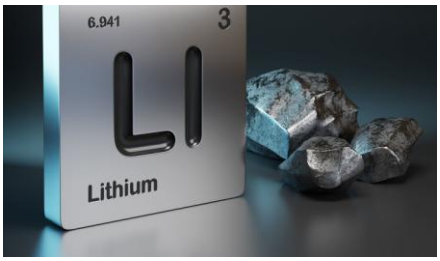
Lithium Extraction from Conventional and Emerging Sources

Geological origin, lithium concentration, extraction technologies and production of battery-grade lithium compounds



Abstract

Lithium has become a strategic raw material because of its role in rechargeable batteries for electric vehicles, stationary energy storage and portable electronics. Industrial lithium supply has historically relied on two dominant resource families: continental brines hosted in endorheic salt flats and hard-rock pegmatites, principally spodumene. Rapid growth in battery demand is now accelerating the evaluation of additional sources, including lithium-bearing clays, geothermal brines, oil and gas produced waters, desalination brines, mine waters and battery recycling streams. This review compares these sources from a process-engineering perspective. It describes their geological origin, typical lithium concentrations, key impurity matrices, current extraction routes and the downstream conversion steps required to obtain commercial lithium carbonate, lithium hydroxide monohydrate, lithium chloride and spodumene concentrate. The analysis shows that lithium concentration alone is not sufficient to define project viability. Selectivity against magnesium, calcium, sodium, potassium, boron, silica, iron and organic contaminants, together with flow availability, water balance, energy integration, reagent consumption, brine reinjection and final product specification, are often decisive. Conventional solar evaporation remains competitive in selected arid salars with favourable chemistry, while hard-rock processing offers a robust but energy- and reagent-intensive supply chain. Direct lithium extraction (DLE) can shorten production time and improve recovery from complex brines, but commercial performance depends on sorbent lifetime, impurity tolerance, regeneration chemistry and treatment of the concentrated eluate. Emerging clay, geothermal and oilfield routes may diversify supply if they can be integrated into closed-loop water, brine and residue management systems.

Keywords: lithium; brines; salars; spodumene; clays; geothermal brines; produced water; direct lithium extraction; lithium carbonate; lithium hydroxide; battery materials.

Currently Lithium sources:

Hard rock lithium ore (*Pegmatites*)

Spodumene ($LiAlSi_2O_6$)

Lithium clays

Lithium salt flats (salar)

Lithium in geothermal brines

Lithium in Produced water

Highlights

- Lithium resources span aqueous brines, mineral deposits, clay-rich sediments and secondary recycling streams.
- For brines, lithium recovery is controlled by matrix selectivity, not only by Li concentration.
- DLE can reduce process time from months to hours or days, but eluate concentration and impurity control remain essential.
- Hard-rock and clay routes require mineral activation or leaching, generating energy, reagent and residue-management challenges.
- Battery-grade Li2CO3 and LiOH·H2O production is a purification and crystallization problem as much as an extraction problem.

Table 1. Abbreviations and units used in this article.

Abbreviation	Meaning
DLE	Direct lithium extraction
DMS	Dense media separation
ED / EDR	Electrodialysis / electrodialysis reversal
LCE	Lithium carbonate equivalent
Li2CO3	Lithium carbonate
LiOH·H2O	Lithium hydroxide monohydrate
NF / RO	Nanofiltration / reverse osmosis
SC6	Spodumene concentrate containing approximately 6% Li2O
TDS	Total dissolved solids

Graphical abstract

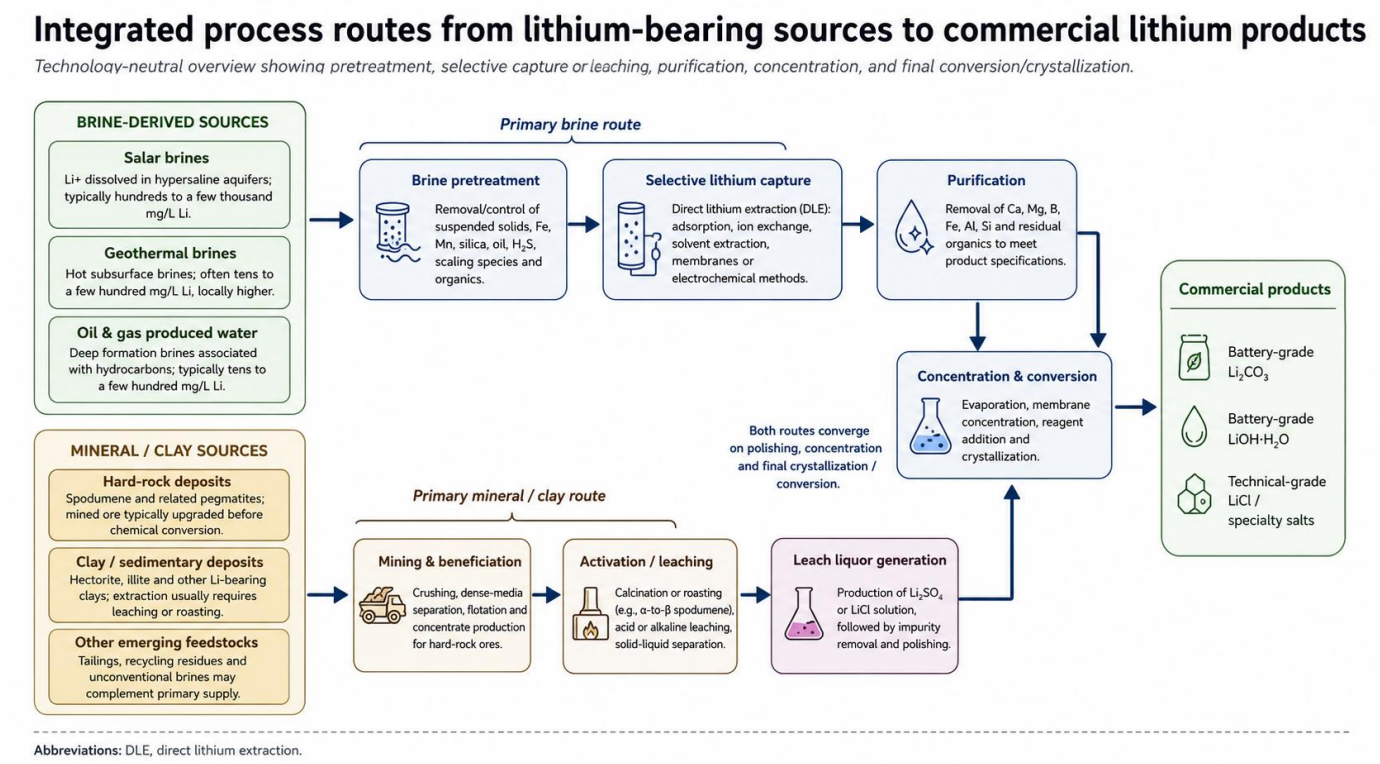


Figure 1. Integrated process routes from lithium-bearing brines and minerals to commercial lithium products. The scheme emphasizes pretreatment, selective capture or leaching, purification, concentration and product crystallization.

1. Introduction: market context and strategic relevance

Lithium is the lightest metal and a highly reactive alkali element. In nature it does not occur as native metal; it is present in silicate minerals, clay minerals and dissolved ionic species in brines. Its industrial importance is based on the electrochemical performance of lithium compounds in rechargeable batteries, but lithium is also used in ceramics and glass, lubricating greases, air treatment, continuous casting fluxes and pharmaceuticals. The 2026 lithium summary of the U.S. Geological Survey (USGS) estimated global end uses in 2025 as 88% batteries, 4% ceramics and glass, 2% lubricating greases and smaller shares in air treatment, casting fluxes, medical uses and other applications [1].

Lithium supply has shifted from a specialty-chemical market to a strategic material supply chain. USGS estimated that world mine production, excluding withheld U.S. production, rose to about 290,000 t of lithium content in 2025, while measured and indicated world resources reached approximately 150 million t of Li [1]. The International Energy Agency (IEA) reports that demand for lithium grew strongly in 2024 and identifies lithium as one of the critical minerals most exposed to clean-energy demand growth, price volatility and supply concentration [2].

The central engineering question is therefore not whether lithium exists in the Earth's crust or in brines. It is whether a specific resource can be converted into a battery-grade product under acceptable economic, environmental and permitting conditions. A brine containing 200 mg/L Li may be attractive if the flow is massive, the Mg/Li ratio is low, and reinjection is possible; the same concentration may be uneconomic if silica, iron, hydrocarbons or scale-forming salts dominate. Conversely, a mineral deposit with several percent Li2O may still require costly mining, comminution, thermal activation, acid leaching and residue management.

This article reviews the main and emerging sources of lithium and compares their process routes in a format suitable for technical publication. It focuses on the interface between geochemistry and process engineering: geological origin, concentration range, impurity matrix, extraction method, concentration strategy and final conversion to commercial lithium compounds.

2. Commercial lithium forms and useful conversions

Lithium projects are frequently compared using lithium content (Li), lithium carbonate equivalent (LCE), lithium carbonate (Li2CO3), lithium hydroxide monohydrate (LiOH·H2O), lithium chloride (LiCl) and spodumene concentrate grades expressed as Li2O. These units are not interchangeable without stoichiometric conversion.

Battery-grade specifications are more stringent than chemical-grade specifications. Li2CO3 and LiOH·H2O used in cathode precursor production generally require very high purity, typically above 99.5%, and tight limits for Na, K, Ca, Mg, Fe, Al, B, sulfate, chloride, moisture and insoluble matter. As a result, final purification and crystallization may control plant design as strongly as the primary extraction step.

Table 2. Stoichiometric conversion factors for lithium products and reporting units.

Basis	Conversion factor	Interpretation / use
1 t Li	5.323 t Li2CO3 (LCE)	Converts lithium content into lithium carbonate equivalent.
1 t Li2CO3	0.188 t Li	Lithium content in pure lithium carbonate.
1 t LiOH·H2O	0.165 t Li; 0.881 t LCE	Lithium hydroxide monohydrate basis for many high-nickel cathode chemistries.
1 t Li2O	0.465 t Li; 2.47 t LCE	Useful for ore and spodumene concentrate grades.
6% Li2O concentrate	approx. 2.8% Li	Typical commercial spodumene concentrate specification, often referred to as SC6.

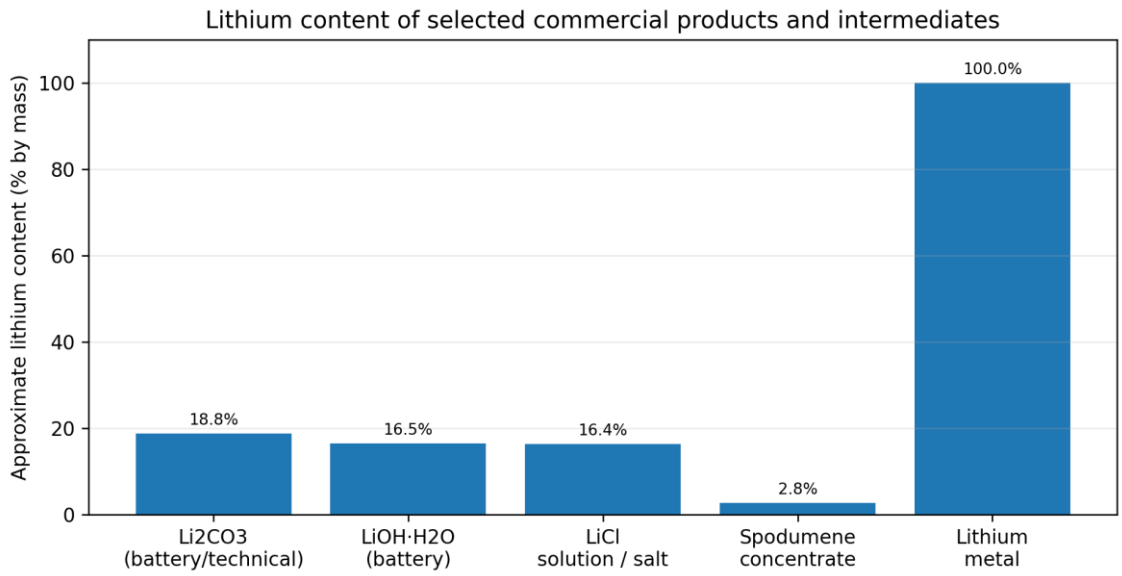


Figure 2. Lithium content of selected commercial products and intermediates. Values are theoretical or typical approximations and do not replace product specifications.

3. Lithium resource types and geochemical occurrence

Lithium resources can be divided into aqueous matrices and solid matrices. Aqueous matrices are generally reported in mg/L Li; solid matrices are reported as % Li, % Li2O or mg/kg Li. Direct comparison requires caution because the process economics of a brine depend heavily on flow rate and chemistry, while the economics of a mineral deposit depend on mining method, grade, liberation, beneficiation, activation and leaching behaviour.

The following subsections summarize the principal sources now considered in industry: salar brines, hard-rock pegmatites, lithium-bearing clays, geothermal brines, oilfield brines and several new or secondary sources such as desalination brines and battery recycling streams.

Table 3. Comparison of lithium sources, origin, concentration range and process maturity.

Source	Geological / industrial origin	Indicative Li concentration	Main matrix issues	Industrial maturity
Salar brines	Closed-basin evaporitic aquifers fed by weathering of volcanic and granitic rocks; concentrated by arid-climate evaporation.	Approx. 50-1,500 mg/L Li; project-specific values may fall outside this range.	Mg/Li ratio, sulfate, boron, Ca, K, water balance, climate, evaporation area.	Commercial and mature in Chile, Argentina, China and other regions.
Hard-rock pegmatites	Lithium-enriched granitic pegmatites containing spodumene, petalite, lepidolite or amblygonite.	Ore commonly approx. 0.5-2.5% Li2O; concentrate commonly approx. 5-6% Li2O.	Liberation, gangue rejection, flotation chemistry, calcination energy, acid consumption.	Commercial and highly mature, especially for spodumene.
Lithium-bearing clays	Altered volcanic ash or hydrothermal/sedimentary deposits where Li is hosted in hectorite, illite, smectite or related minerals.	Approx. 1,000-8,000 mg/kg Li, depending on deposit and cut-off grade.	Mineral lattice attack, acid/alkali consumption, gypsum/sulfate generation, tailings.	Emerging; several projects under development, fewer commercial references.
Geothermal brines	Hot saline fluids circulated through deep reservoirs; in some fields Li is enriched with K, Ca, Fe, Mn, Zn, B and silica.	Approx. 5-400 mg/L Li; Salton Sea is often reported in the hundreds of mg/L.	Temperature, silica scaling, Fe/Mn, corrosion, gas, high TDS, reinjection compatibility.	Emerging; pilot and demonstration projects.
Oil & gas produced waters	Formation brines co-produced during hydrocarbon extraction; historically treated as waste or reinjected.	Smackover data: approx. 1-477 mg/L Li, with many >100 mg/L in southwestern Arkansas [6].	Hydrocarbons, H2S, iron, suspended solids, high salinity, radionuclides in some basins, reinjection permits.	Emerging; demonstration and early commercial projects.

Source	Geological / industrial origin	Indicative Li concentration	Main matrix issues	Industrial maturity
Seawater / desalination brine	Ocean water and concentrated desalination reject streams.	Seawater approx. 0.17 mg/L Li; brines slightly higher depending on concentration factor.	Very low Li concentration, enormous competing ion background, energy demand.	Research and niche concepts; generally not commercial as primary source.
Battery recycling streams	Hydrometallurgical leachates from spent Li-ion batteries and black mass.	Variable, often orders of magnitude higher than natural waters after leaching.	Co, Ni, Mn, Al, Cu, F, organics, electrolyte residues; product purification.	Commercially expanding; secondary source rather than geological source.

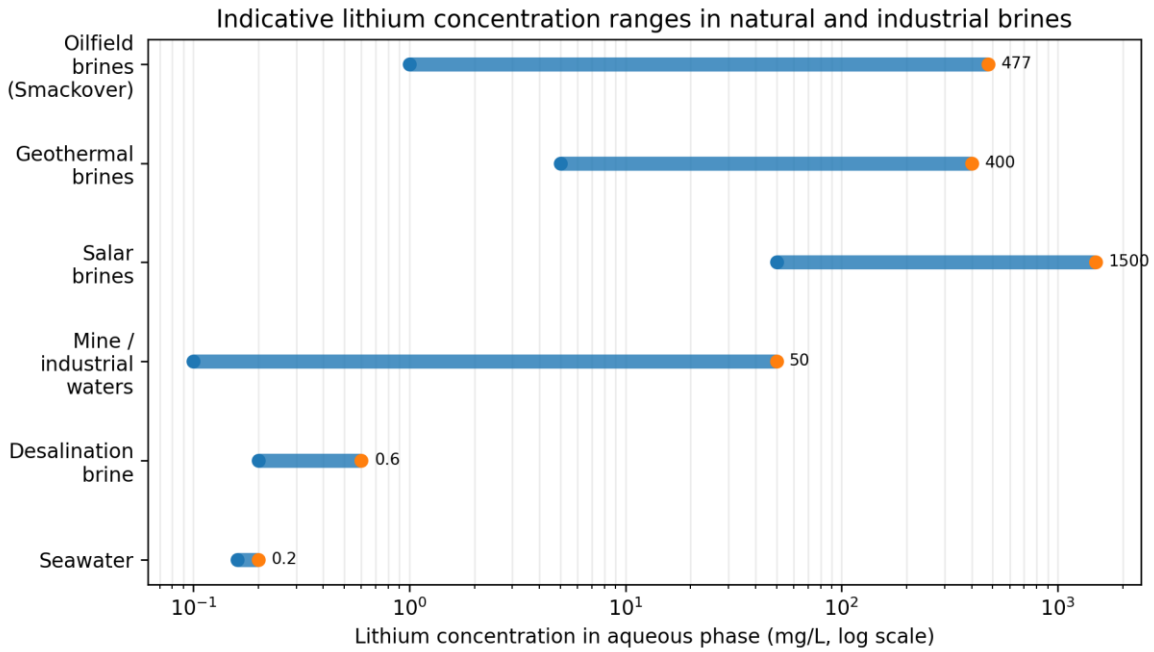


Figure 3. Indicative lithium concentration ranges in aqueous sources. Values are compiled from published reviews and public data, including USGS data for Smackover brines and CEC/NREL data for geothermal brines [4-6].

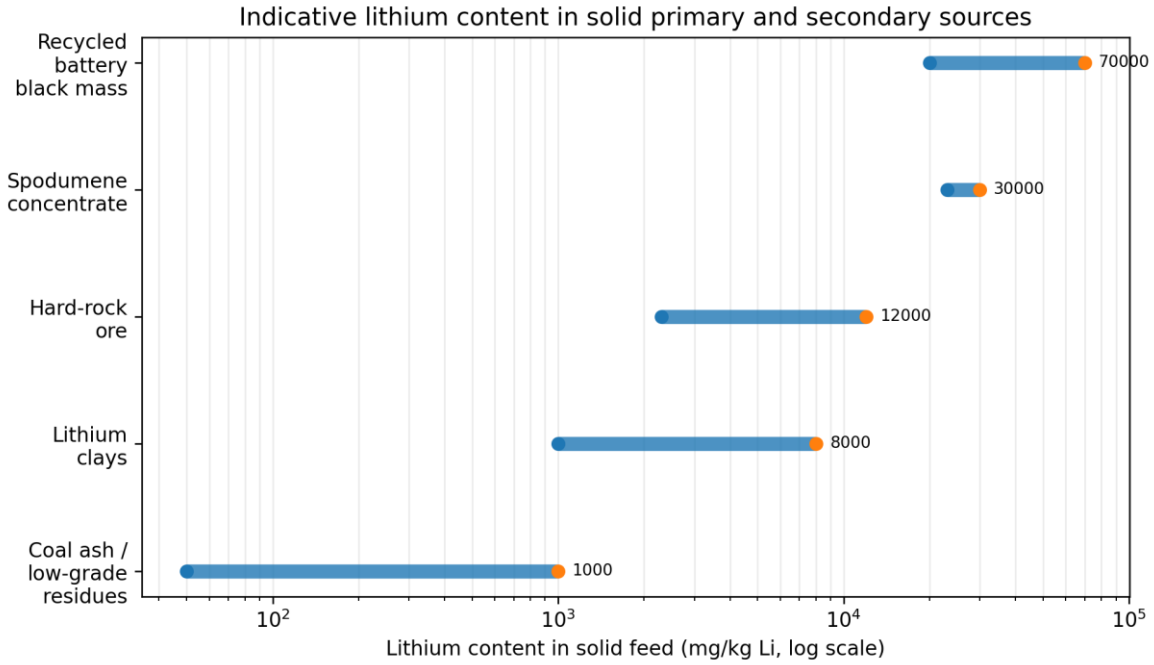


Figure 4. Indicative lithium content in solid primary and secondary sources. Units are mg/kg Li on a logarithmic scale; solid-resource economics also depend on liberation, mineralogy and leachability.

3.1 Salar brines

Salar brines form in endorheic basins where lithium is released by weathering of volcanic rocks, hydrothermal fluids or granitic terrains and transported to closed depressions. In arid climates, long-term evaporation concentrates Na, K, Mg, Ca, sulfate, chloride, boron and lithium. The lithium is already dissolved, which avoids mining and mineral activation, but the brine chemistry and hydrology are decisive.

The conventional salar route uses pumping to solar evaporation ponds. Sequential precipitation removes halite, potassium salts, magnesium salts and other solids while Li becomes enriched in the residual brine. The enriched liquor is then treated with lime, soda ash and purification steps to produce lithium carbonate. This route is simple in principle but slow, land-intensive and dependent on low rainfall and high evaporation rates. It may also cause social and regulatory concern where brine extraction affects water balances and ecosystems.

3.2 Hard-rock lithium deposits

Hard-rock lithium is mainly associated with pegmatites. Spodumene is the dominant industrial mineral because of its relatively high lithium content and established processing route. Petalite, lepidolite and zinnwaldite may also be processed, although they are more complex or less widely commercialized.

The process begins with open-pit or underground mining, crushing, grinding and concentration by dense media separation, flotation and/or magnetic separation. Spodumene concentrate is not directly leachable at attractive rates in its alpha form; it is calcined to beta-spodumene at high temperature to open the crystal structure. Subsequent sulfuric acid roasting and water leaching produce a lithium sulfate solution that is purified and converted to Li2CO3 or LiOH·H2O. Reviews of hard-rock lithium processing emphasize that mineralogy, roasting conditions, reagent stoichiometry and impurity removal define both recovery and environmental burden [7,8].

3.3 Lithium-bearing clays and sedimentary deposits

Lithium-bearing clays and sedimentary deposits are strategically important because they can diversify supply away from established brine and pegmatite provinces. Lithium may be hosted in hectorite, illite or other clay minerals, where it is structurally bound rather than freely dissolved. The extraction challenge is therefore to release lithium from the mineral lattice without excessive reagent consumption or residue generation.

Proposed routes include sulfuric acid leaching, pressure leaching, sulfate or chloride roasting followed by leaching, alkaline treatments and emerging electrochemical activation. Acid leaching can offer rapid kinetics but creates a demanding neutralization and sulfate-management problem. Electrochemical approaches remain at proof-of-concept or early development stages, but recent work on hectorite illustrates the potential to destabilize mineral lattices and release lithium without conventional high-temperature roasting [12].

3.4 Geothermal brines

Geothermal brines are an attractive emerging source because they combine large brine flows, an existing energy asset and the possibility of co-producing lithium with renewable power. The Salton Sea Known Geothermal Resource Area in California is a widely cited example. NREL reported a conservative average lithium concentration of about 200 mg/L in Salton Sea geothermal brine and large annual brine throughput from existing wellfields [4]. California Energy Commission data show that Imperial Valley brines can contain Li in the range of a few mg/L to hundreds of mg/L, while also containing high concentrations of Na, K, Ca, Fe, Mn, Zn, B and silica [5].

The process requirement is different from salar evaporation. The lithium capture step must be rapid, selective and compatible with hot brine circulation. The treated brine generally needs to be reinjected to sustain the reservoir; therefore, the extraction process should avoid chemical changes that cause scaling, plugging, corrosion or reservoir damage. DLE sorbents, ion exchange materials and hybrid systems are therefore central to geothermal lithium development.

3.5 Oil and gas produced water

Oil and gas produced waters are formation brines brought to the surface during hydrocarbon production. These streams are often generated in very large volumes and are typically treated, disposed of or reinjected. Some basins contain lithium concentrations that are high enough to justify recovery studies. The Smackover Formation in the U.S. Gulf Coast is one of the best documented examples; USGS reports lithium concentrations from approximately 1 to 477 mg/L across the formation, with many wells above 100 mg/L in southwestern Arkansas [6].

Produced-water lithium extraction requires pretreatment that may not be needed for clean brines. Oil droplets, dissolved organics, H2S, suspended solids, iron, barium, strontium and scale-forming salts can foul sorbents, membranes or electrochemical systems. The likely commercial configuration is not a stand-alone lithium plant but an integrated brine-management facility: pretreatment, DLE, eluate concentration, lithium product conversion and return or reuse of the depleted brine.

3.6 New and secondary sources

Seawater contains an enormous total mass of lithium but at extremely low concentration, around 0.17 mg/L. Desalination brines are somewhat enriched but still dilute relative to salars, geothermal fluids and oilfield brines. These sources may become relevant where lithium recovery can be combined with zero-liquid-discharge desalination, selective membranes or electrochemical systems, but they are not currently primary commercial sources.

Battery recycling is different: it is a secondary industrial source with high lithium concentration after leaching and with co-recovery potential for nickel, cobalt, manganese, copper, aluminum and graphite. Recycling will not eliminate primary extraction in the medium term because battery demand is still expanding faster than end-of-life returns. However, it can reduce pressure on primary resources and improve supply-chain resilience.

4. Extraction and concentration technologies

Lithium extraction technologies can be grouped into four broad families: evaporation-precipitation routes for brines, pyrometallurgical-hydrometallurgical routes for minerals, direct lithium extraction for brines and hybrid membrane/electrochemical systems. The correct route is determined by the matrix, product target and environmental constraints.

A useful distinction is between lithium recovery and lithium product manufacture. DLE, leaching or roasting may transfer lithium into a smaller process liquor, but the battery-grade product still requires impurity removal, concentration, crystallization, washing, drying and quality control. This downstream section often determines capital cost and operating reliability.

Table 4. Main extraction and concentration technology families for lithium resources.

Technology family	Operating principle	Best suited to	Main advantages	Main limitations
Solar evaporation + precipitation	Evaporate water in ponds; precipitate salts sequentially; purify concentrated lithium brine and carbonate with soda ash.	Arid salars with favourable Mg/Li ratio and climate.	Low direct energy use; mature; large references.	Long residence time, large land footprint, water-balance impacts, weather dependence, moderate recoveries.
Spodumene roasting + leaching	Beneficiate ore, convert alpha-spodumene to beta-spodumene, sulfuric acid roast, water leach, purify lithium sulfate solution.	Hard-rock pegmatites and SC6 concentrate.	Commercially proven; fast production cycle; not climate dependent.	High thermal energy, acid use, residues, emissions and solid waste management.
Acid leaching of clays	Attack clay/sedimentary mineral matrix with acid, then neutralize and purify leach liquor.	Lithium clays and sediments.	Potentially rapid release; can process non-pegmatite resources.	Acid consumption, sulfate/gypsum residues, tailings volume, corrosion, permitting.
Adsorptive DLE / ion exchange	Selective sorbent captures Li+; regeneration produces a lithium-rich eluate.	Salar, geothermal and oilfield brines with manageable fouling species.	Short process time; potentially high recovery; smaller footprint; enables reinjection.	Sorbent lifetime, selectivity vs. Mg/Ca/Na, regeneration chemicals, fouling and eluate concentration.
Solvent extraction	Organic phase extracts Li selectively; stripping produces Li-rich aqueous phase.	Selected brines after pretreatment.	High selectivity possible; compact equipment.	Solvent losses, emulsions, chemical cost, safety and environmental management.
Membranes / electrodialysis	Use pressure, electrical potential or selective membranes to separate monovalent ions or concentrate Li streams.	Polishing, preconcentration, Mg/Li separation or DLE hybrids.	Modular, controllable, useful in hybrids.	Scaling, fouling, energy consumption, selectivity limits in complex brines.
Electrochemical intercalation	Electrode materials selectively intercalate Li+ under applied potential and release it in recovery electrolyte.	Low-to-moderate concentration brines and recycling streams under development.	High selectivity potential; reagent reduction possible.	Electrode stability, current efficiency, scaling, stack cost and scale-up.

4.1 Conventional solar evaporation of brines

Conventional salar processing relies on natural evaporation. Brine is pumped to pond systems and progressively concentrated; NaCl, KCl and magnesium salts precipitate before the lithium-rich liquor is processed chemically. Lime is often used to remove magnesium and sulfate, and soda ash is used to precipitate lithium carbonate. The product may require redissolution with CO2, ion exchange and reprecipitation to reach battery grade.

The method is robust where climate and chemistry are favourable, but it is not universally transferable. High Mg/Li ratios require more reagent, wet climates reduce evaporation efficiency, and pond footprints can be environmentally and socially sensitive. Recovery can also be limited by entrainment, co-precipitation, residual lithium in spent brines and operational variability.

4.2 Mineral processing and hydrometallurgy for hard rock

Hard-rock lithium processing begins as a mineral-processing operation and becomes a hydrometallurgical refinery. After concentration, spodumene is calcined and then reacted with acid or other reagents to form a soluble lithium salt. The leach solution is purified through pH adjustment, precipitation, filtration, ion exchange or crystallization. Lithium hydroxide may be produced directly from lithium sulfate solution through caustic conversion or electrochemical routes, or indirectly through lithium carbonate conversion [9].

This route is less dependent on climate and can be deployed close to mining operations or chemical hubs. Its disadvantages are higher energy intensity and the need to manage tailings, lithium slag, neutralization residues and sulfate- or chloride-containing effluents.

4.3 Direct lithium extraction from brines

DLE is not a single technology; it is a class of selective extraction methods. Sorbents based on manganese oxides, titanium oxides, aluminum hydroxides, ion-exchange resins, imprinted polymers and hybrid materials are being developed. Membrane, solvent-extraction and electrochemical DLE approaches are also under active development [10,11].

A typical DLE plant includes brine conditioning, lithium capture, washing, regeneration, eluate purification and concentration. The depleted brine may be reinjected or returned to the salar. The key performance indicators are lithium recovery, impurity rejection, sorbent capacity, cycle time, water consumption, acid/base consumption, sorbent degradation, fouling resistance and the quality of the eluate. DLE can reduce production time and pond area, but it does not remove the need for downstream concentration and crystallization.

4.4 Concentration and purification of lithium liquors

The intermediate lithium liquor generated by DLE or leaching may be too dilute for direct precipitation or crystallization. Concentration may be achieved through evaporation, reverse osmosis, nanofiltration, electrodialysis, mechanical vapour recompression, thermal crystallization or combinations of these technologies. The choice depends on chloride/sulfate chemistry, scaling potential, temperature, corrosivity and product route.

Purification focuses on divalent cations such as Mg2+ and Ca2+, transition metals, Al, Fe, Mn, Zn, boron, silica, sulfate, chloride and organic matter. Techniques include pH adjustment, precipitation, oxidation/reduction, activated carbon, ion exchange, chelating resins, membrane separations and recrystallization. In many projects, impurities rather than lithium define the flowsheet.

5. Production of lithium carbonate, hydroxide and other commercial products

Commercial lithium products are not simply extracted; they are manufactured through controlled purification, concentration and crystallization. The most important battery-chain products are lithium carbonate and lithium hydroxide monohydrate. Lithium chloride solutions are also important intermediates, while spodumene concentrate is a traded mineral product that feeds conversion plants.

Lithium carbonate is commonly produced by reacting a purified lithium-bearing solution with sodium carbonate. Product quality depends on supersaturation control, particle size, washing, filtration and impurity rejection. Battery-grade carbonate may be produced by bicarbonate redissolution, filtration, ion exchange and recrystallization. Lithium hydroxide can be produced by causticization of carbonate with lime, by direct conversion of sulfate/chloride liquors, or through membrane and electrochemical routes. The best route depends on the feed solution and target specification [9].

Table 5. Commercial lithium products and downstream conversion requirements.

Product / intermediate	Typical feed route	Main process steps	Main applications	Critical quality parameters
Spodumene concentrate (SC5-SC6)	Hard-rock ore beneficiation.	Crushing, grinding, DMS/flotation, dewatering, drying, export.	Feedstock for chemical conversion plants; ceramics in some cases.	Li2O grade, Fe2O3, mica, moisture, particle size.
Lithium carbonate (Li2CO3)	Salar brine, DLE eluate, lithium sulfate/chloride solution, recycled battery leachate.	Purification, concentration, soda ash precipitation, filtration, washing, drying; optional recrystallization.	LFP batteries, cathode precursors, glass/ceramics, chemicals.	Na, K, Ca, Mg, Fe, B, sulfate, chloride, moisture, particle size.
Lithium hydroxide monohydrate (LiOH·H2O)	Spodumene-derived sulfate liquor, carbonate conversion, DLE solution.	Caustic conversion or electrochemical/membrane conversion, crystallization, drying.	High-nickel cathode materials; specialty chemicals.	Carbonate impurity, chloride/sulfate, Na/K, Ca/Mg, Fe, moisture.
Lithium chloride (LiCl)	Brine concentration or DLE eluate after purification.	Concentration, impurity removal, crystallization or solution stabilization.	Intermediate for metal, chemicals or further conversion.	Water content, Mg/Ca, sulfate, boron, organics.

Product / intermediate	Typical feed route	Main process steps	Main applications	Critical quality parameters
Lithium metal / specialty products	High-purity LiCl or LiOH feedstock.	Electrolysis or specialized conversion.	Primary batteries, alloys, specialty materials.	Very high purity, moisture and oxygen control.

6. Global production snapshot

Lithium mine production remains concentrated in a small number of countries. USGS reported that Australia, China and Chile accounted for the largest shares of 2025 mine production, with significant volumes also reported from Zimbabwe, Argentina, Brazil, Mali, Canada and Portugal. U.S. production was withheld to avoid disclosing company proprietary data [1].

The production map is important because processing routes are geographically coupled to resource type. Australia is dominated by hard-rock spodumene; Chile and Argentina are historically brine-based; China combines mineral and brine production; Zimbabwe and Mali are hard-rock entrants. Emerging geothermal and oilfield brines could alter the regional balance if commercial DLE systems achieve reliable scale-up.

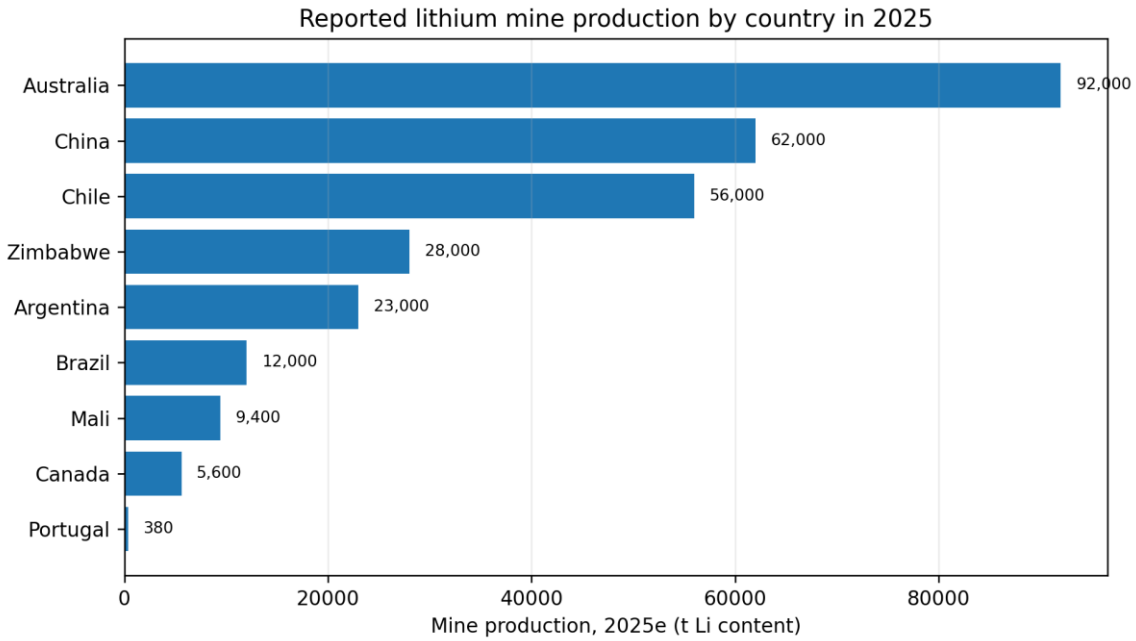


Figure 5. Reported lithium mine production by country in 2025, expressed as tonnes of Li content. Source: USGS Mineral Commodity Summaries 2026 [1].

7. Technical criteria for selecting an extraction route

The first screening of a lithium project should use a mass balance rather than a concentration value alone. The balance should include lithium in the feed, lithium recovered in product, lithium lost in residues or spent brine, water consumption, reagent consumption, impurity load, purge streams and solid residues. Laboratory tests must be designed to generate scale-up parameters, not only proof-of-concept recovery values.

For brines, the most important design parameters include Li concentration, Mg/Li and Ca/Li ratios, total dissolved solids, sulfate/chloride balance, boron, silica, Fe/Mn, organic matter, temperature, flow stability, suspended solids, scaling tendency and reinjection requirements. For mineral sources, the key parameters are grade, mineralogy, liberation size, concentrate recovery, calcination behaviour, leaching kinetics, acid or alkali consumption, impurity solubility and residue stability.

Table 6. Project-screening criteria for lithium extraction and refining projects.

Criterion	Why it matters	Indicative tests / design outputs
Lithium concentration and throughput	Defines potential annual lithium mass. Low concentration can be offset by very high flow only if selectivity and energy demand are favourable.	Representative sampling, flow history, seasonal variability, reservoir model, Li mass balance.
Impurity matrix	Mg, Ca, Na, K, B, Si, Fe, Mn, organics and sulfate may control reagent demand, fouling and product purity.	Full ionic analysis, speciation, scaling indices, impurity removal tests.
Selectivity and recovery	High lithium recovery is valuable only if selectivity is adequate and product purification remains feasible.	DLE cycling tests, breakthrough curves, leach recovery, impurity rejection factors.
Water and brine management	Determines environmental acceptability, permitting and operating cost.	Water balance, reinjection test, depleted brine chemistry, ZLD/MLD options.
Energy and heat integration	Controls operating cost and carbon footprint, especially in hard-rock roasting and thermal concentration.	Thermal balance, MVR/evaporation evaluation, waste-heat integration, power demand.
Residues and by-products	Tailings, gypsum, salts, lithium slag and spent sorbents affect permits and long-term liabilities.	Residue characterization, leachability, stabilization, by-product market assessment.
Final product specification	Battery-grade materials require consistent impurity levels and particle morphology.	Crystallization tests, washing/drying tests, product analysis, customer specification mapping.

8. Environmental and integration considerations

Each lithium source has a different environmental profile. Salar projects must manage brine extraction, freshwater use, pond footprint, salt residues and potential impacts on local ecosystems and communities. Hard-rock projects must manage mining disturbance, tailings, energy use, acid consumption and conversion-plant residues. Clay projects face similar mining issues plus acid or alkaline leaching and large volumes of neutralization residue. Geothermal and oilfield brines can use existing industrial infrastructure, but they introduce high-temperature corrosion, scaling, gas management, organic contamination and reinjection constraints.

From an environmental engineering perspective, the lithium value chain creates opportunities for integrated water and waste treatment. These include brine pretreatment, selective removal of Mg/Ca/B/silica, membrane preconcentration, evaporation and crystallization of eluates, treatment of acid leachates, recovery of by-product salts, management of gypsum and sulfate streams, closed-loop water recycling, control of acidic or fluorinated emissions and stabilization of residues.

DLE is often presented as a lower-impact alternative to evaporation ponds, and it can be. However, a complete assessment must include chemical regeneration, water demand, eluate concentration, sorbent replacement, wastewater treatment and the fate of the depleted brine. Similarly, hard-rock and clay projects can improve their environmental performance through heat recovery, acid recycling, dry stacking, residue valorization and renewable power integration.

Table 7. Environmental considerations and mitigation options by lithium source.

Resource type	Dominant environmental concerns	Potential engineering mitigation
Salar brines	Brine and freshwater balance, pond footprint, salt residues, long production time.	Hydrogeological monitoring, selective DLE hybrids, brine return strategies, water recycling, reduced pond area.
Hard rock	Mining disturbance, tailings, calcination energy, acid roasting, lithium slag.	Efficient beneficiation, waste-heat recovery, renewable energy, dry tailings, residue stabilization.
Clays	Acid consumption, neutralization residues, sulfate management, tailings volume.	Acid regeneration, by-product salt recovery, closed water loops, residue dewatering/stabilization.
Geothermal brines	Scaling, corrosion, high TDS, metals, reinjection compatibility.	Hot-brine compatible DLE, silica/Fe control, corrosion-resistant materials, closed-loop reinjection.
Oilfield brines	Hydrocarbons, H2S, iron, scale, possible NORM, disposal/reinjection permits.	Oil removal, gas stripping, oxidation/filtration, scale control, closed reinjection, monitoring.
Recycling streams	Fluoride, organics, mixed metals, spent electrolyte residues.	Controlled leaching, gas treatment, metal recovery sequence, wastewater polishing, circular reagent use.

9. Future outlook: where innovation is most likely to matter

Future supply will probably remain diversified rather than being replaced by a single breakthrough technology. Spodumene will continue to supply fast-growing conversion capacity; salar brines will remain competitive where climate and chemistry are favourable; DLE will expand where brines are too dilute, too complex or too climate-sensitive for conventional evaporation; and recycling will grow as a secondary resource once large battery cohorts reach end of life.

The most important innovation areas are selective materials for DLE, high-temperature and antifouling brine-contacting equipment, low-reagent clay leaching, membrane and electrochemical concentration, impurity-tolerant lithium carbonate crystallization, LiOH production directly from non-carbonate liquors, and integrated brine-reinjection systems. For all routes, demonstration at realistic flow, impurity and cycle conditions will be more meaningful than short laboratory tests with synthetic brines.

The market will reward projects that combine secure resource access with reliable process integration. In practical terms, a lithium project is a coupled mining, water-treatment, chemical-refining and crystallization project. The winners are likely to be those that control the entire chain from feed variability to final battery-grade specification.

10. Conclusions

1. Lithium supply is no longer limited to two classical sources, although salar brines and hard-rock spodumene remain the dominant commercial routes.
2. The lithium concentration of a feed is necessary but not sufficient for feasibility. Selectivity, impurity load, flow rate, energy integration, reagent consumption and final product quality are decisive.
3. Conventional solar evaporation is well established for suitable arid salars, but it is slow, land-intensive and sensitive to water-balance constraints.
4. Hard-rock processing is robust and scalable, but the conversion route is energy- and reagent-intensive and generates significant solid residues.
5. Lithium-bearing clays may diversify supply, yet their commercial success depends on controlling acid or alkali consumption, neutralization residues and tailings management.
6. Geothermal brines and oilfield produced waters are promising integration opportunities because lithium recovery can be added to existing brine-handling infrastructure; their main challenge is reliable, selective DLE under complex brine conditions.
7. Battery-grade Li2CO3 and LiOH·H2O production requires high-quality purification and crystallization; extraction technology alone does not guarantee a saleable product.

8. Future projects should be evaluated using integrated mass balances, treatability testing and product-quality trials that include pretreatment, extraction, eluate concentration, impurity removal, crystallization and residue management.

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Appendix A. Data used for figures

Table A1. Sources and assumptions behind the figures.

Figure	Data basis	Notes
Figure 2	Theoretical lithium mass fractions in Li2CO3, LiOH·H2O, LiCl, SC6 concentrate and Li metal.	Calculated from molar masses; SC6 assumes 6% Li2O and Li/Li2O = 0.4645.
Figure 3	Indicative aqueous Li concentration ranges from published reviews, USGS Smackover fact sheet and CEC/NREL geothermal brine data.	Ranges are screening values, not deposit reserves.
Figure 4	Indicative solid Li contents compiled from hard-rock, clay, low-grade residue and recycling literature.	Converted to mg/kg Li where needed.
Figure 5	USGS 2026 mine production data for 2025e, excluding U.S. production withheld for confidentiality.	Lithium content, tonnes.

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