use sulfate- and caustic-based routes intended to operate at lower temperatures and to accept lower-grade or fine feeds, including material off-spec6 for conventional roasting (TRL 5–7, pilot scale; Lithium Australia 2023). The expected commercial benefit is lower energy and reagent intensity per tonne of lithium and the ability to process fines and off-spec material that currently has limited economic outlet. At commercial scale, Metso's high-pressure alkaline (soda) leaching process is being deployed at the Keliber project in Finland and soda-ash roasting is being revisited in China for similar reasons—making lower-temperature, lower-reagent conversion the most active cost-reduction direction in hard-rock processing (Jorjani et al. 2025).

Leaching and Purification: In the conventional sulfuric acid process, the sulfated material is water-leached to dissolve the lithium sulfate. Iron, aluminum, magnesium, calcium, and manganese impurities are removed by sequential pH adjustment, precipitation with lime and soda ash, and filtration. Ion exchange polishes the solution to battery-grade specification (Mg < 10 ppm, Ca < 20 ppm).

> **R&D:** Selective chelating ion-exchange resins for divalent-metal polishing are used commercially—for example, Lanxess's Lewatit TP-series and Purolite's S-series chelating resins—and target residual calcium, magnesium, and heavy-metal cations to reach battery-grade specification (Lanxess n.d., Purolite n.d.). In conventional spodumene flowsheets most manganese is already removed upstream during precipitation, with the ion-exchange step polishing calcium and magnesium. Nanofiltration is also being trialed for magnesium/lithium separation, similar to brine plants (TRL 5–6). The benefit is a tighter battery-grade specification (Mg < 5 ppm, currently the limiting impurity for high-nickel cathodes) without the chemical consumption of additional liming steps.

Recovery of Lithium Chemicals: The purified lithium sulfate solution is reacted with sodium carbonate to precipitate Li2CO3, or with sodium hydroxide to produce LiOH · H2O. Both go through redissolution and reprecipitation to reach battery grade (>99.5% Li2CO3>56.5% LiOH). LiOH is now the preferred product for high-nickel NMC and NCA cathodes used in long-range EVs.

> **R&D:** Mangrove Lithium (Delta, British Columbia) is developing a feedstock-flexible electrochemical refining platform that converts lithium sulfate or lithium chloride into battery-grade lithium hydroxide (or carbonate). In the lithium sulfate case, membrane electrolysis produces sulfuric acid as a recyclable byproduct that can be returned upstream, avoiding the sodium sulfate waste stream of the conventional causticization route (Mangrove Lithium 2026a, b, Ramirez 2026). The underlying chemistry is established in the peer-reviewed literature: bipolar-membrane electrodialysis has been demonstrated to convert a purified Li_2SO_4 stream directly into LiOH and H_2SO_4, reaching LiOH purity of about 99.75% at roughly 7 kWh/kg LiOH (Chen et al. 2021). Mangrove's public materials state that its process removes reagents such as soda ash, lime, and caustic soda from the refining flowsheet; a specific reduction in soda ash and lime consumption could not be verified from public sources and is not asserted here absent primary technical documentation. Commercial readiness spans two stages that should be distinguished: Natural Resources Canada's Critical Minerals Research, Development and Demonstration (CMRDD) program, which supports technologies at TRL 6–8, is funding Mangrove's spodumene-processing pilot and engineering study for a planned 20,000 tpa Eastern Canada refinery. The company's Delta facility, opened in April 2026 as North America's first commercial electrochemical lithium refinery, already produces 1,000 tpa of battery-grade lithium hydroxide (NRC 2026b). The platform is among the more credible decarbonization pathways for hard-rock conversion and regionalized refining, particularly for the emerging wave of Australian- and Canadian-integrated facilities.

Waste and Carbon Footprint

Hard-rock processing produces large volumes of solid waste (~7–10 t residue per tonne LCE), mostly leached spodumene tailings rich in silica and sulfates (Karrech et al. 2020). These are usually disposed of in dry-stack tailings facilities. The leached aluminosilicate residue and sodium sulfate byproduct streams are themselves active valorization (converting waste streams into saleable products) R&D areas, with proposed uses in cement, geopolymers, and glass (Tadesse et al. 2019; Petrakis et al. 2025). The main environmental concern is energy intensity, since calcination alone consumes 0.5–1 GJ per tonne of concentrate, and the carbon footprint is roughly 4 to 10 times that of brine, depending on the grid mix (Gao et al. 2023). This is why a number of operators are looking seriously at electrification and at processes that bypass the high-temperature roast.

Cost Structure

Hard-rock processing is structurally more expensive than brine. Integrated cash costs typically run $5,000 to $8,000 per tonne LCE (Karrech et al. 2020; Yersaiynova et al. 2026), though Greenbushes mine operates near the bottom of the global cost curve thanks to its very high grade (~2.0% to 2.5% Li2O in ore versus ~1.0% to 1.5% for most peers). Pilbara Minerals reported FY2024 cash operating costs of AUS$590 to AUS$650/t SC6 at the mine gate. Converting that concentrate to battery-grade chemicals adds another US $3,000 to $5,000/t LCE (Pilbara Minerals 2024). The biggest cost drivers are sulfuric acid, energy for calcination (the 1,000°C to 1,100°C roast is energy-intensive), and reagents for purification. Carbon dioxide intensity is also higher than brine, roughly 9–15 t CO_2/t LCE depending on the energy mix (Gao et al. 2023, who report a 9.3- to 60.4-fold range relative to brine, with the spread reflecting fuel choice).

Rare Earth Elements Production

The rare earth elements are a group of 17 metals: the 15 lanthanides plus scandium and yttrium. In practice, the market divides them into “light” rare earths (such as lanthanum, cerium, neodymium, and praseodymium) and the scarcer, higher-value “heavy” rare earths (such as dysprosium, terbium, and yttrium). The four magnet rare earths—neodymium, praseodymium, dysprosium, and terbium—drive most of the strategic demand because they are essential to the permanent magnets used in EV motors and wind turbines.

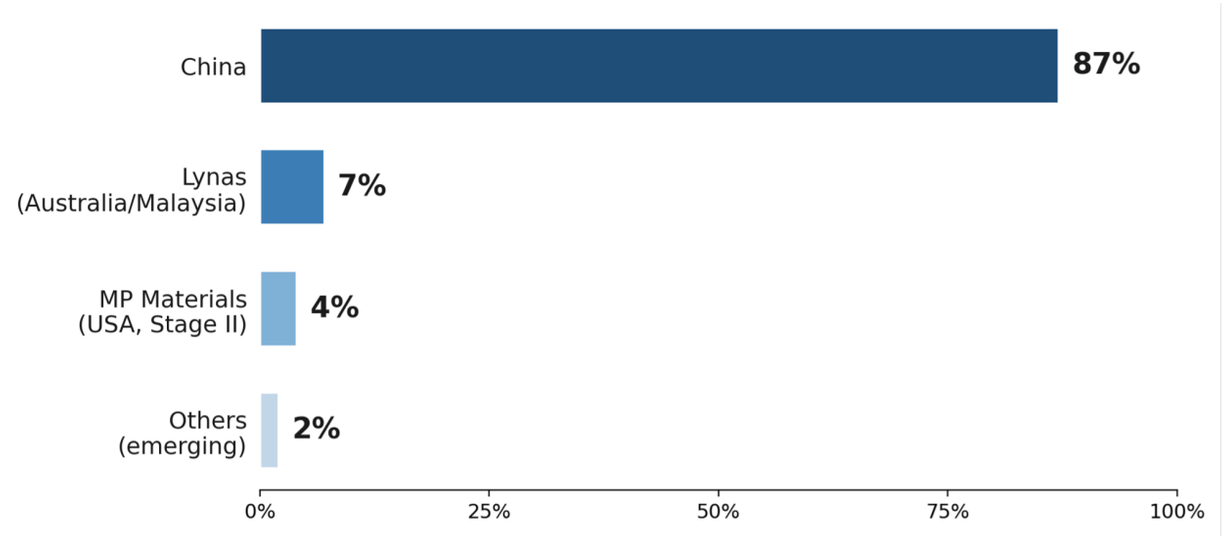
Who Produces and Where

Rare earth production is dominated by China to a degree that is hard to overstate, but it is important to differentiate between mined and processed or refined product. Several countries mine rare earths, yet almost all material flows through Chinese midstream capacity.

China accounts for roughly two-thirds of global mined output, an estimated 85% to 90% of midstream separation and refining capacity (the chemical splitting of mixed rare earths into individual high-purity oxides, a downstream processing step distinct from the physical beneficiation of ore), and close to 90% of rare earth metal and neodymium iron boron (NdFeB) magnet production (IEA 2023; USGS 2025; Adamas Intelligence 2024).

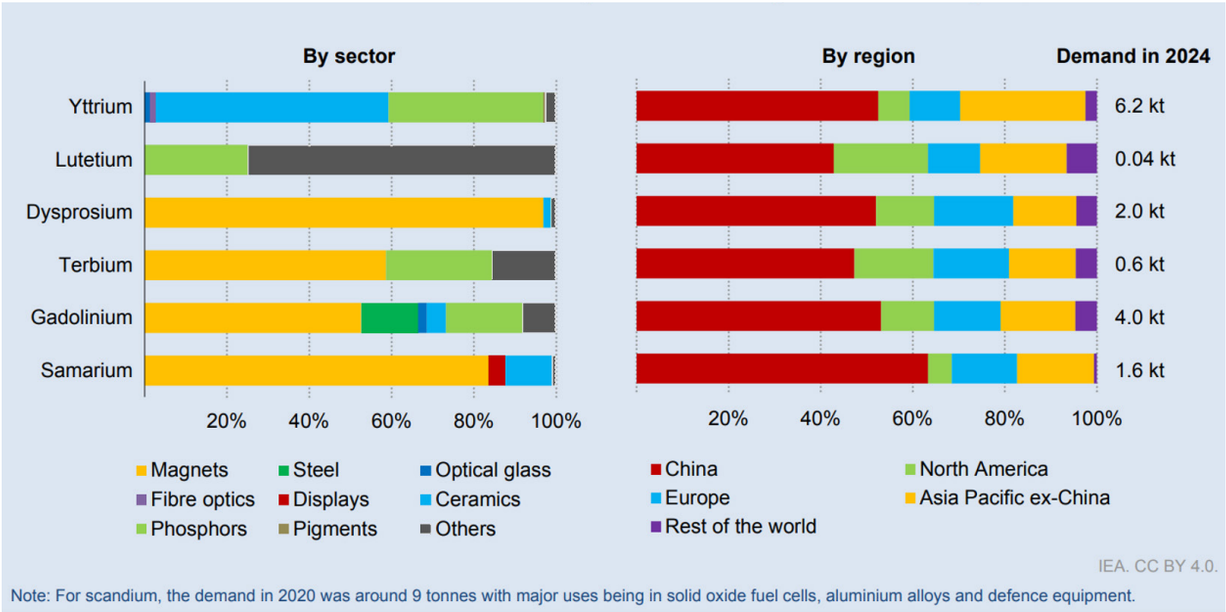
China Northern Rare Earth (Bayan Obo, Inner Mongolia) is the world’s largest single rare earth company. China Southern Rare Earth and China Rare Earth Group (formed by a 2021 merger of Minmetals, Chinalco, and Ganzhou rare earth entities) control much of the rest. Southern China’s ion-adsorption clay deposits are the dominant global source of heavy

Figure 8. Estimated global market share of rare earth separation capacity (2024)



Sources: USGS (2025), Adamas Intelligence (2024), Lynas (2024), MP Materials (2024)

Figure 9. Demand for the rare earth elements under export controls by sector and region (2024)



Note: For scandium, the demand in 2020 was around 9 tonnes with major uses being in solid oxide fuel cells, aluminium alloys and defence equipment.

Source: Global Critical Minerals Outlook 2025

rare earth elements (primarily dysprosium and terbium) (USGS 2025, Adamas Intelligence 2024).

Outside China, Lynas Rare Earths (Australia/Malaysia) is the most significant player, mining at Mt. Weld (one of the highest-grade deposits globally at ~8.4% rare earth oxide [REO]), cracking and leaching at a new facility in Kalgoorlie (Western Australia), and separating at Kuantan, Malaysia. Lynas produced ~12,000 tpa REO in FY2024 with plans to reach ~10,500 tpa of NdPr oxide by 2027 (Lynas Rare Earths 2024).

MP Materials mines and concentrates at Mountain Pass, CA (~43,000 tpa REO concentrate). Its Stage II[6] on-site separation facility began producing separated NdPr oxide in 2023 and is ramping toward full capacity. Until that ramp completes, a portion of concentrate continues to be sold for separation elsewhere (MP Materials 2024). In 2025, MP entered a public-private partnership with the US Department of Defense that includes a guaranteed NdPr price floor and offtake commitments (MP Materials 2025).

Energy Fuels (White Mesa, UT) processes monazite from mineral sands into mixed RE carbonate, with SX separation planned by 2026.

Iluka Resources is building a separation refinery at Eneabba, Western Australia (backed by an AUS$1.25 billion Australian government loan), targeting first production in 2026.

Neo Performance Materials operates Europe's only commercial rare earth separation facility at Sillamäe, Estonia, alongside downstream magnet-powder production (Neo Performance Materials 2025).

USA Rare Earth is building a sintered NdFeB magnet plant in Stillwater, OK, and developing the Round Top heavy-RE deposit in Texas, though it is not yet producing (USA Rare Earth 2025).

The Process

Rare earth production splits into two routes depending on the feedstock, with the main difference occurring at the front end. The first covers hard-rock ores (bastnäsite and monazite), which must be mined, crushed, and beneficiated into a concentrate before chemical processing. The second covers ion-adsorption clays, where the rare earths are loosely bound to clay surfaces and are recovered by in-situ leaching, skipping conventional mining and beneficiation entirely. Both routes converge at the leaching and SX stages, so the mining and beneficiation steps in Figure 10 apply to hard-rock ores; the route with ion-adsorption clays as feedstock replaces them with the leaching step described afterward.

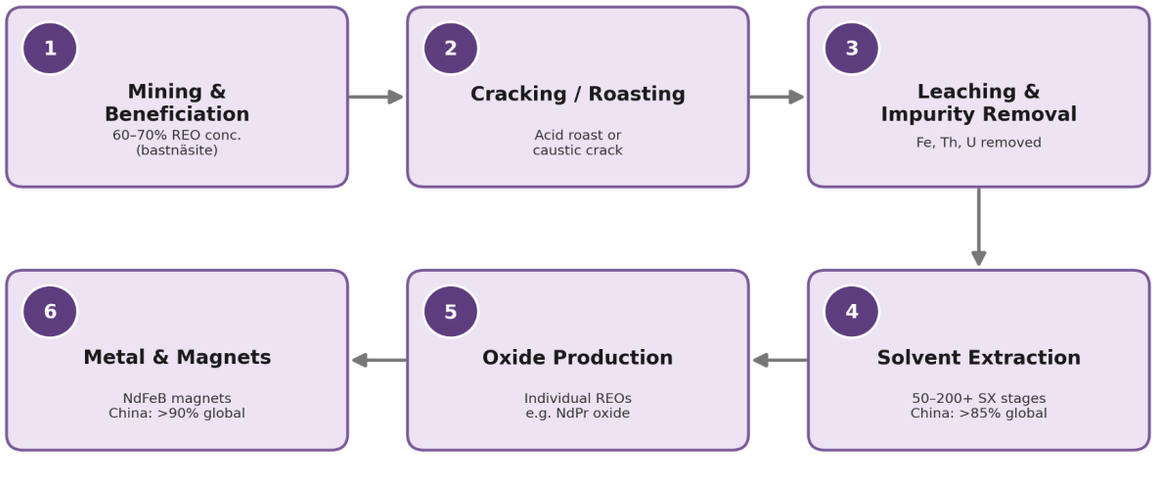
Hard-Rock Ore (Bastnäsite, Monazite)

Mining and Beneficiation: The ore is mined, crushed to ~100–200 µm, and concentrated primarily by froth flotation, with gravity and magnetic separation often employed as complementary techniques, to a 60% to 70% REO concentrate (Jordens et al. 2013).

> **R&D:** MP Materials plans to install a sensor-based ore-sorting (pre-concentration) circuit at Mountain Pass to upgrade low-grade run-of-mine ore in the 2.5% to 5.0% TREO range before flotation, rejecting gangue early to improve mill efficiency and extend reserves; the integrated crushing and ore-sorting facility is expected to begin

6 MP's term for restoring on-site separation and refining at Mountain Pass. Stage I is mining and concentration and Stage III is magnet production.

Figure 10. Simplified flow of hard-rock rare earth processing



Adapted from Krishnamurthy and Gupta (2016) and Xie et al. (2014)

ramping up in 2027 (MP Materials 2025). In parallel, hydroxamate-based collector chemistries for bastnäsite/calcite separation remain an active research area aimed at improving flotation selectivity and recovery (Jordens et al. 2013). For context, Mountain Pass overall TREO recovery has averaged in the mid-70% range in recent years (about 74.7% in 2024 monitoring, up from the mid-60s% in 2022–2023), with rougher-circuit recovery above 80% (SKR Consulting 2026).

Cracking/Roasting: The concentrate is decomposed to make the rare earths soluble, either by acid roasting with concentrated sulfuric acid (for bastnäsite) or alkaline cracking with concentrated sodium hydroxide solutions (for monazite). The latter is favored for high-grade ores and concentrates and is more widely practiced in the Western world (Krishnamurthy and Gupta 2016; Kumari et al. 2015). Monazite cracking also liberates thorium and uranium, which must be managed as radioactive byproducts. (The term cracking for this acid or alkali decomposition step is unique to rare earth processing and reflects the extremely refractory nature of REE minerals.)

R&D: Mechanochemical cracking (ball-milling with NaOH; TRL 3–4) and microwave-assisted roasting (TRL 4) are early-stage approaches aimed at lowering the temperature and reagent intensity of the cracking step. Mechanochemical NaOH decomposition converts REE-phosphate to REE-hydroxide at markedly lower roasting temperatures (~400°C) than conventional cracking (Kim et al. 2009). Microwave roasting of bastnäsite/monazite has achieved substantially higher REE and fluoride recoveries than conventional heating in bench tests (Zhang et al. 2019). Energy savings at commercial scale remain unproven, however, and the milling step itself can add energy demand (Zhou et al. 2025).

Leaching and Impurity Removal: The cracked product is leached with water or hydrochloric acid to dissolve rare earths into solution, with iron, thorium, and uranium removed by pH-controlled precipitation.

R&D: Current initiatives focus on cleaner radioactive waste handling and reagent reduction. Selective precipitation and solvent-based routes to separate thorium and uranium before solvent extraction are being studied to cut radioactive waste volumes and recover thorium as a byproduct (Kumari et al. 2015; TRL 4-5). Resin-in-pulp and chelating ion-exchange systems for direct impurity capture from leach liquors are at bench-to-pilot scale (TRL 4–6) and aim to lower the lime and reagent consumption of conventional pH-controlled precipitation (Kumari et al. 2015).

Solvent Extraction (Separation): The clean rare earth solution then enters solvent extraction, the most technically challenging and capital-intensive step. Because the individual rare earths are chemically almost identical, they cannot be separated in one step. Instead, the solution is passed through long chains of 50 to 200-plus mixer-settler units (tanks where the solution is mixed with an organic solvent, then allowed to settle into two layers). Specialized organic extractant chemicals, with industry names like D2EHPA, PC88A (also called P507), and Cyanex 272, each grab certain rare earths slightly more strongly than others. By repeating this selective tug-of-war hundreds of times in sequence, the mixed feed is gradually split into individual rare earths at over 99% purity. The scale, chemical complexity, and operational know-how required are the main reason China's dominance is most pronounced at this stage.

R&D: Selective oxidative leaching that pulls cerium out early (Ce^{3+} to Ce^{4+}) is being trialed to reduce SX load by 30% to 40%, since cerium is typically half the mass of a bastnäsite-derived feed (Xie et al. 2014; TRL 5). Bioleaching with *Acetobacter* and other organic-acid-producing microbes is laboratory-stage only (TRL 2–3) (Qu et al. 2019; Rasoulnia et al. 2021). REEtec (Norway) has developed a proprietary solvent-free separation process that avoids the organic extractants used in conventional solvent extraction and reportedly recovers and re-uses virtually all consumables, cutting CO_2 emissions by around 90% versus conventional routes (company-reported; TRL 7, industrial-scale demonstration operating since 2019). REEtec does not publicly disclose the underlying separation chemistry. Phoenix Tailings (USA) is developing an acid-free extraction (TRL 5–6) and is partnered with the US Department of Energy on demonstration funding. Ionic-liquid extractants are under academic study at Idaho National Laboratory and at Solvay (TRL 4–5) (Menser 2020). Membrane-assisted solvent extraction and molecularly imprinted polymers (MIPs) have also emerged as promising alternatives to conventional solvent extraction but remain at an early stage of development (TRL 3–4). In the United States, Oak Ridge National Laboratory is developing tailored diglycolamide (DGA) extractants for rare earth separation (Stamberga et al. 2020; Lyon et al. 2023), and ReElement Technologies is scaling ligand-assisted displacement chromatography at commercial-track facilities in Indiana (Tsao et al. 2025). Machine-learning optimization of SX cascades is a genuine emerging area (Liu et al. 2022); separately, Ucore Rare Metals' RapidSX platform is a column-based reconfiguration of conventional solvent extraction with automated process control—600-plus sensors and programmable logic controllers rather than AI/ML—that an independent evaluation found roughly three times as efficient as conventional solvent extraction, enabling an approximately two-thirds smaller footprint (Ucore n.d., company-reported).

Oxide Production: The separated rare earth solutions are precipitated (typically as oxalates), filtered, and calcined at 800°C to 1,000°C to produce individual rare earth oxides (e.g., NdPr oxide for magnets).

Metal and Magnets: For magnet applications, these oxides are further reduced to metals via molten salt electrolysis at ~1,050°C, then alloyed with iron and boron, strip-cast, hydrogen-decrepitated, jet-milled, pressed in a magnetic field, and sintered at 1,050°C to 1,100°C to produce NdFeB permanent magnets—the kind that power EV motors and wind turbines. China produces more than 90% of global NdFeB magnets (~200+ kt/y; Adamas Intelligence 2024).

R&D: Phoenix Tailings' molten salt electrolysis produces rare earth metals from oxides while avoiding the solvent extraction and hydrofluoric acid–based steps used conventionally. It has now moved from lab scale to a commercial metallization facility in Exeter, New Hampshire, producing neodymium-praseodymium (NdPr) and dysprosium-iron (DyFe) alloy and targeting 200–1,000 tpa (Phoenix Tailings 2025). Boston Metal (spun out from Massachusetts Institute of Technology) is developing molten oxide electrolysis, with rare earth applications at an earlier stage (TRL 3–4) (Boston Metal 2026). On the magnet side, grain boundary diffusion (Shin-Etsu, TDK, Japan) cuts dysprosium use by 30% to 50% versus bulk dysprosium alloying and is fully commercial. This is now standard for high-coercivity grades used in EV traction motors (Gutfleisch et al. 2011). NdFeB recycling via hydrogen processing of magnet scrap (HPMS) is being scaled by HyProMag (UK); the core HPMS powder step is mature (company-cited TRL 8), while the broader magnet-to-magnet value chain is less developed. HyProMag's first commercial line at Tyseley Energy Park, Birmingham, UK, was officially opened in January 2026 at ~100 tpa initial capacity (single shift; company-reported) (HyProMag 2026b). Separately, Cyclic Materials (Canada) is scaling a long-loop hydrometallurgical route that recovers mixed rare earth oxides from end-of-life magnets (Cyclic Materials n.d.). Beyond these, MagREEsource (France) is piloting hydrogen-based magnet-to-magnet recycling, Noveon Magnetics (USA) already produces commercial sintered NdFeB magnets from recycled feed in Texas (Noveon Magnetics 2026), and Less Common Metals (UK) supplies the rare earth alloys and strip-cast material that sit between oxide and magnet, a critical and often overlooked bottleneck outside China. Vulcan Elements is building a ~1 million ft² NdFeB facility (10,000 tpa capacity) in Benson, North Carolina, which the company describes as the largest planned outside China (Vulcan Elements 2025).

Ion-Adsorption Clays (Heavy REEs)

Ion-adsorption clays follow a shorter route than hard-rock ore. Because the rare earths are loosely bound to clay surfaces rather than locked inside mineral crystals, this route skips conventional mining, crushing, and beneficiation, and instead recovers the rare earths directly by leaching. It then rejoins the same purification and separation steps as those for hard-rock ore. Extraction from ion-adsorption clays therefore offers substantial environmental and process-efficiency advantages over hard-rock mining, avoiding mining, comminution, and high-temperature cracking entirely, though historical unregulated leaching in southern China caused serious nitrogen and groundwater pollution that newer practice aims to correct (Moldoveanu and Papangelakis 2012). These deposits, concentrated in southern

China (Jiangxi, Guangdong, Fujian), are the world's primary source of the heavy rare earths dysprosium, terbium, and yttrium (Krishnamurthy and Gupta 2016).

In-Situ Leaching: A salt solution, traditionally ammonium sulphate ((NH4)2SO4), is injected into boreholes in the clay deposit. The ammonium ions (NH4+) exchange with the rare earth ions (REE3+) held on the clay surface, releasing the rare earths into solution. The resulting pregnant leach solution is collected from the base of the deposit. Recovery is typically 60% to 80% (Moldoveanu and Papangelakis 2012).

> **R&D:** Several Chinese provinces are mandating a switch from (NH4)2SO4 to MgSO4 leaching to reduce nitrogen runoff into rivers (TRL 7–8, in adoption since 2018 in Jiangxi). Academic groups at Tsinghua University and the Chinese Academy of Sciences have reported similar REE recoveries (60% to 75%) with substantially lower water and reagent footprints. Bio-leaching with organic acids (TRL 2–3) and phytomining (using hyperaccumulator plants like *Phytolacca americana*, TRL 1–2) remain very early-stage and are unlikely to be commercial within this decade (Moldoveanu and Papangelakis, 2012)

Ion-adsorption deposits are also emerging outside China. Myanmar now supplies a large share of China's heavy rare earth feedstock, with significant environmental and governance concerns attached. In Brazil, Serra Verde began commercial production in 2024, the first major ion-adsorption operation outside China and Myanmar, and Meteoric Resources' Caldeira project is under development (USGS 2025). These deposits are strategically important heavy rare earth sources for emerging economies.

Impurity Removal and Purification: The pregnant leach solution is treated to remove iron, aluminum, and other impurities by pH-controlled precipitation before it enters separation, the same approach used with hard-rock ore.

Solvent Extraction (Separation): The purified solution is fed into the same SX circuits described in the section on hard-rock ore, where the individual heavy rare earths are separated at high purity. Because ion-adsorption clays are enriched in heavy rare earths, this route supplies most of the world's dysprosium and terbium for permanent magnets.

Oxide and Metal Production: As in the section on hard-rock ore, the separated solutions are precipitated, calcined to oxides, and where needed reduced to metals for magnet manufacturing.

Cost Considerations

Detailed rare earth processing costs are difficult to obtain because the largest producers—Chinese state-owned groups—do not publicly report per-unit costs. However, MP Materials reported mining and beneficiation operating costs of ~$2,600/t REO in 2023 (MP Materials 2024). Building a full SX separation plant is capital-intensive, with an estimated cost of $200 million to $500 million USD depending on scale and location (SCRREEN2 2023). NdPr oxide, the most commercially important product for permanent magnets, was traded at roughly $55 to $75/kg in 2024, while heavy REE oxides like Dy2O3 ranged from $250 to $350/kg and Tb4O7 reached $800 to $1,200/kg (Adamas Intelligence 2024).

These prices are highly volatile, swinging 30% to 50% year-over-year based on Chinese policy and demand cycles. Beyond capital intensity, ex-China plants also face a structural operating-cost disadvantage: Chinese separators benefit from co-located reagent supply chains,

integrated heavy-RE feed from ion-adsorption clays, and decades of operational learning. Industry analyses often place the ex-China processing cost penalty at roughly 1.5 to 2 times before environmental compliance costs (Baskaran and Schwartz 2023, Adamas Intelligence 2024). This structural gap, not capital alone, is why price floors and offtake guarantees feature in recent Western policy (MP Materials 2025).

KEY R&D OPPORTUNITIES ACROSS THE VALUE CHAIN

Recovery technologies for both lithium and rare earth families have advanced significantly over the past decade, mainly through optimization of conventional technologies. More effective and selective flotation reagents, improved solvent extractants, and better process control have lifted recovery rates and economic viability incrementally (Jordens et al. 2013; Xie et al. 2014; Petrakis et al. 2025). The step-change innovations summarized in this section have mostly emerged at pilot or demonstration scale within the past five years. Table 1 lists the opportunities an identifiable developer or research group with documented pilot- or commercial-scale results. Figure 11 places the same technologies on a technology maturity ladder grouped into the three technology readiness bands defined in the methods section.

A few patterns stand out:

1. Brine and ore-sorting innovations are mostly at or near the implementation band, while rare earth metal and recycling technologies cluster in validation and demonstration.
2. The geographic spread is wider than commonly assumed: outside China, meaningful R&D is happening in Australia, Norway, Canada, the United Kingdom, the United States, and Japan.
3. Several of these technologies (DLE, membrane electrolysis, NdFeB recycling, grain boundary diffusion) are now commercially relevant to procurement decisions, not just academic curiosities.

Ranking these opportunities is necessarily judgment-based, but weighing current readiness (TRL 6 or above), documented cost or environmental benefit, and transferability to new entrants, five stand out following this assessment:

1. **Aluminum-based adsorption DLE:** The only DLE family already commercial across multiple brine chemistries.
2. **Lower-temperature sulfate and chloride roasting for spodumene:** Among the most credible cost and energy levers in hard-rock conversion, with Metso's high-pressure alkaline (soda) leach reaching industrial scale at the Keliber project (2025) and Lithium Australia's SiLeach/LieNA routes at pilot/demonstration scale.
3. **Continuous ion exchange for rare earth separation:** The most advanced solvent-free alternative to SX.
4. **Sensor-based ore sorting:** Commercial today and transferable across commodities.
5. **Membrane electrolysis for direct lithium chemical recovery:** The leading reagent-reduction play. This ranking reflects evidence available as of mid-2026 and will quickly become outdated.

Table 1. Key R&D Opportunities with Credible Momentum

Step/ Domain	R&D Opportunity	Lead Developer/ Academic Entity(s)	Country	TRL	Stage
Brine, DLE	Direct lithium extraction (adsorption/ion exchange / solvent extraction/ membrane)	Sunresin, Rio Tinto (Fénix), Eramet, Lilac Solutions, Standard Lithium	China, Argentina, USA	6–9	Commercial (Al-adsorption)/ pilot
Brine, chemical recovery	Membrane electrolysis: LiCl → LiOH directly	Mangrove Lithium	Canada	6	Pilot
Brine, purification	Nanofiltration for Mg/Li separation	Sunresin, East China University of Science & Tech (academic)	China	5–7	Pilot
Brine, pre-treatment	NMG resins for boron removal	East China University (EUST), Ben-Gurion University (academic)	China, Israel	5–6	Lab/bench
Hard-rock, ore prep	Sensor-based ore sorting (XRT/XRF)	TOMRA, Steinert	Norway, Germany	8–9	Commercial
Hard-rock, roasting	Lower-temperature sulfate/chloride roasting	Lithium Australia (SiLeach, LieNA); Metso (Keliber, high-pressure soda leach)	Australia, Finland	5–8	Pilot/demo; commercial (Keliber 2025)
Hard-rock, chemical recovery	Direct Li2SO4 → LiOH electrolysis	Mangrove Lithium	Canada	6-8	Commercial (Delta 2026)/ scaling
REE, ore prep	Sensor-based ore sorting (pre-concentration)	MP Materials	USA	6–7	Planned (ramp-up 2027)
REE, separation	Solvent-free separation (proprietary)	REEtec	Norway	7	Pilot
REE, separation	Chromatographic, membrane, and MIP separation	ReElement Technologies, Oak Ridge National Laboratory (academic)	USA	3–6	Lab/demo
REE, metal	Molten salt electrolysis (no fluoride flux)	Phoenix Tailings (MIT origin)	USA	7-8	Commercial (Exeter, 2025)/ scaling
REE, magnets*	NdFeB recycling via HPMS	HyProMag, Cyclic Materials, Noveon Magnetics	UK, Canada, USA	6–7	Pilot/commercial
REE, magnets	Grain boundary diffusion to cut Dy use 20% to 50%	Shin-Etsu, TDK	Japan	9	Commercial

**NdFeB recycling is the single secondary-source (recycling) technology included, given its direct commercial relevance to magnet supply chains; all other entries are primary-route technologies.*

Technologies were selected where (a) an identifiable developer or research group is active, (b) pilot- or commercial-scale results are documented or company-reported, and (c) the technology addresses a cost, energy, or environmental constraint identified in Section 3. TRL groupings: TRL 1–3 = early-stage research; TRL 4–6 = validation and demonstration; TRL 7–9 = implementation.

Sources: company press releases and disclosures, including Eramet 2024a; Rio Tinto 2025; Mangrove Lithium 2026a, c, d; TOMRA Mining 2025; SRK Consulting 2026; Steinert 2025; Lithium Australia 2024; REEtec 2022; American Resources Corporation 2022; Phoenix Tailings 2025; HyProMag 2026a; Bunting Dubois 2024; TDK 2026; SCRREEN2 2023; DOE 2023;NRC 2026a; ORNL 2021; University of Birmingham 2023; Tabelin et al. 2021; Farahbakhsh et al. 2024; Razmjou 2024; Adamas Intelligence 2024; Dara and Zahiri 2019; Ramirez 2026; Sun et al. 2015; Lu et al 2023; Bonin et al. 2021; Jorjani et al. 2025; and authors' synthesis.

DISCUSSION

This review maps the most credible R&D opportunities across two of the most strategically important critical mineral value chains: lithium (from both brine and hard-rock spodumene) and rare earth elements (from hard-rock ores and ion-adsorption clays).

We identified more than 25 distinct innovation tracks across these chains, ranging from early-stage research (TRL 1–3; e.g., ionic-liquid extractants, bio-leaching, and phytomining) to fully commercial deployments (TRL 8–9; e.g., sensor-based ore sorting and grain boundary diffusion in NdFeB magnets), as grouped in the three maturity bands shown in Figure 11. The dominant cluster sits at TRL 5–7, the validation-to-demonstration range. This is the middle stage where most technologies either fail or get acquired—not for technical reasons, but because of capital availability and offtake risk.

This review emphasizes that work on processing is quite scattered. We identified pilots and pre-commercial efforts across at least eight countries: Australia, Canada, China, Norway, Japan, the United Kingdom, the United States, and several Latin American operating sites. There is no shared registry or common evaluation framework, and the result is duplication of effort and inconsistent technology claims.

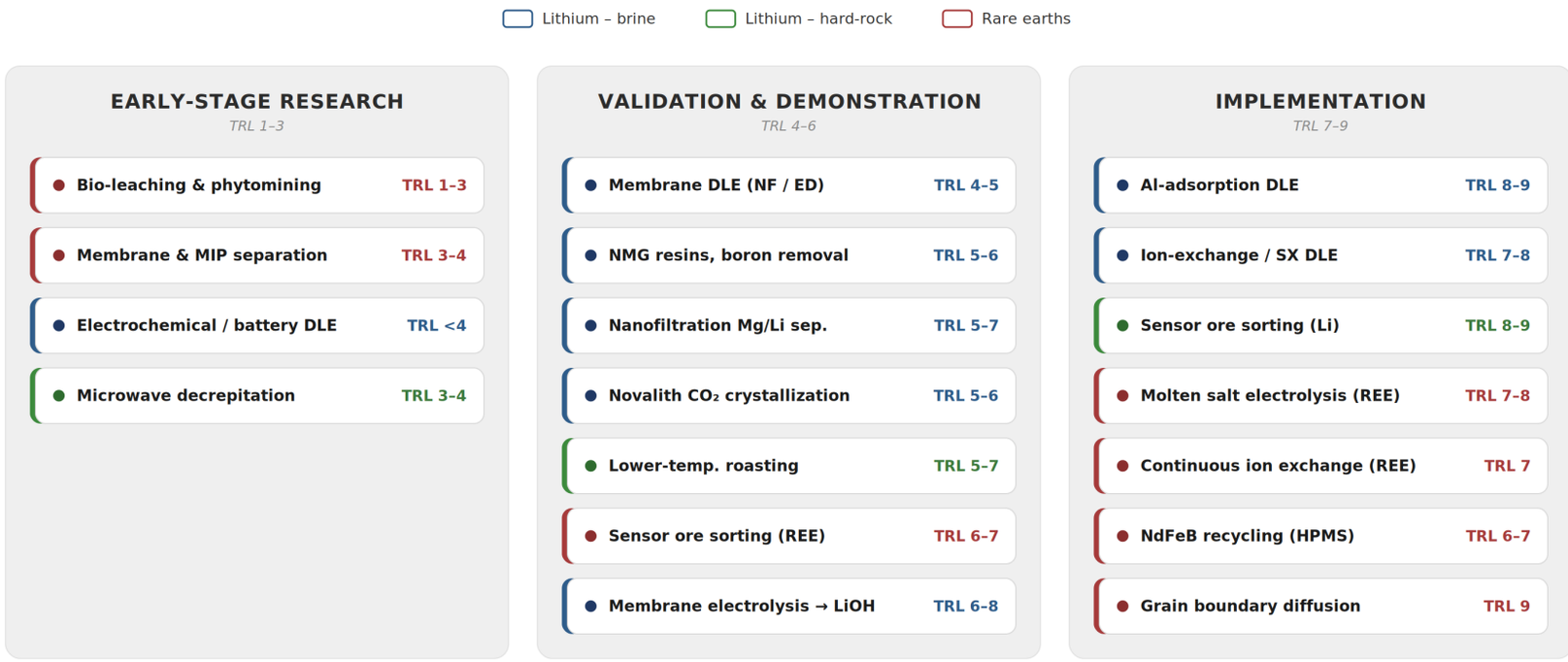
Ultimately, this report identifies three overarching findings:

1. The binding constraint in both chains is midstream processing, and it is economic as well as physical. Capital availability and offtake security, not technical uncertainty, are what hold back the strongest technologies at TRL 5–7.
2. Credible innovation is far more geographically distributed than production itself, spanning at least eight countries, but it is fragmented and would benefit from a shared registry and common evaluation framework.
3. A handful of technologies—led by adsorption-based DLE, lower-temperature roasting, continuous ion exchange, sensor-based sorting, and membrane electrolysis—lower the capital and skill barriers enough to give new entrants, including in the Global South, a realistic path into midstream processing, provided technology transfer is paired with offtake and training support.

CONCLUSION

For emerging economies looking to enter the critical mineral value chain, the implications are mixed. The downstream stages (chemical conversion, solvent extraction, magnet manufacturing) remain capital-intensive and concentrated, which makes leapfrogging difficult. However, several of the most promising R&D opportunities (DLE, sulfate roasting, sensor-based sorting, NdFeB recycling) lower the capital and skill barriers compared to conventional plants, and could enable mineral-rich countries in Africa and Latin America to capture more value than the current export-of-concentrate model allows. This will require deliberate technology transfer, training, and offtake support; the technologies alone do not solve the political-economy bottleneck. We recommend countries and companies within the Global South interested in lithium and rare earth midstream processing to embrace domestic research and development on technologies identified in this review. We also recommend forming new partnerships with companies and labs identified in this review.

Figure 11. Technology maturity ladder for the R&D opportunities reviewed, grouped into early-stage research (TRL 1–3), validation and demonstration (TRL 4–6), and implementation (TRL 7–9)



Note: Chip outline color indicates the value-chain domain.

We acknowledge several limitations. Cost data for Chinese state-owned producers is largely unavailable, which constrains direct cost comparisons across chains. TRL assessments rely on a mix of company self-reporting and academic publication, both of which have known biases. Where the two conflict, we have taken the more conservative value and labeled company-reported claims as such. All technology and project-status assessments reflect information available as of mid-2026 and will quickly become dated in a field moving this fast. Finally, our evidence base skews toward Western, English-language, publicly reporting companies. Substantial Chinese corporate R&D (for example at CATL, BYD, Ganfeng, and the rare earth majors) is not publicly disclosed and is therefore under-represented, which likely understates the global innovation frontier rather than overstating ex-China readiness.

REFERENCES

Abdullah, A. A., B. Z. Dlugogorski, H. C. Oskierski, and G. Senanayake. 2024. "Kinetics of Spodumene Calcination (□-LiAlSi2O6)." Minerals Engineering 216 (September): 108902. https://doi.org/10.1016/j.mineng.2024.108902.

Adamas Intelligence. 2025. Rare Earth Magnet Market Outlook to 2040. Adamas Intelligence. https://www.adamasintel.com/new-report-rare-earth-magnet-market-outlook-to-2040-2/.

Albemarle Corporation. 2024. Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934. Form 10-K. Albemarle Corporation. https://s201.q4cdn.com/960975307/files/doc_financials/2024/ar/ALBEMARLE-CORP_2024_Annual_Report-for-website.pdf.

American Resources Corporation. 2025. "U.S. Department of Defense to Increase Domestic Rare Earth Elements Supply Chain with ReElement Technologies' Advanced Chromatographic Separation Platform." Access Newswire (Fishers, IN), September 9. https://www.accessnewswire.com/newsroom/en/metals-and-mining/u.s.-department-of-defense-to-increase-domestic-rare-earth-elements-supply-chain-1070484.

An, J. W., D. J. Kang, K. T. Tran, M. J. Kim, T. Lim, and T. Tran. 2012. "Recovery of Lithium from Uyuni Salar Brine." Hydrometallurgy 117–118 (April): 64–70. https://doi.org/10.1016/j.hydromet.2012.02.008.

Baskaran, G., and M. Schwartz. 2025. Developing Rare Earth Processing Hubs: An Analytical Approach. Center for Strategic & International Studies. https://www.csis.org/analysis/developing-rare-earth-processing-hubs-analytical-approach.

Bonin, L., D. Deduytsche, M. Wolthers, V. Flexer, and K. Rabaey. 2021. "Boron Extraction Using Selective Ion Exchange Resins Enables Effective Magnesium Recovery from Lithium Rich Brines with Minimal Lithium Loss." Separation and Purification Technology 275 (November): 119177. https://doi.org/10.1016/j.seppur.2021.119177.

Boston Metal. 2026. "Molten Oxide Electrolysis (MOE) for Critical Metals Production." Woburn, MA. https://www.bostonmetal.com/moe-critical-metals/.

Bunting Dubois. 2024. "Grain Boundary Diffusion of Heavy Rare Earth Elements (HREE) in Sintered NdFeB Magnets." Magnet Applications, July 16. https://www.magnetapplications.com/blog/grain-boundary-diffusion-of-heavy-rare-earth-elements-hree-in-sintered-ndfeb-magnets.

CEFC. 2023. CEFC Congratulates Novalith on Series A Raise to Boost Sustainable Lithium Production. (Sydney), April 17. https://www.cefc.com.au/media/media-release/cefc-congratulates-novalith-on-series-a-raise-to-boost-sustainable-lithium-production/.

Chen, Q.-B., Z.-Y. Ji, J. Liu, Y.-Y. Zhao, S.-Z. Wang, and J.-S. Yuan. 2018. "Development of Recovering Lithium from Brines by Selective-Electrodialysis: Effect of Coexisting Cations on the Migration of Lithium." Journal of Membrane Science 548 (February): 408–20. https://doi.org/10.1016/j.memsci.2017.11.040.

Chen, X., M. Yang, S. Zheng, et al. 2023. "Spatially Separated Crystallization for Selective Lithium Extraction from Saline Water." Nature Water 1 (9): 808–17. https://doi.org/10.1038/s44221-023-00131-3.

Chen, X., X. Ruan, S. E. Kentish, G. K. Li, T. Xu, and G. Q. Chen. 2021. "Production of Lithium Hydroxide by Electrodialysis with Bipolar Membranes." Separation and Purification Technology 274 (November): 119026. https://doi.org/10.1016/j.seppur.2021.119026.

Cook, B. K., and C. E. Gibson. 2023. "A Review of Fatty Acid Collectors: Implications for Spodumene Flotation." Minerals 13 (2): 212. https://doi.org/10.3390/min13020212.

Cyclic Materials. 2026. "Recycling Rare Earth Elements and Critical Minerals." https://cyclicmaterials.earth/.

Dara, S., and B. Zahiri. 2021. Li recovery processes and onsite chemical production for li recovery processes. Patent WO2020128619A1, filed December 19, 2019, and issued August 5, 2021. https://patents.google.com/patent/WO2020128619A1/en.

Deloitte. 2023. Direct Lithium Extraction: Revolutionary Potential Still to Be Proven in the Field. https://www.deloitte.com/content/dam/assets-shared/docs/collections/2023/gx-greenspace-tech-research-direct-lithium-extraction.pdf.

DOE. 2023. 2023 DOE Critical Materials Assessment. US Department of Energy. https://www.energy.gov/cmei/ammto/articles/2023-doe-critical-materials-assessment.

Energy Fuels. 2025. Energy Fuels Announces 2024 Results, Including Active U.S. Uranium Mining, Uranium and Mineral Sand Sales, Commercial U.S. Rare Earth Production, and Strong Balance Sheet. (Denver), February 27. https://investors.energyfuels.com/2025-02-27-Energy-Fuels-Announces-2024-Results,-Including-Active-U-S-Uranium-Mining,-Uranium-and-Mineral-Sand-Sales,-Commercial-U-S-Rare-Earth-Production,-and-Strong-Balance-Sheet.

EPA. 2026. "Scope 1 and Scope 2 Inventory Guidance." EPA Center for Corporate Climate Leadership, US Environmental Protection Agency. https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance.

Eramet. 2024a. "Eramet Inaugurates Its Direct Lithium Extraction Plant in Argentina, Becoming the First European Company to Produce Battery-Grade Lithium Carbonate at Industrial Scale." (Paris), July 3. https://www.eramet.com/en/news/eramet-delivers-first-lithium-carbonate-from-centenario-dle-plant-in-argentina/.

Eramet. 2024b. "Eramet Delivers First Lithium Carbonate from Centenario DLE Plant in Argentina." (Paris), December 24. https://www.eramet.com/en/news/eramet-delivers-first-lithium-carbonate-from-centenario-dle-plant-in-argentina/.

European Commission. 2014. "G. Technology Readiness Levels (TRL)." In Horizon 2020 Work Programme 2014-2015. https://www.cesaer.org/content/10-library/2021/technology-readiness-level/h2020-wp1415-annex-g-trl-en.pdf.

Farahbakhsh, J., F. Arshadi, Z. Mofidi, et al. 2024. "Direct Lithium Extraction: A New Paradigm for Lithium Production and Resource Utilization." Desalination 575 (April): 117249. https://doi.org/10.1016/j.desal.2023.117249.

Flexer, V., C. F. Baspineiro, and C. I. Galli. 2018. "Lithium Recovery from Brines: A Vital Raw Material for Green Energies with a Potential Environmental Impact in Its Mining and Processing." Science of The Total Environment 639 (October): 1188–204. https://doi.org/10.1016/j.scitotenv.2018.05.223.

Gao, T.-M., N. Fan, W. Chen, and T. Dai. 2023. "Lithium Extraction from Hard Rock Lithium Ores (Spodumene, Lepidolite, Zinnwaldite, Petalite): Technology,

Resources, Environment and Cost." China Geology 6 (1): 137–53. https://doi.org/10.31035/cg2022088.
Giurco, D., B. McLellan, D. M. Franks, K. Nansai, and T. Prior. 2014. "Responsible Mineral and Energy Futures: Views at the Nexus." Journal of Cleaner Production 84 (December): 322–38. https://doi.org/10.1016/j.jclepro.2014.05.102.Gutfleisch, O., M. A. Willard, E. Brück, C. H. Chen, S. G. Sankar, and J. P. Liu. 2011. "Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient." Advanced Materials 23 (7): 821–42. https://doi.org/10.1002/adma.201002180.
Gutfleisch, O., M. A. Willard, E. Brück, C. H. Chen, S. G. Sankar, and J. P. Liu. 2011. "Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient." Advanced Materials 23 (7): 821–42. https://doi.org/10.1002/adma.201002180.
Hund, K., D. La Porta, T. P. Fabregas, T. Laing, and J. Drexhage. 2023. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank. https://doi.org/10.1596/40002.
HyProMag. 2026a. "About the Company." https://hypromag.com/about/.
HyProMag. 2026b. "UK Minister for Industry Officially Opens Rarae Earth Magnet Recycling and Manufacturing Facility at Tyseley Energy Park, Birmingham." Dallas-Fort Worth, January 15. https://hypromagusa.com/uk-minister-for-industry-officially-opens-rare-earth-magnet-recycling-and-manufacturing-facility-at-tyseley-energy-park-birmingham/.
IEA. 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency. https://www.iea.org/reports/net-zero-by-2050.
IEA. 2023. Critical Minerals Market Review 2023. International Energy Agency. https://www.iea.org/reports/critical-minerals-market-review-2023.
IEA. 2024. Global Critical Minerals Outlook 2024. International Energy Agency. https://www.iea.org/reports/global-critical-minerals-outlook-2024.
IEA. 2025. Global Critical Minerals Outlook 2025. International Energy Agency. https://www.iea.org/reports/global-critical-minerals-outlook-2025.
IGO Limited. 2024. Annual Report 2024. https://www.igo.com.au/site/pdf/db560842-6410-48a5-a911-3e45093eb372/2024-Annual-Report.pdf.
IPCC. 2018. Global Warming of 1.5oC. International Panel on Climate Change. https://www.ipcc.ch/sr15/.
Jordens, A., Y. P. Cheng, and K. E. Waters. 2013. "A Review of the Beneficiation of Rare Earth Element Bearing Minerals." Minerals Engineering 41 (February): 97–114. https://doi.org/10.1016/j.mineng.2012.10.017.
Jorjani, E., J. Sauvageau, D. Mrabet, and M. Rejeb. 2025. "Advances in Lithium Extraction from Spodumene: Alternatives to Sulfuric Acid Digestion." Minerals 15 (6): 574. https://doi.org/10.3390/min15060574.
Karrech, A., M. R. Azadi, M. Elchalakani, M. A. Shahin, and A. C. Seibi. 2020. "A Review on Methods for Liberating Lithium from Pegmatites." Minerals Engineering 145 (January): 106085. https://doi.org/10.1016/j.mineng.2019.106085.
Khalil, A., S. Mohammed, R. Hashaikeh, and N. Hilal. 2022. "Lithium Recovery from Brine: Recent Developments and Challenges." Desalination 528 (April): 115611. https://doi.org/10.1016/j.desal.2022.115611.

Kim, W., I. Bae, S. Chae, and H. Shin. 2009. “Mechanochemical Decomposition of Monazite to Assist the Extraction of Rare Earth Elements.” Journal of Alloys and Compounds 486 (1–2): 610–14. https://doi.org/10.1016/j.jallcom.2009.07.015.
Krishnamurthy, N., and C. K. Gupta. 2016. Extractive Metallurgy of Rare Earths. 2nd ed. CRC Press. https://www.routledge.com/Extractive-Metallurgy-of-Rare-Earths/Krishnamurthy-Gupta/p/book/9781466576346.
Kumari, A., R. Panda, M. K. Jha, J. R. Kumar, and J. Y. Lee. 2015. “Process Development to Recover Rare Earth Metals from Monazite Mineral: A Review.” Minerals Engineering 79 (August): 102–15. https://doi.org/10.1016/j.mineng.2015.05.003.
Lagos, G., L. Cifuentes, D. Peters, L. Castro, and J. M. Valdés. 2024. “Carbon Footprint and Water Inventory of the Production of Lithium in the Atacama Salt Flat, Chile.” Environmental Challenges 16 (August): 100962. https://doi.org/10.1016/j.envc.2024.100962.
Lanxess. n.d. “Ion Exchange Resins for the Mining and Metallurgy Industry.” https://lanxess.com/en/products/brands/lewatit/industries/mining-and-metallurgy.
Liu, T., K. R. Johnson, S. Jansone-Popova, and D.-e. Jiang. 2022. “Advancing Rare-Earth Separation by Machine Learning.” JACS Au 2 (6): 1428–34. https://doi.org/10.1021/jacsau.2c00122.
López Steinmetz, R. L., and S. Salvi. 2021. “Brine Grades in Andean Salars: When Basin Size Matters A Review of the Lithium Triangle.” Earth-Science Reviews 217 (June): 103615. https://doi.org/10.1016/j.earscirev.2021.103615.
Lu, M., L. Shao, Y. Yang, and P. Li. 2023. “Simultaneous Recovery of Lithium and Boron from Brine by the Collaborative Adsorption of Lithium-Ion Sieves and Boron Chelating Resins.” Industrial & Engineering Chemistry Research 62(3): 1508–22. https://doi.org/10.1021/acs.iecr.2c03650.
Lynas Rare Earths. 2024. 2024 Annual Report. Lynas Rare Earths. https://lynasrareearths.com/investors-media/reporting-centre/annual-reports/.
Lyon, K. L., M. M. Warner, M. R. Greenhalgh, et al. 2023. “Intra-Lanthanide Separation Processes Using Neutral Diglycolamide Extractants.” Paper presented at 9th International Symposium on Hydrometallurgy 2023, Phoenix, AZ. https://impact.ornl.gov/en/publications/intra-lanthanide-separation-processes-using-neutral-diglycolamide/.
M.S., S., T. Elmakki, S. Zavahir, et al. 2024. “Enhanced Lithium Separation from Brines Using Nanofiltration (NF) Technology: A Review.” Desalination 592 (December): 118148. https://doi.org/10.1016/j.desal.2024.118148.
Mangrove Lithium. 2026a. “Lithium Refining for Hard Rock Li Producers.” https://www.mangrovelithium.com/our-customers/hard-rock-li-refining/.
Mangrove Lithium. 2026b. “Our New Lithium Refining Process: How It Works.” https://www.mangrovelithium.com/lithium-refining-process/.
Mangrove Lithium. 2026c. Mangrove Lithium Opens North America’s First Commercial Electrochemical Lithium Refining Facility. (Delta, British Columbia), April 16. https://www.mangrovelithium.com/mangrove-lithium-opens-north-americas-first-commercial-electrochemical-lithium-refining-facility/.
Mangrove Lithium. 2026d. “Mangrove Lithium.” https://www.mangrovelithium.com/.

Marinova, S., L. Roche, A. Link, and M. Finkbeiner. 2025. “Water Footprint of Battery-Grade Lithium Production in the Salar de Atacama, Chile.” Journal of Cleaner Production 487 (January): 144635. https://doi.org/10.1016/j.jclepro.2024.144635.

Menser, P. 2020. “Peculiar Fluids Offer Clean Alternative to Traditional Rare Earth Separation.” Idaho National Laboratory (Idaho Falls, ID), June 8. https://inl.gov/feature-story/rare-earth-element-separation/.

Meshram, P., B. D. Pandey, and T. R. Mankhand. 2014. “Extraction of Lithium from Primary and Secondary Sources by Pre-Treatment, Leaching and Separation: A Comprehensive Review.” Hydrometallurgy 150 (December): 192–208. https://doi.org/10.1016/j.hydromet.2014.10.012.

Mineral Resources. 2024. 2024 Annual Report. Osborne Park, Australia. https://www.mineralresources.com.au/investor-centre/annual-reporting-suite/.

Moldoveanu, G. A., and V. G. Papangelakis. 2012. “Recovery of Rare Earth Elements Adsorbed on Clay Minerals: I. Desorption Mechanism.” Hydrometallurgy 117–118 (April): 71–78. https://doi.org/10.1016/j.hydromet.2012.02.007.

Mousavinezhad, S., S. Nili, R. Fahimi, and E. Vahidi. 2024. “Environmental Impact Assessment of Direct Lithium Extraction from Brine Resources: Global Warming Potential, Land Use, Water Consumption, and Charting Sustainable Scenarios.” Resources, Conservation and Recycling 205 (June): 107583. https://doi.org/10.1016/j.resconrec.2024.107583.

MP Materials. 2024. Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934. Form 10-K. Las Vegas. https://s201.q4cdn.com/960975307/files/doc_financials/2024/ar/ALBEMARLE-CORP_2024_Annual_Report-for-website.pdf.

MP Materials. 2025. MP Materials Announces Transformational Public-Private Partnership with the Department of Defense to Accelerate U.S. Rare Earth Magnet Independence. (Las Vegas), July 10. https://investors.mpmaterials.com/investor-news/news-details/2025/MP-Materials-Announces-Transformational-Public-Private-Partnership-with-the-Department-of-Defense-to-Accelerate-U-S--Rare-Earth-Magnet-Independence/default.aspx.

Munk, L. A., S. A. Hynek, D. C. Bradley, D. Boutt, K. Labay, and H. Jochens. 2016. “Lithium Brines: A Global Perspective.” In Rare Earth and Critical Elements in Ore Deposits, edited by P. L. Verplanck and M. W. Hitzman. Society of Economic Geologists. https://doi.org/10.5382/Rev.18.14.

Neo Performance Materials. 2025. Neo Performance Materials Reports Fourth Quarter and Full Year 2024 Results. (Toronto), March 18. https://www.neomaterials.com/neo-reports-fourth-quarter-2024-results/.

Novalith. 2023. “Novalith Technologies Raises AU$23 Million in Series A Funding to Revolutionise Lithium Production.” (Sydney), April 17. https://www.novalith.com.au/news/novalith-technologies-raises-au-23-million-in-series-a-funding-to-revolutionise-lithium-production.

Noveon Magnetics. 2026. “Noveon Magnetics Completes $215 Million Series C to Expand U.S. Rare Earth Magnet Manufacturing Capacity.” PR Newswire (San Marcos, TX), January 19. https://www.prnewswire.com/news-releases/noveon-magnetics-completes-215-million-series-c-to-expand-us-rare-earth-magnet-manufacturing-capacity-302664196.html.

NRC. 2026a. “Backgrounder: Government of Canada Invests to Unlock Canada’s Critical Minerals Advantage.” Natural Resources Canada. https://www.canada.ca/en/natural-resources-canada/news/2026/03/backgrounder-government-of-canada-invests-to-unlock-canadas-critical-minerals-advantage.html.

NRC. 2026b. “Government of Canada Supports Mangrove Lithium’s next Step in Building a Made-in-Canada Battery Supply Chain.” (Delta, British Columbia), April 16. https://www.canada.ca/en/natural-resources-canada/news/2026/04/government-of-canada-supports-mangrove-lithiums-next-step-in-building-a-made-in-canada-battery-supply-chain.html.

Opoku, P. A., B. Tadesse, B. Albijanic, and A. N. Nikoloski. 2025. “An Overview of Coarse Particle Beneficiation of Lithium Ores.” Scientific Reports 15 (1): 29091. https://doi.org/10.1038/s41598-025-14059-z.

Palacios, N. A., J. R. Lezama, E. Erdmann, and V. Flexer. 2026. “Calculations on Chemicals, Water, and Energy Consumption for the Evaporitic Process for Lithium Carbonate Recovery from Brines: A Baseline for Technology and Environmental Impact Assessment.” Industrial & Engineering Chemistry Research 65 (9): 4681–702. https://doi.org/10.1021/acs.iecr.5c05085.

Peltosaari, O., P. Tanskanen, E.-P. Heikkinen, and T. Fabritius. 2015. “□→□→□-Phase Transformation of Spodumene with Hybrid Microwave and Conventional Furnaces.” Minerals Engineering 82 (October): 54–60. https://doi.org/10.1016/j.mineng.2015.04.012.

Petrakis, E., I. Alexopoulos, O. Pantelaki, V. Karmali, and K. Komnitsas. 2025. “Advances in Mineral Processing of Hard-Rock Lithium Ores: A Comprehensive Review.” Mining, Metallurgy & Exploration 42 (3): 1251–83. https://doi.org/10.1007/s42461-025-01227-y.

Phoenix Tailings. 2025. “Phoenix Tailings Opens Cutting-Edge U.S. Rare Earth Metallization Facility Entirely Independent From China.” (Exeter, NH), October 23. https://phoenixtailings.com/press/phoenix-tailings-opens-cutting-edge-u-s-rare-earth-metallization-facility-entirely-independent-from-china.

Pilbara Minerals. 2024. Annual Report 2024: Powering a Sustainable Energy Future. https://1pls.irmau.com/site/pdf/a6148fec-a633-4aa7-ab4f-a251fddb8507/2024-Annual-Report-incorporating-Appendix-4E.pdf.

Poore, C. 2025. Princeton Startup Tackles Soaring Demand for Lithium and Other Critical Minerals. (Princeton, NJ), May 9. https://www.princeton.edu/news/2025/05/09/princeton-startup-tackles-soaring-demand-lithium-and-other-critical-minerals.

Qi, J., J. Tu, X. Xie, H. Wang, and R. Xie. 2025. “Flotation Enhancement of Spodumene with a □-Amino-Hydroxamate Surfactants.” Applied Surface Science 686 (March): 162166. https://doi.org/10.1016/j.apsusc.2024.162166.

Qu, Y., H. Li, X. Wang, et al. 2019. “Bioleaching of Major, Rare Earth, and Radioactive Elements from Red Mud by Using Indigenous Chemoheterotrophic Bacterium Acetobacter Sp.” Minerals 9 (2): 67. https://doi.org/10.3390/min9020067.

Ramirez, V. B. 2026. “New Path to Battery-Grade Lithium Uses Electrochemistry.” IEEE Spectrum (New York), February 26.

Rasoulnia, P., R. Barthen, and A.-M. Lakaniemi. 2021. “A Critical Review of Bioleaching of Rare Earth Elements: The Mechanisms and Effect of Process Parameters.” Critical Reviews in Environmental Science and Technology 51 (4): 378–427. https://doi.org/10.1080/10643389.2020.1727718.

Razmjou, A. 2024. Direct Lithium Extraction (DLE): An Introduction. International Lithium Association. https://lithium.org/wp-content/uploads/2024/06/Direct-Lithium-Extraction-DLE-An-introduction-ILiA-June-2024-v.1-English-web.pdf.

Rio Tinto. 2025. “Rio Tinto Completes Acquisition of Arcadium Lithium.” Business Wire, March. https://www.riotinto.com/en/news/releases/2025/rio-tinto-completes-acquisition-of-arcadium-lithium.

Rioyo, J., S. Tuset, and R. Grau. 2022. “Lithium Extraction from Spodumene by the Traditional Sulfuric Acid Process: A Review.” Mineral Processing and Extractive Metallurgy Review 43 (1): 97–106. https://doi.org/10.1080/08827508.2020.1798234.

S&P Global. 2019. “Lithium Sector: Production Costs Outlook.” S&P Global Market Intelligence. https://pages.marketintelligence.spglobal.com/lithium-sector-outlook-costs-and-margins-confirmation-CD.html.

S&P Global. 2025. Lithium Sector: Production Costs Outlook. S&P Global Commodity Insights. https://www.spglobal.com/content/dam/spglobal/ci/en/documents/products/pdf/CI_0825-Global-CEH-Lithium-Lithium-Minerals-Lithium-Chemicals-Abstract.pdf?utm_source=chatgpt.com.

Salakjani, N. K., P. Singh, and A. N. Nikoloski. 2021. “Production of Lithium –A Literature Review. Part 2. Extraction from Spodumene.” Mineral Processing and Extractive Metallurgy Review 42 (4): 268–83. https://doi.org/10.1080/08827508.2019.1700984.

SCRREEN. 2023. “Critical Raw Materials Factsheets 2023.” BRGM, France. https://scrreen.eu/crms-2023/.

SQM. 2023. Sustainability Report 2023. https://sqm-ynv.com/wp-content/uploads/2025/05/SQM-Reporte-2023_Ingles_vff_baja.pdf.

SQM. 2024a. Annual Report 2024. https://ir.sqm.com/system/files-encrypted/nasdaq_kms/assets/2025/06/12/2-37-42/MEMORIA%20SQM%202024_eng.pdf.

SQM. 2024b. Sustainability Report 2024. https://ir.sqm.com/static-files/f0432736-0ae4-432d-9262-b2163e3de49a.

SRK Consulting. 2026. SEC Technical Report Summary 2025 S-K 1300 TRS Update Mountain Pass Mine San Bernardino County, California. MP Materials. https://www.sec.gov/Archives/edgar/data/1801368/000180136826000008/mpmcexhibit961123125.htm.

Stamberga, D., M. R. Healy, V. S. Bryantsev, et al. 2020. “Structure Activity Relationship Approach toward the Improved Separation of Rare-Earth Elements Using Diglycolamides.” Inorganic Chemistry 59 (23): 17620–30. https://doi.org/10.1021/acs.inorgchem.0c02861.

Stausholm, J. 2024. “Acquisition of Arcadium Lithium.” October 9. https://www.riotinto.com/en/invest/presentations/2024/acquisition-of-arcadium-lithium.

Steinert. 2025. “Steinert in Brazilian Lithium Valley: Sensor-Based Sorting Technology to Optimize the Spodumene Concentration.” (Cologne, Germany), August 28. https://steinertglobal.com/company/news/news-detail/steinert-in-brazilian-lithium-valley-sensor-based-sorting-technology-to-optimize-the-spodumene-concentration/.

Sun, Shu-Ying, Li-Juan Cai, Xiao-Yao Nie, Xingfu Song, and Jian-Guo Yu. 2015. “Separation of Magnesium and Lithium from Brine Using a Desal Nanofiltration Membrane.” Journal of Water Process Engineering 7 (September): 210–17. https://doi.org/10.1016/j.jwpe.2015.06.012.

Sunresin. 2022. “Sunresin’s 4000t/a Jintai Salt Lake Lithium Extraction Project Put into Operation.” (Xi’an, Shaanxi, China). https://www.seplite.com/sunresin-s-4000t-a-jintai-salt-lake-lithium-extraction-project-put-into-operation/.

Tabelin, C. B., J. Dallas, S. Casanova, et al. 2021. “Towards a Low-Carbon Society: A Review of Lithium Resource Availability, Challenges and Innovations in Mining, Extraction and Recycling, and Future Perspectives.” Minerals Engineering 163 (March): 106743. https://doi.org/10.1016/j.mineng.2020.106743.

Tadesse, B., F. Makuei, B. Albijanic, and L. Dyer. 2019. “The Beneficiation of Lithium Minerals from Hard Rock Ores: A Review.” Minerals Engineering 131 (January): 170–84. https://doi.org/10.1016/j.mineng.2018.11.023.

TDK. 2026. “Magnets.” https://product.tdk.com/en/products/magnet/index.html.

Tianqi Lithium. 2025. 2024 Annual Report. https://www1.hkexnews.hk/listedco/listconews/sehk/2025/0429/2025042901173.pdf.

TOMRA Mining. 2025. “TOMRA Mining’s Advanced Sorting Technology Used in the World’s Largest Lithium Ore Sorting Plant at Pilbara Minerals’ Pilgangoora Operation.” (Western Australia), January 9. https://www.tomra.com/mining/media-center/news/2025/pilbara---lithium-sorting-plant.

Tsao, C.-Y., Y. Ding, and N.-W. L. Wang. 2025. “Three-Zone Ligand-Assisted Displacement (LAD) Chromatography Method for Producing High-Purity Neodymium, Praseodymium, Cerium, and Lanthanum from Mineral Concentrates.” Separation and Purification Technology 376 (December): 133947. https://doi.org/10.1016/j.seppur.2025.133947.

Ucore. n.d. “RapidSX.” https://ucore.com/rapidsx/.

UNCC. 2021. The Paris Agreement. United Nations Climate Change. https://unfccc.int/process-and-meetings/the-paris-agreement.

USA Rare Earth (2025). Company overview. https://www.usare.com

University of Birmingham. 2023. “First Production of Recycled Magnets at Tyseley Energy Park, Birmingham.” (Birmingham, UK), December 19. https://www.birmingham.ac.uk/news/2023/first-production-of-recycled-magnets-at-tyseley-energy-park-birmingham.

USGS. 2025. Mineral Commodity Summaries 2025. US Geological Survey. https://doi.org/10.3133/mcs2025.

USGS. 2026. Mineral Commodity Summaries 2026. US Geological Survey. https://doi.org/10.3133/mcs2026.

Vulcan Elements. 2025. “Vulcan Elements Selects Benson, North Carolina, for $1 Billion Magnet Facility.” PR Newswire, November 18. https://www.prnewswire.com/news-releases/vulcan-elements-selects-benson-north-carolina-for-1-billion-magnet-facility-302619130.html.

Wilkomirsky, I. 1999. Production of lithium carbonate from brines. Patent US5993759A, filed March 28, 1997, and issued November 30, 1999. https://patents.google.com/patent/US5993759A/en.

Xie, F., T. A. Zhang, D. Dreisinger, and F. Doyle. 2014. “A Critical Review on Solvent Extraction of Rare Earths from Aqueous Solutions.” Minerals Engineering 56 (February): 10–28. https://doi.org/10.1016/j.mineng.2013.10.021.

Yang, M., et al. 2023. “Spatially Separated Crystallization for Selective Lithium Extraction from Saline Water.” Nature Water 1 (September) doi:10.1038/s44221-023-00131-3.

Yersaiynova, A. A., Z. B. Karshyga, N. A. A. Muhammad, A. M. Yessengaziyev, and B. M. Orynbayev. 2026. “Lithium Extraction Methods and Its Application Prospects: A Review.” Complex Use of Mineral Resources 337 (2): 95–107. https://doi.org/10.31643/2026/6445.21.

Zhang, T., W. Zheng, Q. Wang, Z. Wu, and Z. Wang. 2023. “Designed Strategies of Nanofiltration Technology for Mg2+/Li+ Separation from Salt-Lake Brine: A Comprehensive Review.” Desalination 546 (January): 116205. https://doi.org/10.1016/j.desal.2022.116205.

Zhou, L., F. Zhang, et al. 2025. “Research Progress on the Alkaline Medium Decomposition Process of Rare Earth Concentrates.” ACS Omega 10 (23): 23904–23925. https://doi.org/10.1021/acsomega.5c00818.