

Environmental impact of direct lithium extraction from brines

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Abstract

Evaporitic technology for lithium mining from brines has been questioned for its intensive water use, protracted duration and exclusive application to continental brines. In this Review, we analyse the environmental impacts of evaporitic and alternative technologies, collectively known as direct lithium extraction (DLE), for lithium mining, focusing on requirements for fresh water, chemicals, energy consumption and waste generation, including spent brines. DLE technologies aim to tackle the environmental and techno-economic shortcomings of current practice by avoiding brine evaporation. A selection of DLE technologies has achieved Li^+ recovery above 95%, $\text{Li}^+/\text{Mg}^{2+}$ separation above 100, and zero chemical approaches. Conversely, only 30% of DLE test experiments were performed on real brines, and thus the effect of multivalent ions or large Na^+/Li^+ concentration differences on performance indicators is often not evaluated. Some DLE technologies involve brine pH changes or brine heating up to 80 °C for improved Li^+ recovery, which require energy, fresh water and chemicals that must be considered during environmental impact assessments. Future research should focus on performing tests on real brines and achieving competitiveness in several performance indicators simultaneously. The environmental impact of DLE should be assessed from brine pumping to the production of the pure solid lithium product.

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Key points

- Fresh water consumption of direct lithium extraction (DLE) needs to be urgently quantified. Many DLE technologies might require larger freshwater volumes than current evaporative practices, compromising their applicability in arid locations.
- Chemical processing is not completed until a pure solid product is obtained. Energy consumption of DLE should be estimated for the overall process, including potential water extraction or evaporation from pure but dilute LiCl solutions, as is the case with many DLE technologies.
- Lithium ions are only a minor component in continental, geothermal and oilfield brines. Thus, from a circular economy perspective, there is potential for extraction of more than one valuable mineral, notably, borates, magnesium, potassium and sodium salts.
- Knowledge of the precise number, distribution and depths of brine and fresh water wells is vital for hydrogeological modelling of lithium brine deposits. The distinct hydrogeology of each salar means that each deposit should be modelled independently, and results from one exploitation cannot be directly extrapolated to another.
- Environmental monitoring should be permanent and precede the start of the exploitation as environmental impacts might only be observable in the long term. Water monitoring requires gathering precipitation data, river flows and a sufficient number of observation wells to follow water tables at different locations.
- Environmental monitoring guidelines have been drafted with evaporitic technology in mind, but they should also be applied to the implementation of any DLE technology, which still consumes brine, uses fresh water and produces residues, the latter two hopefully at considerably lower volumes.

Introduction

Lithium is a fundamental raw material for the renewable energy transition owing to its widespread use in rechargeable batteries and the deployment of electric vehicles^{1–4}. The electric vehicle stock has increased strongly from a few thousands in 2010 to 11.3 million in 2020, and 142 million electric vehicles are forecast to be on the road by 2030⁵. Global lithium production has tripled between 2010 and 2020⁶. Different projections estimate that the demand for lithium will grow by 18–20-fold by 2050 if existing extraction policies are followed. However, if new, more sustainable extraction policies are implemented, demand is estimated to increase by as much as 40-fold by 2050 (refs. ^{7,8}).

Currently, lithium extraction is exclusively from hard-rock ores and continental brines^{6,9}, with continental brine resources being more abundant than hard-rock ores^{6,9–11}. The evaporitic technology currently used to extract lithium from continental brine deposits relies on open air evaporation to concentrate the brine. Large volumes of water, 100–800 m³ per tonne of lithium carbonate, depending on the deposit, are lost through evaporation, raising concerns about the overall sustainability of the process. Furthermore, continental brine concentration is intrinsically slow, taking 10–24 months, which means that this process is not responsive to short-term changes in

demand. Consequently, production cannot be reduced if demand drops, for example, during the onset of the COVID-19 pandemic in March 2020. In addition, ramping up production takes approximately 4 years. The locations of suitable continental brines are also geographically restricted, with an estimated 50–85% of lithium-rich continental brine deposits located in the Lithium Triangle and with China as the next richest source⁹. Hard-rock ores are also geographically concentrated in Australia and China^{10,12,13}.

Conversely, many more countries have access to less-concentrated lithium brine sources, such as geothermal brines and oilfield brines^{14–17}, which have lower lithium concentrations (Supplementary Table 1). Unfortunately, evaporitic technology is not applicable to these more dilute brines^{18,19}. The non-viability is due to the different chemistry, the much longer time frames that would be required for successful concentration and the fact that most of these deposits are not located in arid regions. Economically sound technologies to exploit these more dilute lithium resources are being explored with urgency to diversify lithium production. These new lithium extraction technologies, generically termed direct lithium extraction (DLE), could enable the processing of both continental and other more dilute brines without the need for evaporation ponds.

DLE encompasses a wide variety of technologies, including, for example, thermal and electrochemical processes. For the key process of lithium capture or concentration, very thorough chemical analysis and quantitative data are available. Unfortunately, quantitative data regarding native brine pre-processing, leading to the feasibility of the specific DLE process, are scarce or not available. Information on post-processing after the DLE is often also missing. However, all aspects of the multistep brine processing procedure should be comprehensively analysed for a full environmental impact analysis and costs estimation. As of 2022, several advanced DLE methods have been proposed that produce remarkable efficiencies. As such, it is now timely to review and compare traditional and new technologies by providing an analysis of the entire extraction process from brine pumping to packaging of the final lithium product, with the aim of identifying the required inputs and outputs for different technologies.

In this Review, we discuss the environmental impact of lithium mining from continental brines, outline the challenges in the nascent field of lithium mining from geothermal brines and assess the proposed DLE technologies in the framework of an overall mining and processing technology. The scope of the Review includes an assessment of DLE in terms of input of chemicals, production and fate of spent brines, energy and freshwater requirements and the potential for exploiting the by-products produced. These are factors that need to be considered in a discussion of the potential environmental impact of DLE. We also discuss the potential of DLE for scaling up to industrial levels.

Environmental impacts of current practice

Lithium is a fundamental element driving sustainable mobility and energy and its mining is therefore under scrutiny and will require social licensing²⁰. A major open question regarding the sustainability of evaporitic technology is its intensive water usage, which is discussed subsequently.

Lithium mining from continental brines

As of 2022, worldwide, there are eight full-scale active facilities that produce lithium compounds from continental brines⁹ and more are likely to become active before 2030 (Fig. 1a). The evaporitic technology (Fig. 1b) is currently in use at seven of those facilities^{18,19}. Brines are

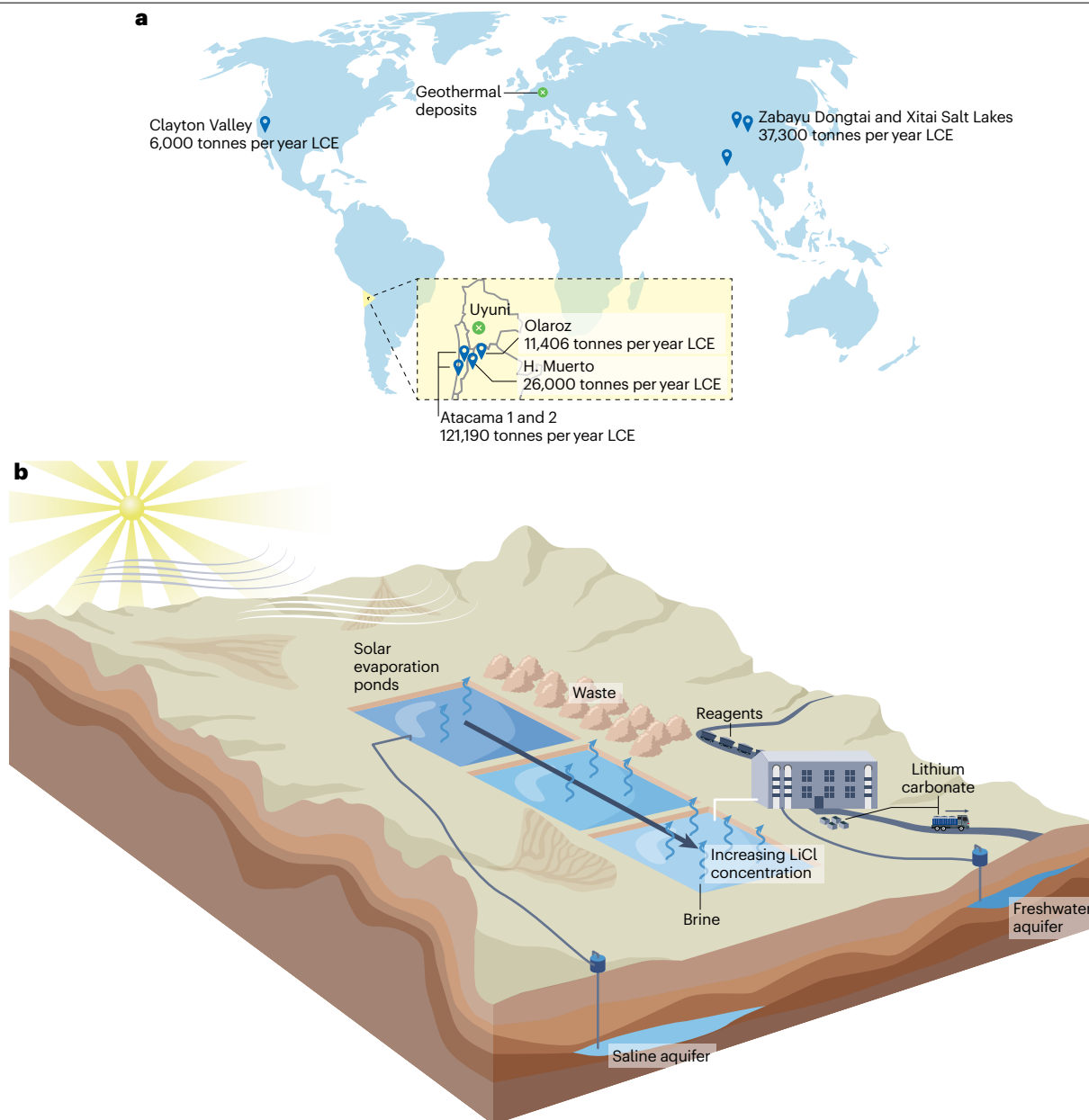


Fig. 1 | Lithium sources and exploitation. **a**, Active lithium mining from brine facilities and corresponding production capacities in 2022 for the following salars: Clayton Valley (USA); Lake Zabayu (or Zabuye), Dongtai Salt Lake and Xitai Salt Lake (China); Salar de Atacama 1 and 2 (Chile) and Salar del Hombre Muerto and Salar de Olaroz (Argentina). The inset zooms in on the Lithium Triangle in South America, which has the largest identified deposits in continental brines worldwide. Deposits that are mentioned in the Review but are not currently exploited are also shown: Salar de Uyuni (Bolivia) and geothermal fields in the Rhine region (France–Germany). LCE: Lithium carbonate

equivalent. **b**, Schematic representation of evaporitic technology. The first step is brine pumping from underground reservoirs. Brines are poured into large shallow open air ponds, where over 90% of the original water content is lost via evaporation accelerated by solar radiation and wind. LiCl concentration increases gradually and salts from other cations crystallize in the ponds as saturation is reached. Concentrated brines then enter a refining plant for crystallization of the final product (usually lithium carbonate). Fresh water and chemicals are used at several steps of processing.

pumped from underground reservoirs into open air ponds, in which over 90% of the original water content is lost through evaporation. Concentrated brines are then transferred to a refining plant for removal of impurities, followed by Li_2CO_3 precipitation via the addition of Na_2CO_3 . Fresh water is needed at multiple steps of the process, including to

dissolve CaO (needed to precipitate Mg^{2+}) and Na_2CO_3 , in the scrubbing of organic solvents (used for the removal of borates), for washing Li_2CO_3 crystals and for steam generation^{18,19}. Over 90% of the salts other than LiCl in the original brines spontaneously crystallize in the ponds¹⁸ and are considered waste.

Starting in the early 2000s, environmental concerns have been raised about lithium mining from continental brines by local populations, non-governmental organizations and the press, first in Chile where operations started 10 years earlier and then in Argentina^{18,21–26}. Communities close to these operations are all rural, and environmental conditions are very poorly documented²⁶. Surprisingly, environmental life-cycle analysis of lithium brine mining has quantified energy consumption and carbon emissions, while disregarding the impacts on the water cycle or specific land uses^{27–31}. Solid quantitative evidence of the negative environmental impacts of lithium mining was only reported from 2018. The data are still quite limited and relate only to Salar de Atacama, the first salar to be mined aside from Clayton Valley, which has a much smaller production capacity¹⁹.

In brine mining, two distinct aquifers are exploited, brine and fresh water^{18,32}, which can potentially become physically connected. The question arises as to whether these water volumes should be considered when calculating the water footprint of the process²⁴. Clearly, the freshwater volume should be included, whereas the brine volume that should be considered in the water footprint is less straightforward to estimate. Arguing that brine water is far from being suitable for either human consumption or agricultural use^{18,32}, strong proponents of mining propose that brine should be completely disregarded in water footprint calculations. However, we suggest that brine must be considered, as the brine volume that is pumped will directly determine the amount of fresh water that naturally flows from outside the brine aquifer (Box 1), is mixed with brine and thus is no longer considered fresh water or can be used as such^{18,32–36}. The volume of fresh water that flows or moves towards the salar is different during brine pumping or in the absence of mining. As both fresh water and brine are extracted from underground aquifers, salars are a hydrogeological case study (Box 1).

Determining whether excessive water extraction is occurring is difficult in the absence of hydrological data, and unfortunately, hydrological records in the Lithium Triangle are either unavailable or incomplete^{18,25,26,37}. For example, a decrease in lagoon area or stream flow is a direct indication of water shortages. The surface area of lagoons on Salar de Atacama has decreased by half in the period 1985–2020 in winter but not in summer³⁸. To the best of our knowledge, no other quantitative information is available on surface water trends for the Lithium Triangle. However, it is of the utmost importance to also consider the decrease in underground water reservoirs, both brine and fresh water. Satellite data reveal that the total water storage in Salar de Atacama decreased by -1.16 mm per year in the period 2010–2017²⁶ and soil moisture indexes decreased on average by -0.005 yearly in the period 1997–2017³⁷. Direct observation wells showed a radical reduction in the water table from pre-extraction to current time frames (1986–2015)^{33–35,39}. In the region where brine wells are located, water table decreases of up to 9 m were recorded in 1990–2015. To date, these decreases are limited to the nucleus of the salar and do not seem to reach the salar borders or the regions where brine and fresh water mix³³.

Another consideration in assessing underground water reservoirs is phreatic evaporation, a natural form of evapotranspiration that occurs in salars, even in the absence of brine pumping. Discordant results have been reported regarding evapotranspiration in Salar de Atacama. In two studies using satellite data, one study found no change in the phreatic evaporation rate in the period 2000–2017 for either the salar or the surrounding areas³⁷, whereas the other found a 6% decrease in the period 1960–2020³⁸. A third study coupling field measurements with hydrogeological simulations estimated an average decrease in the evapotranspiration rate of approximately 15% over the whole salar

surface since the start of brine mining in 1994³³. Evapotranspiration is strongly dependent on brine pumping volumes because of its dependence on the water table^{35,40,41}. Thus, the decrease in evapotranspiration is a direct indication of a decreasing water table depth.

It has been hypothesized that changes in natural evaporation rates might serve, at least partially, as a compensation or damping mechanism to counteract brine pumping^{33,35}. The idea is that while more water is lost through brine pumping, this is partially compensated for by a decrease in the amount of water that evaporates. Phreatic evaporation decreases exponentially with depth, so the damping capacity only works if water table levels do not drop below 2 m, being most efficient between 0 and 0.5 m (ref. ³³). In the Salar de Atacama in particular, the damping capacity has already been exhausted in the region where the brine wells are located, since the water table depth is already below 2 m (ref. ³⁵).

A reduction in water levels can also be inferred from changes in flora and fauna. Flamingos could be a strong indicator of environmental damage, owing to the landscape scale at which they use wetlands⁴². In the Salar de Atacama, a reduction of 10% and 12% has been reported in the populations of James and Andean flamingos, respectively, which is linked to the reduction of surface water, particularly in winter³⁸. Reduced reproductive success in flamingos in 2017–2019 resulted in the population barely reaching the minimum number of 1,000 nestlings required for population size maintenance, below historical records⁴³. Monitoring of the abundance of the brine shrimp *Artemia* could aid understanding of ecosystem dynamics owing to the role of this crustacean in trophic ecology. Unfortunately, no data on *Artemia* abundance or temporal evolution in the region has been reported, only a suggestion that it is an important taxa to be monitored⁴³.

Three variables indicate a trend towards desertification. Satellite imaging data revealed a reduction in normalized difference vegetation index in the period 1997–2017, indicating an overall trend of more sparsely vegetated areas^{37,38}. The same satellite data showed land surface temperature increases averaging 0.74% and 2.68% yearly in summer and winter, respectively. Finally, in one of the mining properties, a third of carob trees, a species known to be drought-tolerant, died in the period 2013–2017, strongly indicative of underground water shortages³⁷.

Although segmented and not sufficient to generate an overall measure of sustainability²⁶, publications from 2018 onwards strongly suggest that a negative impact is being produced, mostly regarding the water balance. Because of the complex nature of hydrogeological studies, it is difficult to quantify the extent of the impact.

Lithium mining from geothermal sources

Geothermal sources are deposits of interest for the production of lithium and other metals and for energy production. Mining from geothermal sources requires the development of new technologies adapted to specific operating conditions. Particularly in Europe, lithium deposits are found in the vicinity of densely populated areas, as opposed to the rural location of most salars and hard-rock ores deposits^{14,15}.

A pilot scale DLE process, adapted from the one originally developed for brines in Argentina, successfully extracted lithium from geothermal brines located in north-eastern France that are used for energy production. After extracting the 180 °C geothermal fluid located at a depth of between 2,600 and 5,000 m, 90% of lithium was selectively extracted using patented ion exchange resins^{15,44}. The lithium-depleted geothermal fluid is then re-injected underground. This type of lithium production from geothermal brines faces challenges, especially in the

Box 1

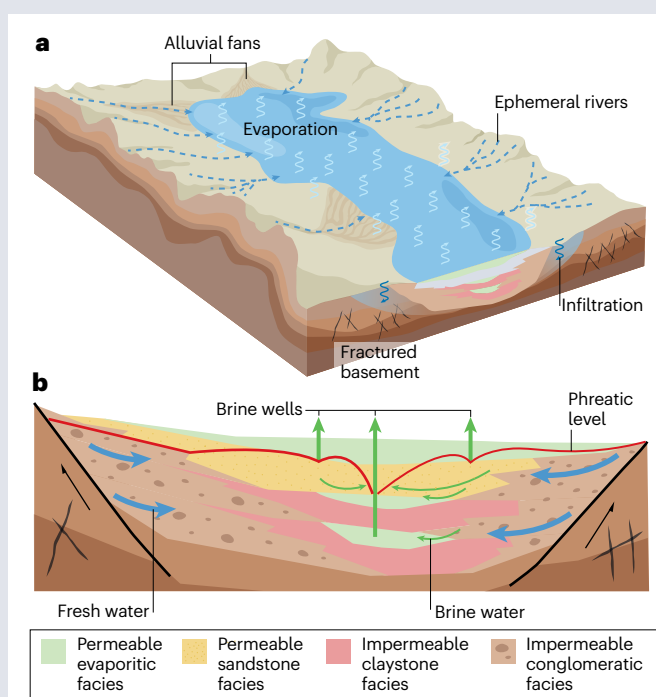
Hydrogeology and sedimentary characteristics of salars and the water footprint from brine pumping

Brine water is located in the centre of the salar (see the figure, part **a**). Fresh water is found at the border of the salar basin in both free and confined aquifers¹⁸. Fresh water infiltrating the salar is mixed with brine or dissolves the evaporitic facies and becomes brine (see the figure). Even at continental brine deposits that have never been exploited, brine is in dynamic equilibrium with the surroundings, with a sluggish turnover controlled by loss by phreatic evaporation and recharge from infrequent rain and upstream water sources^{171,172}. The analysis suggests that brine pumping could provoke an increase in recharge from underground fresh water towards brine deposits^{1,4–6} (see the figure, part **b**). If this recharge becomes substantial, it will affect the level of nearby fresh water lagoons, rivers and streams and the water table in the surrounding soil.

Reports agree that the brine volume that is pumped will directly determine the amount of underground fresh water recharge^{18,33–36}. An unanswered question is how the volume of pumped brine relates mathematically to underground fresh water recharge. Different conceptual and numerical models have been proposed to predict the hydrogeology of salars and to estimate the freshwater recharge.

One conceptual model classifies salars as mature or immature, arguing that the porosity and permeability of the layers determine the amount and rate of recharge^{18,36}. Around extraction wells, brine pumping induces depression cones in the fluid. With time, depression cones will extend to the boundaries of the brine aquifer. If the boundaries are permeable, fresh water will flow in³⁶. Diminishing the freshwater recharge is in the economic interest of mine operators to avoid resource dilution^{18,36}. Another numerical model placed special emphasis on geochemical processes that might define fluid flows, facies composition and the concentrations of dissolved minerals¹⁷³. A third conceptual and numerical model used extensive field data to calibrate a model that is strongly affected by fault systems^{33–35,39}.

As each individual salar has its own unique characteristics, each salar should be considered on a stand-alone basis when proposing numerical models. Each hydrogeological model should consider the sedimentary fill and facies of the salar, and these aspects should



show a good correlation with the information from exploratory wells. Each different sedimentary fill will condition the aquifers, the movement of groundwater and ultimately the results of the exploitation. Independent and potentially different conclusions might be drawn from the analysis of each specific brine deposit^{18,36}. The distribution, depths and number of wells from which both brine and fresh water are pumped at specific mining facilities are usually unknown. Feeding hydrogeological models with precise data on wells and the unique characteristics for each salar improve the predictions from numerical simulations.

case of deep extraction because of the risk of micro-earthquakes⁴⁵, as occurred during testing in late 2020 near Strasbourg, which halted drilling activities. If geothermal energy harvesting is stopped, lithium extraction would also be affected. However, it should be kept in mind that this area near Strasbourg is a seismic zone known to be potentially active. Furthermore, these risks can be reduced by using geothermal fluids located at a shallower depth⁴⁶.

The high pressure and high temperature of geothermal fluids are additional difficulties when comparing the processing of geothermal and continental brines. After energy recovery, the temperature of the brine is close to 60–80 °C and the pressure is maintained at a minimum of 25 bars to avoid precipitation phenomena and excessive changes in the composition of the geothermal fluid to be re-injected⁴⁷. Membrane

technologies cannot be used at these temperatures without risking premature membrane ageing, whereas liquid–liquid extraction cannot be easily implemented at these pressures^{48,49}. The best solution is probably to extract the lithium by high-pressure chromatography in columns filled with ion exchange resins, as well as using other technologies that are discussed in the following sections.

Direct lithium extraction

DLE technologies aim to tackle both the environmental and techno-economic shortcomings of evaporitic technology. Ideally, DLE should completely avoid open air evaporation ponds. Many different proposed technologies have been put forward, including ion exchange resins, thermally assisted processes, electrochemical methods, among others.

General working principles of DLE

DLE technologies can be classified into seven general categories⁵⁰ (Fig. 2).

Ionic exchange resins (Fig. 2a) are materials that have a high affinity for Li^+ cations^{51–53}, which are adsorbed onto small resin particles (often packed in columns) from brines, even when Li^+ cations are at much lower concentrations than coexisting cations. Freshwater or acidic solutions are usually used to desorb Li^+ cations from the resins to produce a fairly pure Li^+ solution (usually LiCl).

Some organic solvents or solutions, such as tri-*n*-butylphosphate and FeCl_3 (refs. ^{54,55}), and ionic liquids, such as imidazole ionic liquids that serve as solvents in conjunction with tri-*n*-butylphosphate^{56,57}, have a high affinity for Li^+ (Fig. 2b). When brine comes into contact with these solvents, a large proportion of Li^+ cations is transferred to the organic or ionic liquid phase. The Li^+ -loaded phase is then mixed with an aqueous phase to liberate the Li^+ cations. pH changes are commonly needed to promote Li^+ transfer between different phases.

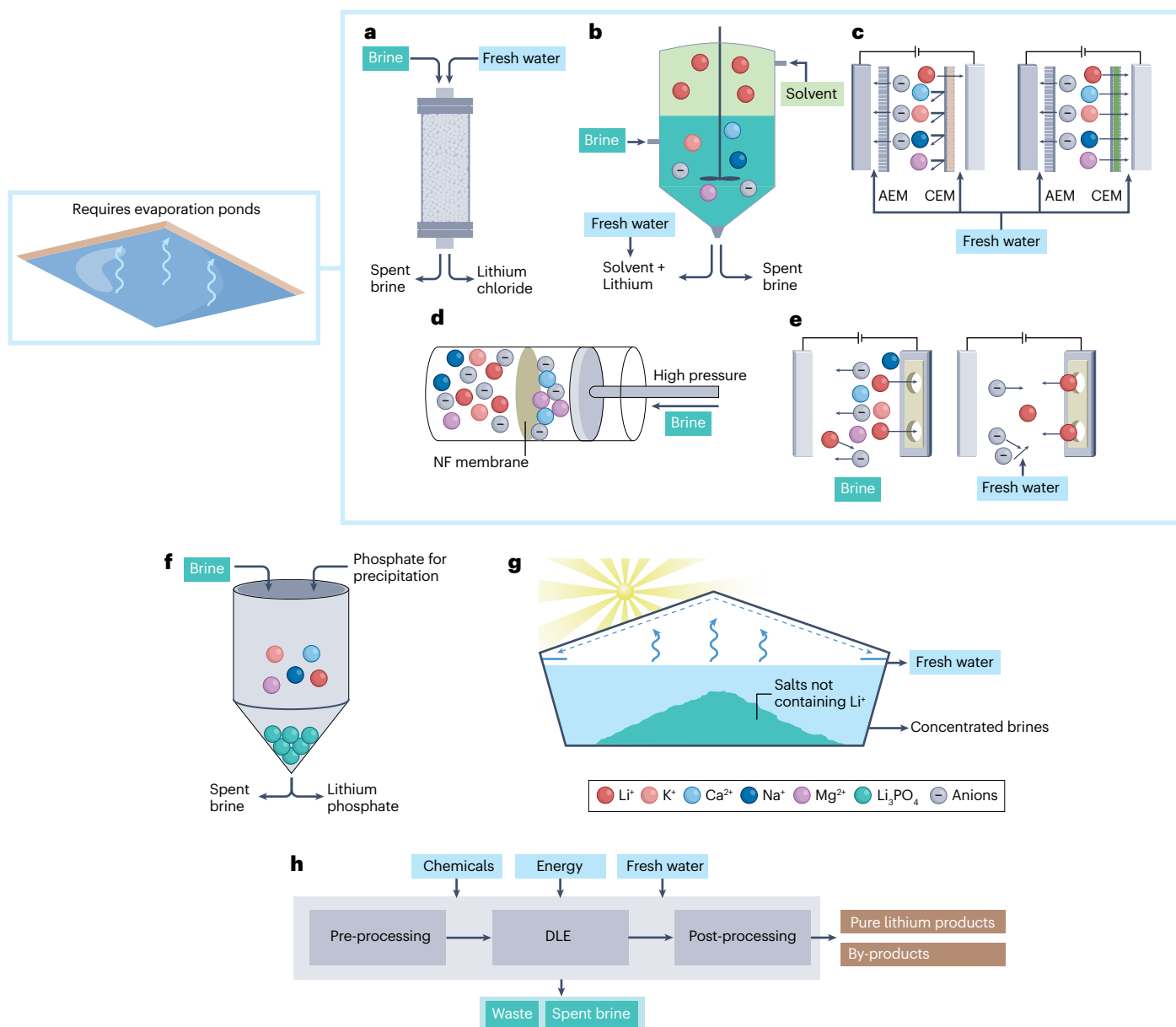


Fig. 2 | Direct lithium extraction (DLE) technologies, freshwater inputs and spent brine production. **a**, Ion exchange resins, also known as ion sieves or specific sorbents. **b**, Solvent or liquid-liquid extraction. **c**, Electromembrane processes with Li^+ -selective membranes (left) or permselective membranes (right) that are selective to anions or cations. **d**, Nanofiltration, NF. **e**, Electrochemical ion pumping, which is sometimes also termed electrochemical ion insertion or

electrochemically switchable ion exchange. **f**, Selective precipitation of Li_3PO_4 via addition of Na_3PO_4 . **g**, Thermal-assisted methods for brine concentration, other than open air evaporation. These methods include any type of evaporator, distillation device or membrane distillation. **h**, General scheme of DLE as part of an overall processing strategy. AEM, anion exchange membrane; CEM, cation exchange membrane.

Alternatively, membrane processes for selective lithium recovery can be driven by electrical fields (Fig. 2c) or mechanical forces (Fig. 2d). The use of electrical fields usually requires membranes selective for either anions or cations^{58,59} (Fig. 2c, right), with few membranes showing specific selectivities⁶⁰ (Fig. 2c, left). Mechanical forces are used to drive brines across nanofiltration membranes, with multivalent species usually being retained^{61–63}.

Electrochemical ion-pumping technology^{64,65} is based on materials that are highly specific for Li^+ cations, similar to the case for ion exchange resins. However, in electrochemical ion pumping, Li^+ is inserted in an electrode material subjected to a potential gradient (Fig. 2e, left), which undergoes an electrochemical reaction. No chemicals are needed and no species are concomitantly liberated to the brine. Subsequently, Li^+ is de-inserted from the electrode material using recovery solutions requiring fresh water, producing a diluted LiCl solution (Fig. 2e, right). Electrochemical ion pumping is often coupled to ion-selective membranes^{66–69}.

Selective precipitation (Fig. 2f) is based on the very low aqueous solubility of lithium phosphate (Li_3PO_4)^{70,71}. A large proportion of Li^+ from brines can often be recovered by the addition of different phosphates, provided that the brine has previously been depleted of multivalent species^{70–72}.

A final DLE technology comprises processes in which the main objective is to concentrate native brines with concomitant water recovery^{73,74}. Brine concentration is also the objective of open air evaporation ponds, except that in this case the evaporated water is lost to the atmosphere. Examples of these processes include membrane distillation and solar evaporators (Fig. 2g).

The sustainability and the potential scalability of the seven DLE working principles (Fig. 2a–g) for the capture or concentration of Li^+ cations were assessed from compiled data (Supplementary Table 2). An analysis of the chemistry of the diverse materials (adsorbents, membranes, insertion electrodes, solvents) in these reports is beyond the scope of this Review; however, interested readers are referred to several previous reviews^{50,58,59,65,66,75–78}. The capture or concentration of Li^+ ions is a crucial processing step. However, native brine pre-processing (for example, heating or adjusting the pH of the brine) is often needed for the key DLE step to work. Furthermore, most proposed DLE technologies do not directly produce a pure lithium product but instead a purified solution that thus requires post-processing (Fig. 2h).

Testing of different lithium sources

Lithium brine processing involves the separation of a very diluted species, Li^+ , from a broth containing other much more concentrated species with similar chemical properties (Fig. 3 and Box 2). However, real brines were tested in only 30.4% of the analysed reports (Supplementary Fig. 1). Technology validation on simulated solutions is acceptable, provided that these solutions mimic reported ion concentration values for real brines. Unfortunately, this is often not the case, as 24.1% of the analysed reports work with either a single salt or binary mixtures (Supplementary Fig. 1). Matching ion concentrations to those of real systems is often achieved for Li^+ and/or Mg^{2+} but not for other ions^{79–82}. In addition, the effect of divalent cations is omitted⁸³ or the effect of anions other than Cl^- is not considered⁸⁴. Beyond the specific chemistry of ions that are not included in these laboratory experiments, the activity coefficient of Li^+ and the ionic strength of the solution are also modified in the absence of these ions. For example, Na^+ and K^+ have often been omitted or included at concentrations very similar to that of Li^+ (refs. ^{85–87}).

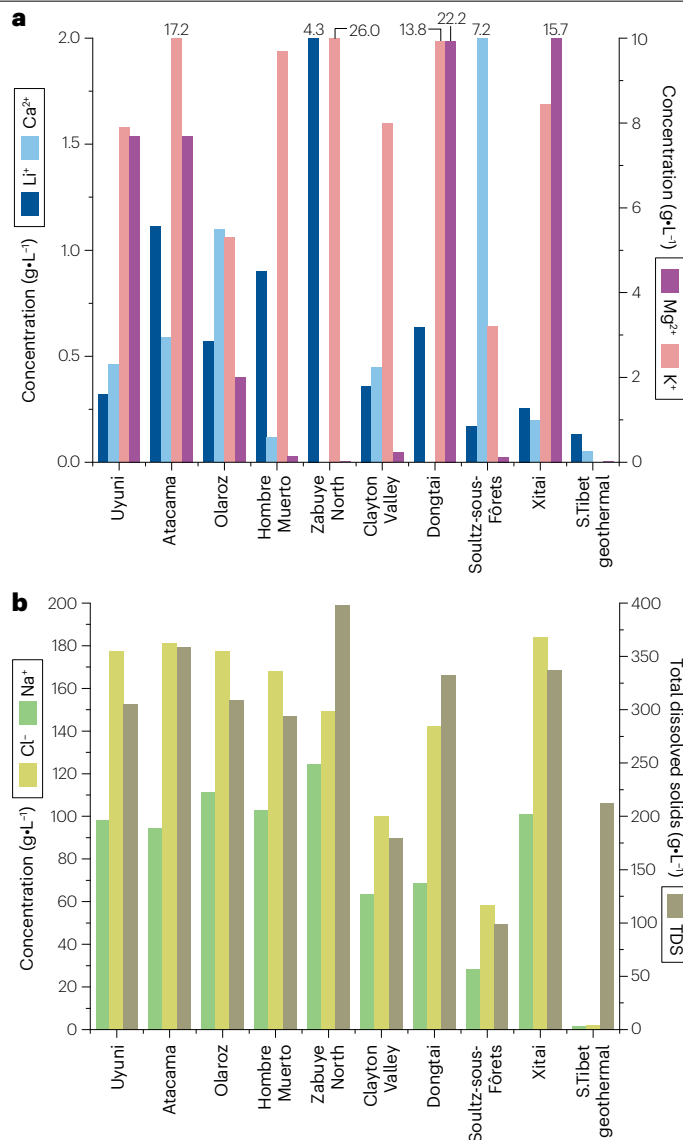


Fig. 3 | Ion concentrations in selected continental and geothermal brines worldwide. The concentrations of Li^+ , other ions, and total dissolved solids in brines. The data are provided in Supplementary Table 1. **a**, Li^+ , Ca^{2+} (left axis), and K^+ and Mg^{2+} (right axis) concentrations. **b**, Major species, Na^+ and Cl^- (left axis) and total dissolved solids (TDS, right axis). Numbers on the bars correspond to concentrations that are larger than the corresponding Y-axis maximum. Li^+ is usually the most diluted species and always 10 times more diluted than Na^+ .

In an analysis of the composition of the test solutions in 77 articles (Supplementary Table 2), only 41 test solutions contained Mg^{2+} and only 33 contained Na^+ , of which only 34 and 23 (respectively) report changes in the concentrations of these ions after DLE. The different DLE technologies result in reductions in the $\text{Mg}^{2+}/\text{Li}^+$ (Fig. 4a) and Na^+/Li^+ (Fig. 4b) concentration ratios after processing, but the magnitude of the change is markedly different. Moreover, many studies depart from solutions with Na^+/Li^+ molar ratios below 5. These results highlight how many reports work with solutions that do not mimic real brines (Box 2).

Box 2

Inorganic chemistry and process engineering concepts relating to Li⁺-rich brine processing

A few simple concepts are at the root of any processing technology for selective recovery of lithium compounds from aqueous solutions. First, Li⁺ is only a minor component in a multicomponent solution of high ionic strength — in the very best scenario, Li⁺ only accounts for about 1.5% of the total dissolved solids (Fig. 3). Second, Li⁺ is mixed with cations exhibiting very similar chemical properties. For example, the ionic radii of Mg²⁺ and Li⁺ are almost identical. Mg²⁺, and most multivalent cations in general, will directly crystallize in the presence of either CO₃²⁻ or OH⁻ species; consequently, complete abatement of multivalent cations is essential if high purity Li₂CO₃ or LiOH is the desired final product⁸⁹.

In addition, the Na⁺/Li⁺ concentration ratio is approximately 60–120 (in units of mass), whereas the K⁺/Li⁺ ratio is approximately 3–10 (refs. 19,103) (Fig. 3 and Supplementary Table 1). Although most Na⁺ and K⁺ salts are usually much more soluble than their Li⁺ counterparts¹⁴⁴ (Supplementary Table 4), the difference in concentrations eventually requires a reduction of these concentration ratios. The chemistry of the three monovalent cations is again very similar, but unlike with multivalent cations, complete abatement is not necessary.

Two examples involving the use of Li⁺-selective membranes were analysed (Fig. 2c, left), which were able to increase the Li⁺/Na⁺ molar ratio by 2.84 (ref. 60) and showed an Li⁺/Na⁺ separation factor of 2.2 (ref. 87). These are very promising results, although it should be noted that in both examples the starting Li⁺/Na⁺ molar ratio was 1, which is quite different from native brine concentrations (Fig. 3). If the selectivity could be maintained for lower Li⁺/Na⁺ ratios, then the final solution would be enriched in Li⁺ but would still have a higher concentration of Na⁺ than Li⁺. Alternatively, the methodology might work as part of a more complex processing strategy that involves pre-processing and post-processing steps (Fig. 2h).

Electromembrane processes with commercial membranes are another interesting case example to illustrate the importance of using realistic concentrations. By varying temperature and applied voltage over a wide range, there were no experimental conditions in which Li⁺ could be selectively separated from either Na⁺ or K⁺ (refs. 85,86,88). Thus, attempting cation extraction through a cation-selective membrane will only concentrate a mixture of Li⁺, Na⁺ and K⁺. Despite this obvious limitation, research on electromembrane processes is still largely focused on separating Li⁺ from Mg²⁺ by testing binary solutions⁸⁸. However, by using simple electrodialysis setups only, currently Li⁺ cannot be separated from the other monovalent cations in native brines⁸⁹.

Because of the difficulty in comparing results obtained using solutions of different compositions, a proposal was put forward that the scientific community should agree to the use of a standard concentration of brine⁶⁵. This is important from an academic perspective. However, reported data show that not all methods will be equally efficient for all concentrations. For example, Li⁺ recovery ratios increasing from 66% to 80% were obtained when four solutions with Li⁺ concentrations

Next, the brine volume that needs to be processed should be considered. A simple mass balance shows that for a hypothetical brine that is 700 ppm Li⁺, 383 m³ of brine will need to be processed to obtain 1 tonne of Li₂CO₃ (ref. 18). Another hypothetical feed with a Li⁺ concentration of 100 ppm requires processing of 2,684 m³ tonne_{Li₂CO₃}⁻¹ (considering a 70% overall recovery). For example, for a facility to produce 20,000 tonnes of Li₂CO₃ annually, it would need to process 7,668,254 m³ of a 700 ppm Li⁺ brine annually (averaging 21,009 m³ of brine processed daily). These volumes directly testify to the size of the equipment that will be required, imposing limitations on the technology of choice. For example, methodologies that are well established in related separation fields might not be applicable to brine processing owing to the volumes required. The same reasoning applies to environmental concerns. For example, in solvent extraction technologies, with potential spillovers, the volume of organic reactants is generally on the same order of magnitude as the volumes of aqueous phases (although the solvent is recirculated). Finally, because NaCl is usually the major component in all Li⁺-rich sources, corrosion-resistant equipment will need to be used.

from 0.14 to 1.03 g l⁻¹ and varying total salinity were tested on the same selective electrodialysis setup⁸⁵. For a titanium oxide, the absorption capacity was tripled⁹⁰ when increasing the Li⁺ concentration from 50 to 500 mg l⁻¹. For the five technologies for which Li⁺ recovery data were compiled (Fig. 4c), large divergences are explained by different specific chemistries in each report, but also by concentrations in the tested solutions. An industrial-scale mining facility could therefore be implemented if a given methodology applied to a real native brine produces a high recovery rate, among other performance indicators. If the performance of this methodology is reduced for other Li⁺ concentrations, it should still be implemented in the first instance. Thus, we believe that it is still important to perform tests on different brine compositions, provided that these mimic the concentrations of some real deposits.

Fate of spent brines

In most of the analysed reports, with very few exceptions, a spent brine is produced, as most of the DLE technologies discussed here are focused on the selective capture of Li⁺ cations only (Fig. 2). This issue pertains to both geothermal and continental deposits but very often is not even mentioned¹⁸. Many researchers and technologists propose the re-injection of spent brines^{18,91–93}, although from a technological perspective re-injection could dilute a valuable resource^{18,36}. For example, in 80% of the cases in geothermal fields, re-injection wells show a rapid interference with production wells⁹⁴.

Little practical knowledge is available regarding brine re-injection in salar basins, although re-injection could disrupt the layered stratigraphic structure of these basins¹⁸. Considering varying geological structures (Box 1), each deposit should be modelled and analysed

individually to assess the risks and benefits of re-injection. Finally, spent brines are likely to contain chemical species that are exogenous to the salar, because of the leaching of active materials from DLE setups or altered pH. These changes might affect the surrounding ecosystems. On cycling, many adsorbents or electrodes slowly dissolve in brines (Supplementary Table 2), whereas solvent solubility in brines on the order of 200 ppm has been reported¹⁹.

An alternative to re-injection is the slow evaporation of spent brines in open air ponds, which overcomes the slowness of evaporitic technology in terms of production of lithium salts, but still results in evaporative loss of precious water and the production of waste. A second, higher cost option is the use of advanced technologies for desalination of hypersaline brines^{95–103}.

Resources and inputs in DLE

In this section, we analyse aspects relating to fresh water, chemicals and energy consumption, including, as far as possible, inputs and outputs for an overall processing scheme (Fig. 2h) and the requirements for pre-processing and post-processing.

Freshwater usage

Freshwater consumption with current evaporative technology is 22.5 and 50 m³ per tonne Li₂CO₃ for Salar de Atacama and Salar de Olaroz, respectively^{104,105}. These numbers should be considered a reference for comparison, as the freshwater consumption of current practice already raises environmental concerns.

Freshwater inputs are essential in some DLE technologies (Fig. 2). Ion exchange resins, solvent extraction, electromembrane processes and Li⁺ insertion electrodes all require fresh water for Li⁺ elution from a sorbent phase. We compiled data on the freshwater requirements of ion pumping, solvent extraction and ionic exchange resins from 57 articles in the period 2017–2022 (Fig. 4d and Supplementary Table 3). A quarter of these reports do not provide freshwater consumption data, 13 use lower amounts than current practice and 9 require similar amounts. A quarter of the analysed articles report freshwater requirements of over 500 m³ per tonne Li₂CO₃, over 10 times greater than that used in current practice. These volumes of fresh water are not available in the vicinity of salars and would even pose problems around less-arid geothermal resources. Although we acknowledge that the aim of many academic papers is to prove new concepts or materials and not ascertain the engineering details of working conditions, the data in Fig. 4d draw attention to a topic that is hardly ever studied.

One mining operation has been active at Salar del Hombre Muerto (Fig. 1a) since 1996, and this location is a full-scale example of a DLE facility in practice. Li⁺ is selectively captured in ion exchange resins and subsequently, a fairly pure LiCl solution is recovered by elution with fresh water^{19,106,107}. Freshwater volumes required for elution have not been disclosed^{18,19}. The overall water use of the entire facility is reported as 71 m³ per tonne Li₂CO₃ (ref. ¹⁰⁷), 200% and 50% higher than the volume used at Salar de Atacama and Salar de Olaroz, respectively, highlighting that a given DLE might be more water-intensive than standard evaporitic technology.

Mining in Salar del Hombre Muerto testifies to another often neglected issue with many DLE technologies. The solution eluted from adsorption resins is about 10 g l⁻¹ Li⁺ (ref. ¹⁹), which is not considered concentrated enough for crystallization of a pure lithium product. Consequently, the solution is thus sent to evaporation ponds for further concentration^{19,106} (Fig. 2), although for shorter intervals than in standard evaporitic technology. For any DLE technology that produces

an effluent solution that is not concentrated enough, solutions will need to be concentrated by either time-consuming evaporation ponds, with consequent water loss, or ancillary complementary technologies that require high energy inputs. The latest sustainability report of the company operating in Salar del Hombre Muerto mentions an intention to install a mechanical evaporation unit¹⁰⁷, which could be seen as an acknowledgement of the high freshwater consumption (mentioned earlier).

Data on the final Li⁺ concentration after elution are shown in Fig. 4e, using the same data compilation sources as Fig. 4d. Final concentrations are not reported in 20% of the articles, 50% of the articles report elution concentrations that are below the average continental brine concentration (0.5 g l⁻¹) and only 10% report Li⁺ concentrations that could be considered sufficient for direct crystallization of Li₂CO₃. Most of those articles highlight the purity of the Li⁺ solution in comparison to the original solution. However, these pure but dilute Li⁺ solutions will require either solar evaporation or energy-consuming evaporators.

Evaporitic technology seeks to concentrate the brine to both crystallize other salts and produce a substantial increase in Li⁺ concentration. A change of perspective has been proposed by some researchers, with the aim of water recovery while the brine is being concentrated. Membrane distillation^{73,74,108–110} is a thermal method that has achieved freshwater recovery rates of 22.5 kg m⁻² h⁻¹ (ref. ¹⁰⁸) and 3.5 kg m⁻² h⁻¹ (ref. ⁷³) for lower and higher salinity feeds, respectively. These values are much higher than the evaporation rate at Salar de Atacama (0.37 kg m⁻² h⁻¹)¹⁹. Thus, not only is fresh water recovered but processing is also faster. A classical solar still at Salar de Olaroz achieved a lower performance, with a water recovery rate of 0.083 kg m⁻² h⁻¹ (ref. ¹¹¹). Another approach for water recovery used graphite-promoted cyclopentane hydrate formation¹¹². All three systems can be classified as assisted brine concentration (Fig. 2g).

Energy input

Energy requirements are yet to be provided for most DLE technologies. Cost analysis (Supplementary Table 2) and optimization processes are rarely reported^{85,113–115}. Energy requirements are frequently reported only for the key DLE step, with a complete disregard for that of pre-processing and post-processing steps or ancillary equipment (Fig. 2h). For example, in an electrochemical ion-pumping process, the mechanical energy to pump solutions through the electrochemical cells was calculated to be 300-fold higher than the energy required to drive the electrochemical reactions^{83,84}. However, often only the electrical work required for an electrochemical process is calculated^{65,79,85,114,116–120}. The energy value of a single step is relevant but it is only a lower bound. Owing to this frequent partial reporting of energy requirements, it is not possible to make comparisons.

In addition, it is important to consider that pre-processing is a crucial DLE step that must be performed on very large brine volumes (on the order of 21 million litres per day). A thorough study of the efficiency of lithium manganese oxide as a Li⁺ adsorbent found that heating the brine from 10 to 80 °C increased the Li⁺ adsorption efficiency from 15% to 70%, with a consequent increase in separation efficiency from other cations⁵². Other ion exchange resins also show improved absorption efficiency at higher brine temperature^{121–125}. However, operational costs increase considerably if brine volumes on the order of 21,000 m³ daily (Box 2) need to be heated to approximately 80 °C. Brine heating is definitely an energy input that should be considered in the overall process analysis (Fig. 2h).

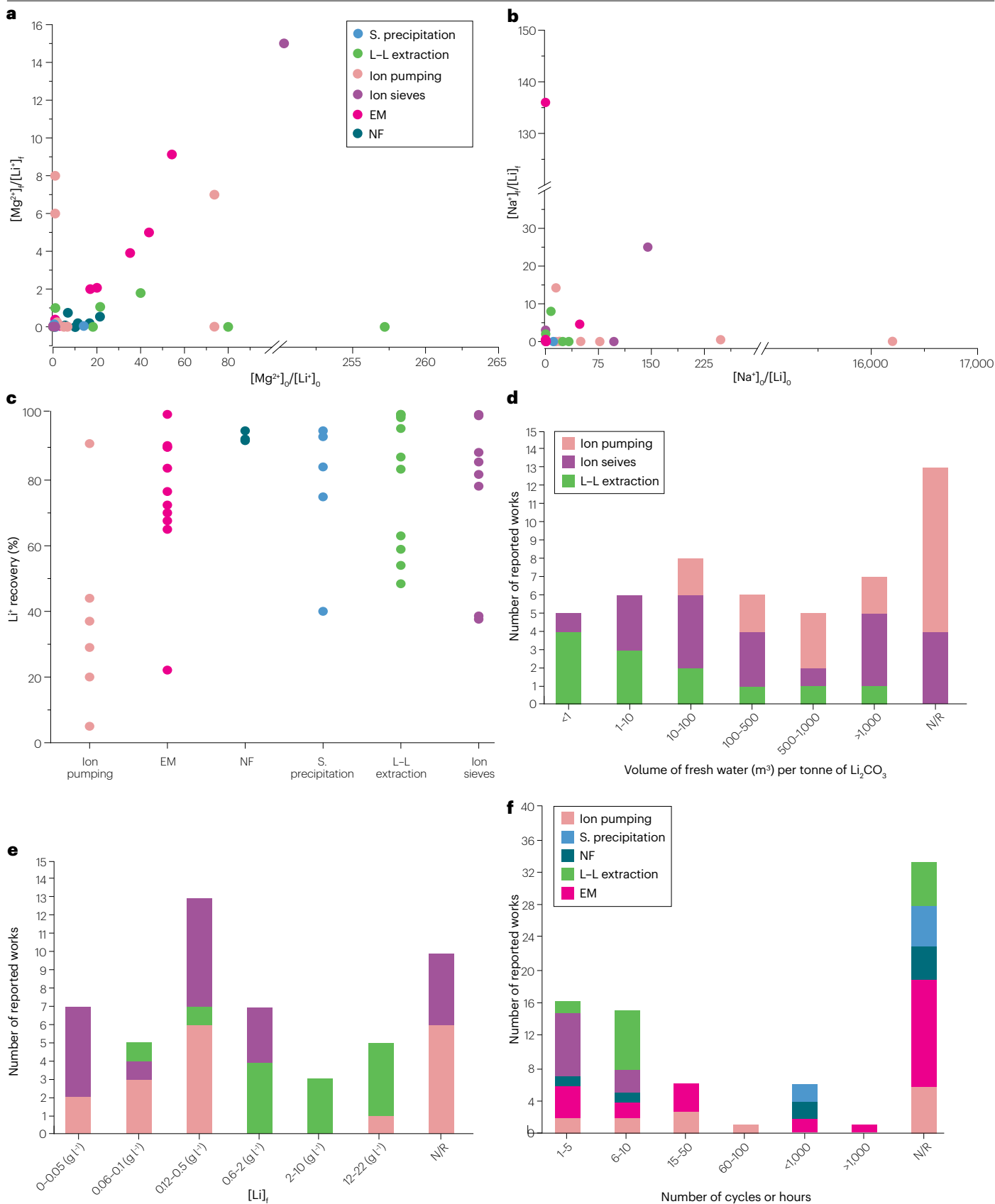


Fig. 4 | Brine processing performance indicators. Full data compilation and data sources are provided in Supplementary Table 2. **a**, $\text{Mg}^{2+}/\text{Li}^{+}$ concentration ratios before ($_{\text{b}}$) and after ($_{\text{f}}$) processing (in molar units). **b**, $\text{Na}^{+}/\text{Li}^{+}$ concentration ratios before and after processing (in molar units). **c**, Li^{+} recovery, defined as the percentage of the absolute amount of Li^{+} in the feed that is recovered in the output solution or solid. **d**, Varying freshwater requirements for direct lithium extraction (DLE) technologies. **e**, Varying final Li^{+} concentrations in the recovery

solutions after DLE. For parts **d** and **e**, only articles on ion pumping, solvent extraction and ion exchange resins were analysed. **f**, Number of reported articles in which materials are cycled or used for a medium–long period of time. NF, nanofiltration; EM, electromembrane processes. S, precipitation, selective precipitation; L–L extraction, liquid–liquid extraction. DLE efficiency can be assessed by different performance indicators, and future research should focus on achieving competitiveness in several performance indicators simultaneously.

In the case of continental brines, it is important to recall that most deposits are located at high altitudes and at latitudes where the average annual horizontal global solar irradiation values are above 2000 kWh m^{-2} (ref. ¹²⁶). These values are among the highest on Earth, making these ideal locations for solar energy harvesting. Installation of photovoltaic cells or solar-concentrating power capacity will increase the capital cost of a mining project but will strongly reduce the operational cost. For the current evaporitic technology, for which the precise energy requirements are known, parabolic trough solar collectors and linear Fresnel reflectors were analysed as options to provide thermal or electric energy in northwest Argentina, with and without thermal energy storage¹²⁷. A parabolic trough plant for electric power generation coupled with energy storage provided a more substantial diversification of the energy matrix than other energy generation and storage configurations. Solar energy could reduce natural gas consumption over 51% and produce an annual CO_2 mitigation of $403.3 \text{ gCO}_2 \text{ kg}^{-1} \text{ Li}_2\text{CO}_3$ (ref. ¹²⁷).

Scaling-up requirements and potential

Published demonstrations of scaling up are scarce^{58,59,78,85,114,128,129}, although it should be acknowledged that these efforts are rarely reported in academic journals¹³⁰. Different technology readiness levels have been reported in the vast field of DLE. With one full-scale facility in operation since 1996¹⁹, ion exchange technologies have an advantage. In addition, provided that efficient operational parameters are found, scaling up could be relatively straightforward for some technologies. For solvent extraction and some electromembrane and thermally assisted brine concentration processes, large-scale plants for the separation of other chemicals are already in place and equipment could be adapted fairly easily. The challenge with adjusting these processes is the application of a known methodology to a new, highly complex chemical system. Conversely, for other methodologies, notably, membrane distillation and ion pumping, no large-scale implementation has yet been developed.

Beyond successful proof-of-concept experiments of new ideas or materials, to increase the technology readiness level, the overall process must be analysed and both inputs and outputs quantified (Fig. 2h). We have already highlighted that energy and freshwater consumption need to be optimized to increase technology readiness levels. Other important aspects that need to be addressed are discussed subsequently.

Irrespective of the technology, long-term performance of the active materials responsible for the selective Li^{+} capture is key. Of 77 analysed reports, 22 do not show any cycling data (Fig. 4f). When data are reported, the average number of cycles is fewer than 10 (that is, <100 h)^{83,131–135}. For the different LiMn_2O_4 -based ion exchange systems, Li^{+} adsorption capacity is reduced by 17.2% after 50 cycles¹³⁶, 2.5% after 5 cycles⁵² and 43% after 30 cycles¹³⁷, pointing to the importance of medium-term to long-term stability tests. Active materials get inactivated¹³⁸ or they are dissolved into either the spent brine or the recovery

solution. Again, the dissolution rate for LiMn_2O_4 is 2.53–4.60% in 5 h of continuous operation¹³⁹, whereas the reported dissolution rate for titanium is approximately 0.25–0.31% for every cycle¹²¹. These very preliminary numbers suggest that the active materials will need to be changed within months. Although this performance is not necessarily poor, it should be evaluated from the perspective of the environmental liability of waste disposal of spent active materials, their costs and the duration for which active material replacement would stop production.

Input of chemicals in DLE processes is another largely neglected topic. Aside from cost, another issue is the transportation of these chemicals to often remote locations¹⁸. In principle, electrochemical methods (Fig. 2c,e) do not require the addition of chemicals, as the driving force is the application of an electric field. However, ion exchange resins and solvent extraction often require that the pH of solutions be changed^{52,140,141}. For example, LiMn_2O_4 seems to be more efficient when the brine pH has been adjusted to values around 10–11 (refs. ^{52,139,141}). Large volumes of brine are processed daily (Box 2), so pH adjustment of $21,000 \text{ m}^3$ of brine will require non-negligible acid or base amounts. Chemical inputs are also required for elution. For example, elution of Li^{+} with an LiFePO_4 -based ion exchange resin requires a $5 \text{ g l}^{-1} \text{ Na}_2\text{S}_2\text{O}_8$ solution (ref. ¹⁴²). Selective precipitation of Li_3PO_4 requires phosphate salts or phosphoric acid⁷⁰ (Fig. 2f). Some approaches, notably those that require phosphate salts, consider the possibility of recycling chemicals to minimize waste and to reduce the constant transport^{71,72}. Unfortunately, regeneration is not always possible. For example, if the brine pH is modified to increase Li^{+} recovery, it is difficult to envision how to regenerate the acid or base.

Another aspect to be considered is final product purity^{71,75}, as various species with water solubility similar to lithium products could co-precipitate during crystallization (Supplementary Table 4). The importance of Mg^{2+} cation removal has been extensively highlighted^{117,120,143}. Removal of NaCl , KCl , Na_2CO_3 and K_2CO_3 will be straightforward by freshwater washing owing to their high-water solubilities¹⁴⁴. However, there are few reports on the potential difficulties in removing borates, Ca^{2+} and SO_4^{2-} products that could co-crystallize with lithium products¹⁴⁴. Experiments with solutions that do not contain these species will likely produce misleading product purity values. Thus, tests on real brines are a necessary key step that should be undertaken for reliable assessment of final product purity^{77,89}.

The circular economy approach

Evaporitic technology produces large amounts of waste. Essentially, all brine constituents other than Li^{+} cations end up as salt mixtures that accumulate in the vicinity of the brine deposits and pose a risk of slow leaching following infrequent rain. The precise amount of waste is estimated by considering brine composition and the recovery ratio. On average, waste production is 115 tonnes per tonne of Li_2CO_3 (ref. ¹⁸). For an annual production of 20,000 tonnes, after 10 years, $1.15 \times 10^7 \text{ m}^3$ of waste will have accumulated, which, if disposed of at the ground level (Fig. 1b) at a height of 1 m, will occupy an area of 11.5 km^2 (ref. ¹⁸).

Glossary

Brine

Aqueous solutions of extremely high ionic strength, with total dissolved solids values of 100–400 g l⁻¹, most solids are inorganic salts.

Circular economy

A model of production and consumption. Following the European Union definition, it involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as much as possible.

Continental brines

Continental brines are found in underground reservoirs within salars, typically in locations with arid climates.

Fresh water

Low salinity water, typically <3 g l⁻¹ TDS, although this cut-off value varies.

Life-cycle analysis

A quantitative methodology implemented to evaluate the environmental impact of a given product through its entire life cycle, from extraction and processing of raw materials, manufacturing, distribution, use, potential recycling and final disposal.

Lithium Triangle

A region encompassing northwest Argentina, southwest Bolivia and northern Chile, where a large concentration of lithium-rich deposits is found.

Native brines

Real brine samples, continental or geothermal brines as they are pumped from underground reservoirs, before undergoing any processing or chemical treatment.

Oilfield brines

Brines that are found during deep rock penetration by drilling during oil and gas extraction and considered as waste by these industries.

Phreatic evaporation

Refers to evaporation of shallow groundwater into the atmosphere directly from the soil through the porous ground surface.

Salar

Salars (Spanish term for salt lake or salt flat) are endorheic sedimentary basins containing thick sequences of continental evaporites and clastic deposits.

Salar de Atacama

The third largest salar in the Lithium Triangle, located in northern Chile; the two largest facilities for lithium mining from brines are located here.

Spent brines

Brine that has undergone processing via some direct lithium extraction technology; with Li⁺ concentration largely depleted, but concentrations from other species similar to native brine.

Total dissolved solids

(TDS). The sum, by mass, of all solids dissolved in an aqueous solution, irrespective of their chemical formulae.

Water table

Surface below which water (or brine) fills any spaces between sediments or rocks. At the water table level, water and atmospheric pressure values are equal.

Sustainable raw material sourcing is interlinked with the idea of the circular economy. Recycling of lithium-ion batteries as a secondary source of raw materials³⁰ is certainly important in the long term. However, in a scenario of continuous growing demand, relying on sourcing from recycling only will not be enough to satisfy this demand^{145–147}. The amount of lithium from spent batteries in 2040 is estimated at 60 ktonnes per year, which corresponds to 5% of the total supply requirements⁷. From a circular economy perspective, research on resource recovery from mine tailings is becoming an active field^{148–153}. In addition, processing of mineral resources should be designed for the simultaneous recovery of two or more products.

Brines are not only lithium resources but also potential sources of magnesium, potassium, calcium, sodium and boron products (Fig. 3 and Supplementary Table 1). None of these products has a market value comparable to pure lithium products, but they are still ubiquitous raw materials in many industrial processes. Variations in brine compositions lead to different amounts of recoverable by-products (Fig. 5), for the lithium deposits shown in Fig. 1a. Except for calcium, these amounts are larger than the equivalent amount of recoverable lithium carbonate.

Although not scarce, magnesium production is limited geographically¹⁵⁴, with ~95% of magnesium chemicals worldwide currently sourced from China. The European Union has therefore listed both magnesium and magnesite as critical raw materials¹⁵⁵. For Salar de Atacama (Fig. 5), MgCl₂ production could potentially be as high as 17-fold the annual production of Li₂CO₃ (refs. ^{18,19}). In turn, KCl is a fertilizer that could be widely used in the vast agricultural soils of South America. Evaporitic technology can be tailored for the joint recovery of Li₂CO₃ and KCl^{156,157}. Indeed, the two mining facilities in the Salar de Atacama jointly recover these two products^{19,156,157}, but this setup is not in place in any of the other six global active facilities we reviewed here.

Despite the favourable context, the large majority of DLE proposals only focus on the selective recovery of lithium products. Among very few examples, one scheme proposes using electromembrane processes for the concomitant production of MgCl₂, MgSO₄, NaCl, KCl and Li₂CO₃ (ref. ⁸⁵), whereas another strategy produces fresh water and Mg(OH)₂, Ca(OH)₂, Na₂CO₃ and Li₂CO₃ (refs. ^{116,117,120,135,143}). Finally, production of fresh water as a by-product during brine concentration^{73,108,111,112} (Fig. 5) as discussed previously should also be considered as contributing to the circular economy.

Summary and future perspectives

In this Review, we present the limitations of the current evaporitic technology for lithium carbonate production from aqueous sources. Water imbalances during mining^{25,26,33,35,37}, in addition to the inherent slowness and its applicability to continental brines only, are major limitations of evaporitic technology. DLE technologies represent an alternative to evaporitic technology, and we classify DLE technologies according to seven general physico-chemical working principles.

Some proposed DLE approaches, such as ion pumping or Li⁺-selective membranes, are completely new and will require more ample engineering efforts to reach industrial scale. Conversely, other proposals, such as ion exchange, solvent extraction or electromembrane processes, have been studied for decades in related industrial separation chemical engineering processes, and the challenge here is to adapt these methodologies to the complexity of lithium-rich brines. Laboratory tests with real brines or solutions that closely mimic real compositions are paramount to increase the readiness level of these technologies. Another important point when aiming at scaling up from laboratory to industrial scale is the huge brine volumes to be processed daily. The analysis performed at laboratory scale in wide pH

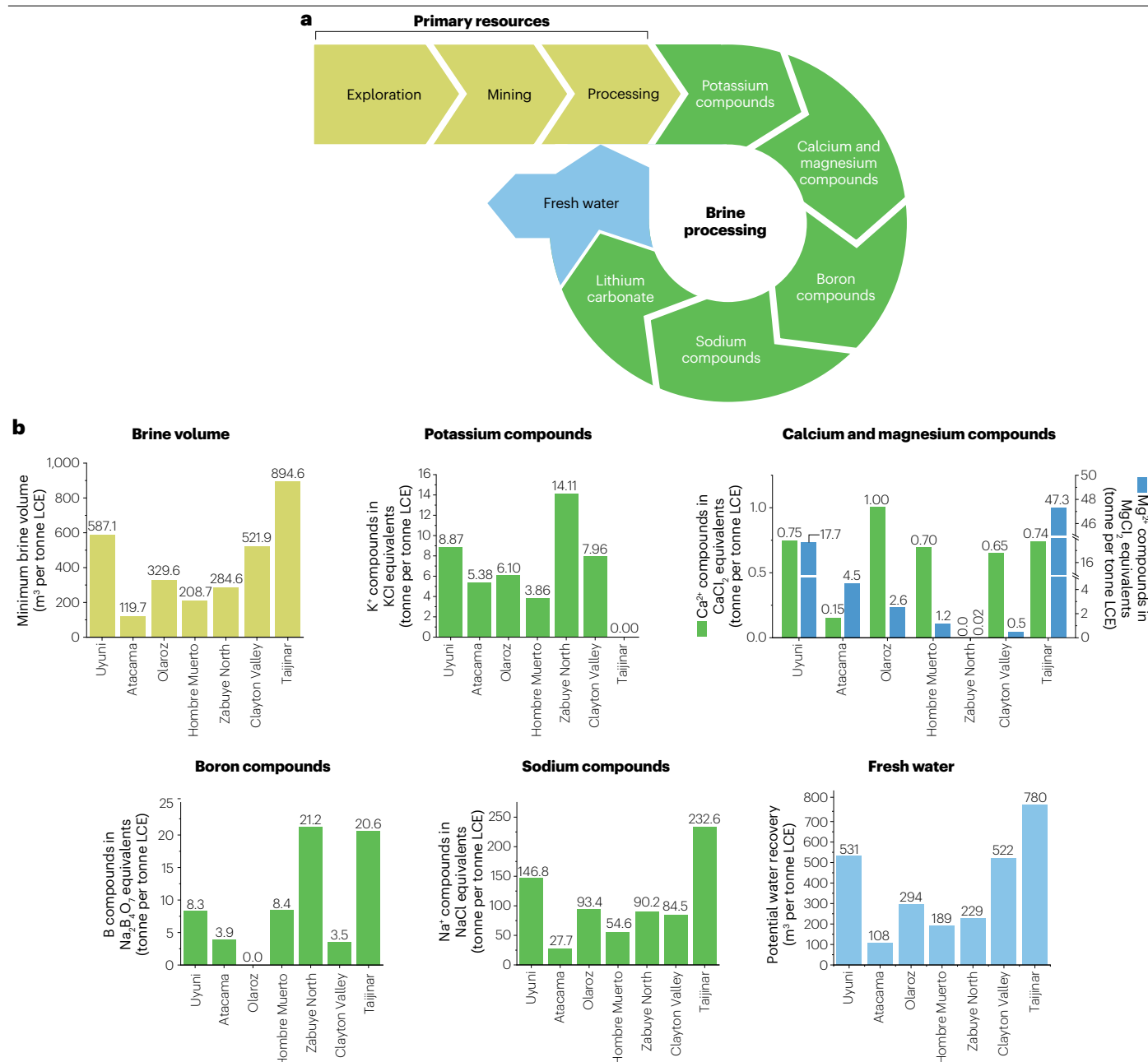


Fig. 5 | Lithium mining in a circular economy framework. **a**, Brine exploration, mining and processing could be tailored for the joint recovery of several minerals from lithium-rich brines. **b**, The volumes of fresh water and by-products that could be recovered while producing 1 tonne of Li₂CO₃ equivalent (LCE) were calculated on the basis of reported brine concentrations

listed in Fig. 3 and Supplementary Table 1. A recovery efficiency of 100% and brine density of 1.2 g l⁻¹ were assumed. If most salts are recovered from brines, fresh water could also be produced and used in the overall mineral processing and for irrigation.

and temperature ranges makes for interesting academic research, but are less likely to contribute to technology implementation. Moreover, the remote location and the aridity of many deposits, particularly continental brines, create logistical issues and add extra costs in transporting chemicals, providing energy away from the grid and securing scarce freshwater sources.

DLE should be assessed as part of an overall mining and processing approach, from brine pumping to obtaining the final product. Although many advances have been produced regarding the specific operational unit for selective lithium capture or brine concentration, a lot of research remains to be undertaken regarding both earlier and later steps in the process. Ideally, DLE should completely avoid brine

evaporation in ponds and thereby have a lower water footprint than evaporitic technology. Production of fairly pure LiCl or LiOH solutions instead of a solid lithium product is often reported, indicating that evaporation ponds might still be necessary to complement some DLE technologies.

The concentration of Li⁺ that can be achieved through different DLE approaches is another aspect that is seldom reported. For comparison, in evaporitic technology, precipitation is only attempted at lithium concentrations greater than 5–6 g l⁻¹. Even at these concentrations, a large percentage of Li⁺ is not recovered and effluents are sent back to the ponds for further evaporation. DLE should produce solutions with Li⁺ concentrations greater than 25 g l⁻¹, otherwise an additional concentration method will be necessary. Thermal methods for concentrating solutions are costly. Thus, if DLE produces LiCl-diluted solutions, open air evaporation is likely to be used, leading to the same issues as with evaporitic technology.

The inflating prices and high demand of lithium compounds have obscured the potential of both continental and geothermal brines as sources of other important raw materials. Following the circular economy concept, new processing methodologies should be developed that consider the simultaneous or sequential recovery of multiple by-products. Currently, some deposits in the Lithium Triangle are used for the production of borates, others for lithium carbonate and still others for sodium chloride. The simultaneous recovery of as many by-products as possible at a single deposit might require fewer mining facilities and produce lower amounts of waste. The harvesting of energy and the simultaneous recovery of lithium products at geothermal fields might bring similar benefits. A lot of knowledge could be transferred from related fields such as desalination of hypersaline brines^{100,102,158,159}, resource recovery from brines produced in seawater desalination^{160,161} and mineral carbonation¹⁶².

The effects of the lithium mining industry on the environment can be assessed by examining the following strongly linked indicators: waterflows, soil composition and ecosystem biodiversity. Physico-chemical parameters and biota are also fundamental in biogeochemical cycles^{163,164}. Ecosystems in the vicinity of lithium deposits are extremely fragile and linked in a food chain in which ecosystem services are crucial for livestock and rural populations^{38,43,165}. Soil composition could be affected by decreasing water tables, but also leaching or drainage from accumulated waste, which could produce an increase in soil salinity^{166–168}.

Records are necessary to assess waterflows, including reliable year-round precipitation data, river flows and a sufficient number of observation wells to follow in real time the water tables at different locations³³. Precise hydrogeological modelling with accurate data regarding brine and freshwater well characteristics is a must, considering the exploitation of underground aquifers in lithium mining. Some researchers have suggested that a conceptual model for one deposit can be extrapolated to others, but our opinion is that each deposit requires a separate model owing to their unique hydrogeological characteristics. Numerical models attempting to quantify¹⁶⁹ reduced evaporation rates are very strong qualitative indicators of the impact of lithium brine mining, but the quantitative figures obtained should be used with caution. Even researchers putting forward the concept of damping capacity acknowledge that a 0.5 m error in water table depths would modify the predicted evaporation rate by 60% (ref.³⁵).

Lithium extraction should be continuously monitored from the start of exploitation, as environmental impacts might only be observable over the long term⁴³. Finally, in addition to monitoring by mine

operators themselves, more measurements should be performed by independent experts or national authorities, a fundamental safeguard that is often not in place in South America¹⁷⁰. Although these suggestions have been drafted with evaporitic technology in mind, they should hold for the application of any DLE technology, which will still consume brine and fresh water and produce residues. However, DLE will likely consume brine and fresh water in considerably less volumes than the evaporitic technology.

Published online: 23 February 2023

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Acknowledgements

M.L.V. acknowledges a post-doctoral fellowship from Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). W.R.T., C.I.G. and V.F. are CONICET permanent research fellows. This work was supported by Agencia Nacional de Promoción de la Investigación, el Desarrollo Tecnológico y la Innovación (ANPCyT), AR (grant number PICT 2019–1939).

Author contributions

M.L.V., W.R.T., A.C. and V.F. researched data for the article. M.L.V., W.R.T. and V.F. contributed substantially to discussion of the content. All authors wrote the article. V.F. reviewed and/or edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43017-022-00387-5>.

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Peer review information *Nature Reviews Earth & Environment* thanks D. Alessi, W. Zhu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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