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Life cycle assessment of lithium carbonate production from brines, supported by material flow analysis

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Increasing demand for lithium-ion batteries necessitates a comprehensive environmental impact analysis of lithium carbonate (Li_2CO_3) production from brines to enhance the sustainability of lithium mining. This study addresses the limitations of previous research by using previously evaluated process calculations and focusing on the Salar de Atacama facility in Chile. It aims to identify and emphasize areas of concern and to establish a comparative framework. This will facilitate identifying the advantages of emerging and future processes compared to traditional methods. Using Life Cycle Assessment (LCA), supported by Material Flow Analysis (MFA) to construct the life cycle inventory (LCI), the research covers the state-of-the-art goal and scope definition, an LCI, and life-cycle impact assessment (LCIA) modelling. It employs the ReCiPe 2016 Midpoint method, using background data from the Ecoinvent database and foreground data from the process at Sociedad Química y Minera de Chile (SQM) Salar de Atacama and Salar del Carmen facilities. The findings present and discuss the results for the 18 impact categories, notably water consumption (218 m^3) and extensive land use ($327 \text{ m}^2 \text{ a crop eq}$), providing a holistic environmental impact assessment of Li_2CO_3 production.

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Sustainability spotlight

Results from life cycle assessment (LCA) studies on lithium mining from brines are not in agreement with field data around lithium brine mining sites. In addition to reports from local communities and NGOs, detailed scientific reports have disclosed alarming results relating to freshwater depletion in the areas of concern. This study presents an environmental analysis of lithium carbonate production, with a focus on Chile's Salar de Atacama. To address gaps in prior research, we incorporate calculated process data for a more site-specific assessment. The findings contribute to advancing sustainable mining technologies and support progress toward three UN Sustainable Development Goals: Affordable and Clean Energy (SDG 7); Responsible Consumption and Production (SDG 12); and Life on land (SDG 15).

1 Introduction

Global demand for lithium has increased since its first commercial production in the 1920s, with a marked acceleration since 2021. From 25 300 metric tons (t) of lithium content in 2010,¹ the demand increased to 150 000–180 000 t in 2022.^{2–4} The increasing demand for electric vehicles and energy storage in lithium-ion batteries is driving demand for lithium salts, mainly lithium carbonate (Li_2CO_3) and lithium hydroxide

(LiOH).^{2,5} Lithium consumption for batteries increased from 23% of the total production in 2010 to 87% in the year 2023.^{1,2,6–8}

Currently, lithium is economically recoverable from two primary resource types. It can be extracted from hard rock (mostly pegmatite containing spodumene) or native brines.^{2,3,9–11} Approximately 21 megatons (Mt) of the estimated 31.1 Mt of global lithium resources are contained in brine deposits.¹² Still, some brine resources are not yet economically exploitable due to insufficient recovery rates or unfavourable conditions.¹² Deposits in brines contain larger reserves, and brines are inherently easier and less costly to process than hard rock ores.⁹ Hence, more attention is paid to these deposits for the medium- and long-term supply. Lithium mining from brines relies primarily on natural open-air evaporation in large and shallow ponds. In addition, certain impurities in this resource, such as magnesium or boron, result in additional and extensive chemical processing,^{13–16} while soda ash (Na_2CO_3) is required for the final crystallization step. These aspects

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highlight the importance of optimizing technology to increase lithium recovery from brines, reduce production losses, and reduce the need for chemical reagents, land use, and waste generation. The wide variety of natural brine compositions underscores the need to adapt the process to each location.

While Garrett provides a detailed foundation for the lithium brine mining industry, it lacks an environmental impact analysis, including details on evaporation and chemical treatment of the concentrated brine.³ Recent studies focus on optimizing brine processing technologies, particularly Direct Lithium Extraction (DLE), which reduces reagent use and aims to reduce brine evaporation in open ponds, but increases energy consumption.^{17,18} Various recent studies examine environmental impacts, including water use, land use, and greenhouse gas emissions, and compare brine production with ore production or assess emerging processes to concentrate brine more efficiently.^{18–22}

Stamp *et al.* conducted a thorough Life Cycle Assessment (LCA) analysis in which three lithium sources (brines, ores, and seawater) were modelled under both favourable and less favourable conditions, assessing Ecoindicator 99 (EI99), Global Warming Potential (GWP), and cumulative energy demand.²³ Brine-favourable conditions are characterized by high Li⁺ content and high solar- and wind-driven evaporation rates. The low impact of lithium extraction under favourable conditions is one of the main conclusions of the LCA. However, the authors explicitly acknowledge that they disregarded water use (both freshwater and brine), by-products, and waste from salt crystallization in the ponds, leading in our understanding to overly favourable conclusions. Their research was incorporated in the Swiss environmental database Ecoinvent.^{23–26}

Ambrose and Kendall combined a life cycle assessment with lithium demand forecasts (2018–2100).^{2,27} The authors report low impacts for high-grade brines using TRACI (Tool for Reduction and Assessment of Chemicals and Environmental Impact). Unfavourable lower grades increase environmental impacts by requiring more chemicals and energy. It was emphasized that site-specific assessments, including social and upscaling factors, are important.²⁸

Kelly *et al.* used four LCA allocation methods and the GREET® model (Greenhouse Gases Regulated Emissions and Energy in Technologies).²⁹ They assessed life-cycle energy use, blue water consumption,³⁰ and emissions, but did not account for extraction waste, except for potash as a coproduct. Chemical inputs other than brine and soda ash are grouped as “other”. With these simplified inputs, they found lower greenhouse gas emissions, energy use, and water consumption (by one to two-thirds) for brine-based lithium compared to hard-rock lithium production. The study also contextualizes lithium’s impact on the overall cathode material.²⁹

Schenker *et al.* focused on the regional production of lithium carbonate from brines for battery applications.³¹ They report lower climate change (CC) impacts (GWP, 100 years) from Salar de Atacama than from Argentinean and Chinese production. Soda ash significantly contributes to health impacts related to particulate matter across all sites. Freshwater use at Atacama is contextualized in an arid region, showing minimal impact

relative to the Chaerhan Salt Lake (China) but high impact relative to other brine-based Li₂CO₃ production sites. The water scarcity footprint of Atacama is comparatively low. In their model, each process step has its own unit and is assembled to produce the Functional Unit of 1 t LCE (lithium carbonate equivalent) in the foreground model. Using this LCA practice makes comparison time-consuming.³¹ In a more recent article, Schenker and Pfister compare climate change and water scarcity of 25 production sites and four technologies to address data gaps and highlight hotspots.²¹

Chordia *et al.* compared current and future supply routes for lithium carbonate and hydroxide from brines and spodumene using various bibliographic and geographical sources.³² They highlight how the lithium concentration impacts water, energy, and chemical use. As in other studies, high-grade brines have lower impacts than low-grade brines, according to data from Ecoinvent and Kelly *et al.*²⁹. Due to data gaps, assumptions were made regarding chemical quantities, and remodelled comparisons were made using the ReCiPe (impact assessment method, containing 18 midpoint and 3 endpoint indicators) and AWARE (available water remaining) methods to calculate water consumption.^{26,30,32,33}

Mas-Fons *et al.* evaluated the carbon and water footprints of brine-based lithium from Atacama and Australian hard rock, using process simulations as the basis for Life Cycle Inventory (LCI) data, and highlight environmental impacts associated with evaporation ponds and brine pumping, especially for lower-grade brines.²⁰ Marinova *et al.* focused solely on the water-related impacts of SQM operations, using AWARE and WAVE+ (Water Accounting and Vulnerability Evaluation). Hotspots mentioned are electricity and soda ash.¹⁹

He *et al.* complemented this picture with a detailed, site-specific LCI for conventional evaporitic brine processing at the Salar de Atacama, built from SQM operational reports, Ecoinvent, and Aspen Plus simulations, using regionalized northern Chile grid data rather than the generalized assumptions of earlier lithium LCAs.²² Using ReCiPe 2016 and AWARE, among others, they find that NaOH and soda ash production drive most impacts, and that water scarcity stems from treating evaporated brine as consumed water. Their focus, however, is on process simulation and optimization, as well as predicting future grid adjustments.

Mousavinezhad *et al.* highlighted an important difference from previous studies: they focus on a DLE method and process development in Nevada.³⁴ The authors use TRACI for a general assessment, GWP and the AWARE method for water consumption, the Land Use Indicator (LUI) and satellite images for direct land use, and ReCiPe for indirect land use. The authors conclude that the energy source and the high impacts across several impact categories result from the use of soda ash.³⁴

To summarize, methodological fragmentation is a central issue across all studies. The authors focus on different functional units and impact assessment methods (EI99, TRACI, ReCiPe, AWARE, WAVE+, GREET, and CED); system boundaries sometimes exclude chemicals, water use, and allocation, or the analysis relies on databases, reports, or simulations. Therefore,

each study highlights only a subset of environmental impacts, making cross-comparison difficult and preventing a holistic understanding of lithium extraction's potential environmental impacts.

Salar de Atacama is most often recognized as the prime example of brine mining with favourable conditions for its high Li content and ultralow precipitation.¹⁷ Overall, low impacts have been calculated in most of the LCA studies described above under favourable conditions or for high-grade brines, such as those in Atacama. Strikingly, field data from the Atacama have revealed alarming results regarding freshwater depletion in the area. The area of lagoons in the Atacama was reported to shrink in winter.³⁵ Underground water storage has shown a decline since 2010;³⁶ in addition, reports on soil moisture indices have decreased since 1997.³⁷ Both results were obtained through satellite data. Sharp changes in water tables relative to pre-extraction values have also been reported.^{38–41} Decreases in evapotranspiration, which is directly linked to the groundwater table, have also been reported.^{35,41} Regarding fauna, a decline in flamingo abundance has been linked to lithium mining.^{35,42,43} A general trend toward sparser vegetated areas,^{35,37} together with the death of a large proportion of drought-tolerant carob trees, has also been recently reported.³⁷

Overall, the observed changes in the natural environment indicate existing environmental impacts. Reports are segmented and do not provide sufficient data to generate an overall sustainability measure.³⁶ However, there are clear indications of negative impacts that will be difficult to quantify due to the complex nature of hydrogeological studies. Research continues into hydrogeological impacts and environmental effects on communities around mining sites, with LCAs potentially underestimating long-term ecological changes.^{7,17,34,44–53} There is clearly a knowledge gap here: LCA calculations show very little impact, while field data show very negative impacts. Alarming field data could be suggesting that LCA calculations are underestimating lithium mining impacts.

This study aims to contribute to a more holistic and realistic understanding of lithium mining from brines and its environmental impact. Existing studies often lack site-specific data or scientific calculations and instead rely on company released figures. Some reports are mostly focused on a few LCA impact categories. Notably, comparability with other studies is important. The focus of the present study is on a detailed, clear presentation of the LCI for the production of lithium carbonate at Atacama (with further processing at Salar del Carmen) in northern Chile, and on the subsequent calculation of the 18 impact categories of the ReCiPe impact assessment method to provide a broader overview. The generated LCA results should be compared with those of emerging technologies once they reach a certain level of maturity. Process data are based on calculations of chemical energy and consumption to fill data gaps and improve accuracy, compared with sometimes vague industrial data.⁵⁴ To conduct the LCA, Ecoinvent²⁶ and SimaPro⁵⁵ are used as an environmental database for solid background data and as an LCA interface, respectively. The LCI and LCA results of this study should provide a more realistic overview of the environmental impacts associated with lithium

carbonate production from brine in the Atacama. Values for land use (327 m²a crop eq) and water consumption (218 m³) are much more consistent with field data than in previous reports.

2 Materials and methods

In accordance with the four LCA stages defined in ISO 14040, the goal and scope are determined, the LCI and the LCA model are composed, and the impact analysis is performed, followed by result interpretation.^{56,57} A Material Flow Analysis (MFA) was used as the methodological approach to track and reconcile mass flows across the process from the cradle (brine from underground deposits) to the production gate (where Li₂CO₃ is exported), providing the basis for constructing the LCI used in the subsequent LCA, rather than being presented as a stand-alone analytical outcome.

2.1 Goal and scope definition of the LCA

The native brine considered for this LCA is extracted from Atacama and after residence in open air evaporation ponds processed at the SQM plant in Salar del Carmen. Table S1 (in the SI) provides the brine chemical composition used for the calculations. Table S2 presents the material densities used for these calculations. The functional unit of this LCA is defined as one ton of battery-grade lithium carbonate (Li₂CO₃) – flow 33 as shown in Fig. 1 (see Fig. S1 for detailed process overview). The system boundaries cover the production of the functional unit from cradle to gate, meaning from brine pumping to Li₂CO₃ shipping, excluding the plant's machinery and equipment. The only additional materials aside from chemical reactants and fuels are the bulk bags and pallets used for shipping.^{58,59} Social and ethical aspects are beyond the scope of this study.

2.2 Life cycle inventory (LCI) based on material flow analysis (MFA)

A full process for Li₂CO₃ production was defined and is shown in Fig. 1, which depicts the unit processes 100–600 (see more details in Fig. S1 and the detailed process description in the SI). Units are specific processes with inputs and outputs, shown as boxes. Flow elements, such as electrical energy for a pump, are represented by arrows (turquoise for energy, blue for other; red for entering flows, and green for exiting flows). The process was outlined by Garrett.^{3,54} Briefly, in Atacama, brine is pumped from underground wells and poured into large open-air ponds to use the traditional evaporation method, which harnesses free energy from solar radiation with additional support from wind and the high altitude at which the Salar is located. Operation 100 (see Fig. 1, S1 and S2) are all operations that take place at the salt lake itself: brine pumping, brine concentration in solar evaporation ponds, accumulation of mixed salt tailings that crystallize in the ponds and transport of the highly concentrated brine to the coast. The subsequent lithium processing steps (see Fig. 1) include liquid–liquid extraction (organic solvents/aqueous phase) to remove boron species, chemical precipitation to remove magnesium and calcium, followed by filtration, heating, carbonation, and finally drying and micronizing of the

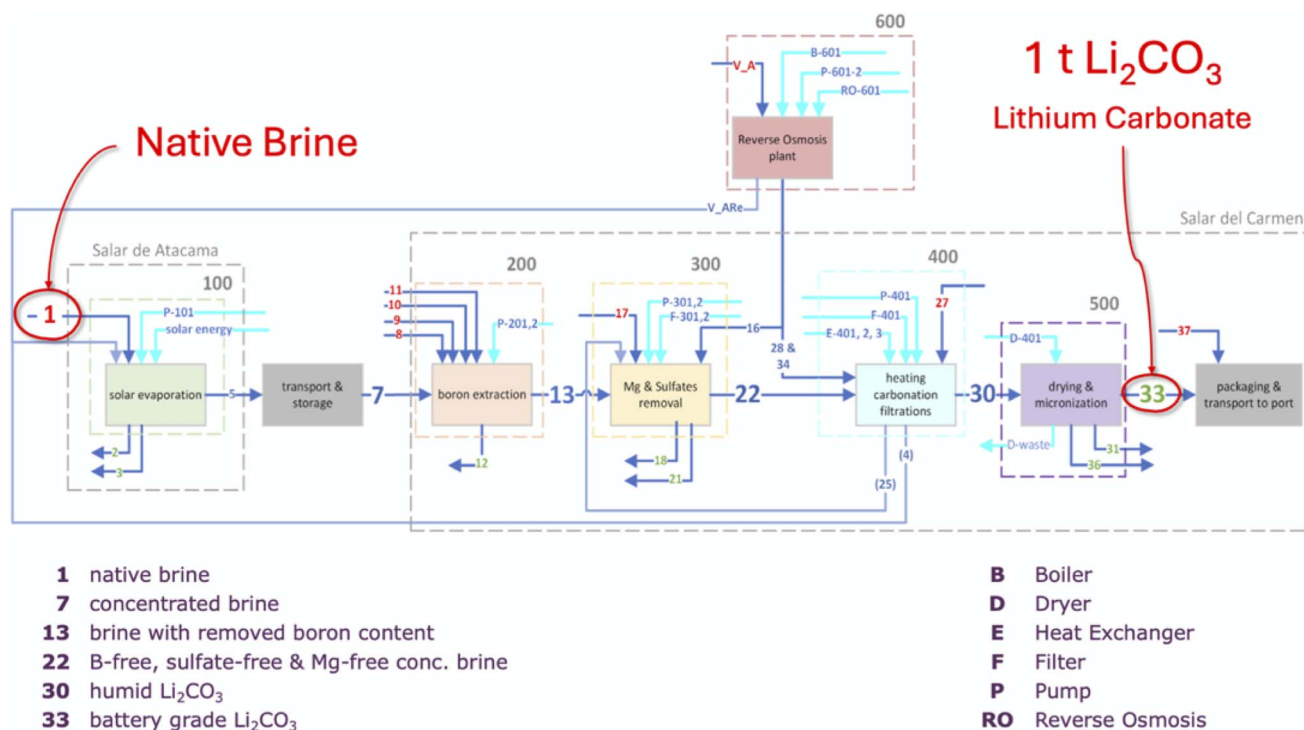


Fig. 1 Simplified process scheme of the lithium carbonate production in Chile (Salar de Atacama and subsequently Salar del Carmen processing) based on ref. 3 and 54 [Main stream shown with larger numbers, red numbers are entering the system, green numbers are exiting the system, and turquoise streams are related to energy: B = boiler, D = dryer, E = heat exchanger, F = filter, P = pump; Mg = magnesium; RO = reverse osmosis; V_A = total process freshwater; V_{ARE} = water rejection in RO plant] See Fig. S1 for a more detailed overview.

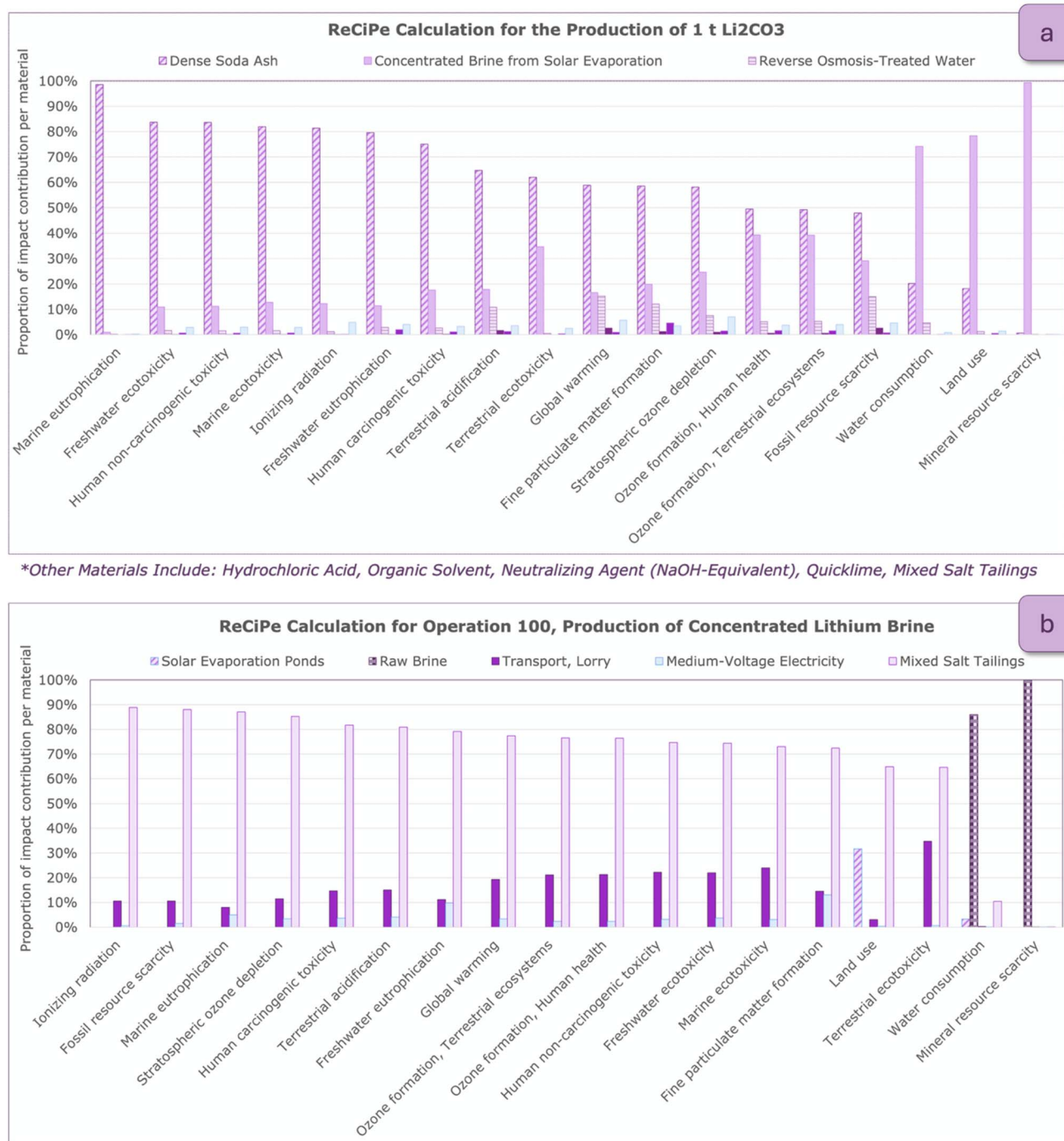
Li₂CO₃ product. In addition, Reverse Osmosis (RO) is used to treat the water in an auxiliary process. Production of 1 t Li₂CO₃ (as referenced in Fig. 2) comprise all operations depicted in Fig. 1, except for packaging, and operation 100, plus all subsequent processes on the concentrated brine.

In operation 100, most of the brine water evaporates due to solar radiation, which is classified in the LCI as “emissions to air”.^{17,26,54} Freshwater is extracted and used untreated in the boron removal unit, while other process steps rely on RO-treated water. Rejected water and liquids are reinjected into solar ponds. An overview of the different types of water and the respective quantity in this process is provided in Table S3 (in the SI). Inputs such as energy (from natural gas and the Chilean electricity grid) and chemicals are assumed to be bought and delivered to the plant. Land-use data are sourced from the Ecoinvent process for brine production.^{24,26} Table 1 provides a condensed overview of the process’s inputs and outputs. The detailed LCI based on Palacios’ calculations is shown in Table S4 (in the SI).⁵⁴ Further information on the assembly of the lithium carbonate product, the packaging, and the transport to the port of Tocopilla, Chile, is provided in Table S5 (SI). The exemplary bulk bag used for packaging is assumed to be produced in China. Its information is presented in Table S6 (in the SI).

Following the process shown in Fig. 1 and S1, stoichiometric calculations were used to estimate the chemical inputs, including excesses and reactant purity. Following Garrett, one of the main assumptions is that 30% of the original lithium content in the native brine is lost during production, mostly due

to brine entrapment within salts crystallized in the ponds and during boron removal.^{3,54} Required energy inputs, *e.g.*, for pumping or heating, used precise engineering relations, considering known temperature values, solution densities, and well-depths, amongst others. A sensitivity analysis was conducted on lithium concentration and processing parameters, although only the results obtained for the base case defined by Palacios *et al.* are used here.⁵⁴ Heat waste from natural gas consumption for heat exchangers, boilers, and dryers was assumed to be 10%, and the Ecoinvent emissions to air “heat, waste”²⁶ were used. The 52.7 t of residual salt waste was modelled using the Ecoinvent process “salt tailing from potash mine”, the closest proxy available in the database.²⁶ Precise information on assumptions and calculations is provided in ref. 54. SI from Ecoinvent was used to fill in data gaps.^{23,26}

Assumptions (*e.g.*, regarding energy loss) aim to fill every slot in the inventory as effectively as possible while also simplifying material flow. Selected ancillary processes, such as the energy for micronization, are neglected. However, a sensitivity analysis considers a worst-case scenario with higher demands for freshwater, soda ash, and electricity, as well as lower lime purity. The variables and values chosen for the sensitivity analysis were those that showed a higher impact in the sensitivity analysis of Palacios *et al.*:⁵⁴ soda ash and lime are the first and second more important chemical inputs in the process. The required amount of electricity strongly depends on brine well depth, while the total freshwater consumption is intrinsically linked to the rejection rate of the RO plant. The



precise values considered in the sensitivity analysis are listed in Table S7 in the SI.

2.3 Life cycle impact assessment (LCIA)

Several assumptions regarding inventory and material selection are made to model the lithium extraction process in an LCA interface, using materials and processes from the Ecoinvent

environmental database and creating new ones based on available information.²⁶ An overview of Ecoinvent material or process choices is provided in the SI (Table S8 for the concentrated brine, Table S9 for the lithium carbonate from said concentrated brine, and Table S10 for the reverse osmosis treatment plant). The impact assessment calculation is performed using the method "ReCiPe 2016 Midpoint (H) V1.10/

Table 1 Overview of the inputs and outputs to produce one ton of lithium carbonate from brines from the Salar de Atacama, processed in Salar del Carmen, packaged in bulk on a pallet, and shipped to Puerto de Tocopilla, t is metric tonne (1000 kg)

Inputs per ton Li_2CO_3	Input	Unit
Extracted native brine (water, from the ground, unknown)	139.000	m^3
Land transformation from unknown	1107.909	m^2
Land transformation to mine	1107.909	m^2
Land occupation, mine	55.558	m^2a
Hydrochloric acid (HCl)	26.800	kg
Organic solvents	20.700	kg
Water, from ground	15.391	m^3
Sodium hydroxide (NaOH)	4.240	kg
(Quick)lime (CaO)	118.000	kg
Soda ash (Na_2CO_3)	2.030	t
Bulk bag	5.566	kg
Pallet	2.518	P
Transport, lorry	1012.250	t.km
Thermal energy, from natural gas	3245.000	kWh
Electrical energy	155.212	kWh
Outputs per ton Li_2CO_3		
Evaporated water (lost to air)	114.624	m^3
Li_2CO_3 (battery grade)	1.000	t
Residual salt waste	52.743	t
Heat waste (from heat exchangers, boilers, and dryers)	324.500	kWh

World (2010) H". Background information on the method and its impact categories is provided in the SI (Tables S11 and S12).

To compare the present LCA results with previous reports, we extracted inventory data from four earlier studies on lithium carbonate production in the Salar de Atacama, primarily from the articles and their SI, and reconstructed them in SimaPro using the same system boundaries and modelling assumptions as in the present study.^{23,26,29,32,34} This harmonized remodelling approach ensures that differences in results arise from the underlying inventory data rather than from methodological inconsistencies across studies. Tables S8 and S9 (in the SI) list the comparable datasets and database modelling choices. By reassessing all inventories within a unified modelling framework, the comparative analysis remains valid and transparent, while acknowledging that the originally reported results were not directly compared but systematically re-evaluated for comparison under consistent methodological conditions.

3 Results and discussion

3.1 Process LCIA results

Table 2 presents the results of a ReCiPe Midpoint Assessment for the entire process from cradle (brine pumping) to gate (production of 1 t of Li_2CO_3). Transport by a lorry is required not only for shipping chemicals and the final product to the port, but, most importantly, for transporting about 3 t of concentrated brine required for production of 1 t lithium carbonate to the fine processing facility located roughly 250 km from the mining facility. Calculations showed that bulk packaging and

transport to the port accounted for only a small share (see Table S13).

Panel (a) in Fig. 2 graphically shows which sub-processes are the most important contributors to the 18 impact categories (for quantitative results, see Table 2). It is first observed that the use of dense soda ash is the most important contributor across 15 of 18 impact categories. As observed in Table 1, production of 1 ton of Li_2CO_3 requires 2.03 tons of Na_2CO_3 (dense soda ash in the LCA model). The production of soda ash *via* the most widely used chemical route requires NaCl, limestone, and thermal energy. Waste beds for CaCl_2 , the main by-product of the process, which is often not reclaimed, account for 1.5 times the weight of the soda ash produced, an increasing problem particularly in inland locations.⁶⁰ Thus, the thermal energy requirements and waste generation explain the large contribution of soda ash across all impact categories.

Energy, chemicals, and miscellaneous inputs are modelled as inputs from the technosphere, while brine, its mineral content, and land use are inputs from nature, represented by "concentrated brine from solar evaporation" in Fig. 2(a) and by "solar evaporation ponds" in Fig. 2(b). The accumulation of residual salts, heat loss, and evaporated water is considered as process outputs. The "concentrated brine from solar evaporation" has a dominant impact in only three categories: mineral resource scarcity, land use, and water consumption, while, in some additional categories, brine also contributes significantly, almost as much as dense soda ash: ozone formation, human health and ozone formation, and terrestrial ecosystems. Non-negligible impacts from the concentrated brine are also evident in the categories terrestrial ecotoxicity and Fossil Resource Scarcity (FRS).

Production of treated water (reverse osmosis treatment of brackish water for fine chemical treatment) is, overall, the third most important contributor to several impact categories: global warming (15%), fossil resource scarcity (15%), fine particulate matter formation (12%), and terrestrial acidification (11%) (see also Table 2). The production of treated water is energy-intensive, requires freshwater, and requires periodic replacement of RO membranes, which explains its contributions across different categories.

Unlike many other mining processes, medium-voltage electricity and heat from natural gas make only a relatively low contribution to selected impact indicators. This could be attributed to the overall process being relatively low-energy-consuming. Indeed, heat and chemicals are used only to process the highly concentrated brine, not the raw ore. On the other hand, in lithium mining from hard-rock ores, concentrated chemicals and heat are required to treat the native ores.²³

Soda ash is by far the largest chemical input in Atacama, corresponding to 79% of the total mass of chemicals required.⁵⁴ In addition, the large environmental footprint of soda ash production somehow obscures the impact of other inputs on the overall process. The relatively low contributions from both natural gas for heating and medium-voltage electricity are also attributable to soda ash's high energy intensity. The impact of other chemicals is also masked by soda ash, although no single other chemical input contributes substantially across all impact

Table 2 LCIA results of ReCiPe 2016 Midpoint (H) V1.10 Assessment of the Li_2CO_3 production from cradle-to-gate. The highest contributions for each category are highlighted in percentages at the bottom of the table. Contributions larger than 50% are shown in bold text. [*Other materials*] regroup those inputs whose minor contributions are not shown in percentages; hydrochloric acid, organic solvent, neutralizing agent (NaOH-equivalent), quicklime, and mixed salt tailings]

Subprocess or input	Marine eutrophication (kg N eq)	Freshwater ecotoxicity (kg 1,4-DCB)	Human non-carcinogenic toxicity (kg 1,4-DCB)	Marine ecotoxicity (kg 1,4-DCB)	Ionizing radiation (kBq Co-60 eq)	Freshwater eutrophication (kg P eq)	Human carcinogenic toxicity (kg 1,4-DCB)	Terrestrial acidification (kg SO_2 eq)	Terrestrial ecotoxicity (kg 1,4-DCB)
Total	1.62	1.07×10^2	3.72×10^3	1.53×10^2	2.50×10^2	8.34×10^{-1}	9.47×10^1	1.65×10^1	2.06×10^4
#33 1 t Li_2CO_3 from brine, battery grade	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
#7 concentrated lithium brine for 1 t Li_2CO_3 , from solar evaporation	1.61×10^{-2}	1.16×10^1	4.17×10^2	1.95×10^1	3.07×10^1	9.48×10^{-2}	1.67×10^1	2.95	7.13×10^3
Hydrochloric acid, without water, in 30% solution state	1.93×10^{-3}	1.96	6.72×10^1	2.69	7.34	2.03×10^{-2}	1.78	2.65×10^{-1}	1.59×10^2
{RoW}	6.04×10^{-4}	6.23×10^{-1}	2.22×10^1	9.02×10^{-1}	1.62	6.52×10^{-3}	5.94×10^{-1}	1.36×10^{-1}	7.08×10^1
Solvent, organic {GLO}	2.76×10^{-4}	1.98×10^{-1}	6.87	2.73×10^{-1}	1.04	2.39×10^{-3}	1.99×10^{-1}	3.08×10^{-2}	1.88×10^1
Neutralising agent, sodium hydroxide-equivalent {GLO}	2.93×10^{-4}	2.04×10^{-1}	1.02×10^1	4.38×10^{-1}	1.99	3.90×10^{-3}	4.52×10^{-1}	1.44×10^{-1}	2.29×10^2
Quicklime, milled, loose {GLO}	1.60	8.95×10^1	3.12×10^3	1.25×10^2	2.04×10^2	6.63×10^{-1}	7.11×10^1	1.07×10^1	1.27×10^4
Soda ash, dense {GLO}	2.54×10^{-3}	1.74	5.46×10^1	2.42	2.95	2.40×10^{-2}	2.46	1.79	1.06×10^2
V_NT, RO-treated water for 1 t Li_2CO_3	1.95×10^{-4}	1.77×10^{-1}	5.67	2.44×10^{-1}	4.95×10^{-1}	1.26×10^{-3}	2.49×10^{-1}	2.92×10^{-1}	5.31
Heat, district or industrial, natural gas {RoW} heat production, natural gas, at boiler modulating >100 kW	1.42×10^{-3}	7.58×10^{-1}	2.30×10^1	1.05	2.89×10^{-1}	1.64×10^{-2}	1.07	2.12×10^{-1}	7.37×10^1
Electricity, medium voltage {CL}	9.16×10^{-5}	5.66×10^{-2}	2.04	9.32×10^{-2}	1.78×10^{-1}	4.91×10^{-4}	8.91×10^{-2}	1.56×10^{-2}	3.02×10^1
Salt tailing from potash mine {GLO}									

Table 2 (Contd.)

Subprocess or input	Marine eutrophication (kg N eq)	Freshwater ecotoxicity (kg 1,4-DCB)	Human non-carcinogenic toxicity (kg 1,4-DCB)	Marine ecotoxicity (kg 1,4-DCB)	Ionizing radiation (kBq Co-60 eq)	Freshwater eutrophication (kg P eq)	Human carcinogenic toxicity (kg 1,4-DCB)	Terrestrial acidification (kg SO ₂ eq)	Terrestrial ecotoxicity (kg 1,4-DCB)
Dense soda ash	98.6%	83.8%	83.6%	82.0%	81.4%	79.6%	75.1%	64.7%	62.0%
Concentrated brine from solar evaporation	1.0%	10.9%	11.2%	12.7%	12.3%	11.4%	17.6%	17.9%	34.7%
Reverse osmosis-treated water	0.2%	1.6%	1.5%	1.6%	1.2%	2.9%	2.6%	10.8%	0.5%
Heat from natural gas	0.0%	0.2%	0.2%	0.2%	0.2%	0.2%	0.3%	1.8%	0.0%
Medium-voltage electricity	0.1%	0.7%	0.6%	0.7%	0.1%	2.0%	1.1%	1.3%	0.4%

Subprocess or input	Global warming (kg CO ₂ eq)	Fine particulate matter formation (kg PM _{2.5} eq)	Stratospheric ozone depletion (kg CFC11 eq)	Ozone formation, human health (kg NO _x eq)	Ozone formation, terrestrial ecosystems (kg NO _x eq)	Fossil resource scarcity (kg oil eq)	Water consumption (m ³)	Land use (m ² a crop eq)	Mineral resource scarcity (kg Cu eq)
Total	3.47×10^3	6.50	1.37×10^{-3}	8.92	9.15	1.26×10^3	2.18×10^2	3.27×10^2	2.63×10^3
#33 1 t Li ₂ CO ₃ from brine, battery grade	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
#7 concentrated lithium brine for 1 t Li ₂ CO ₃ , from solar evaporation	5.76×10^2	1.29	3.38×10^{-4}	3.51	3.59	3.68×10^2	1.62×10^2	2.56×10^2	2.61×10^3
Hydrochloric acid, without water, in 30% solution state {RoW}	4.70×10^1	1.10×10^{-1}	4.46×10^{-5}	1.18×10^{-1}	1.19×10^{-1}	1.22×10^1	1.15	1.33	3.01×10^{-1}
Solvent, organic {GLO}	2.09×10^1	4.68×10^{-2}	2.63×10^{-5}	9.27×10^{-2}	1.15×10^{-1}	2.73×10^1	3.58×10^{-1}	1.45	1.31×10^{-1}
Neutralising agent, sodium hydroxide-equivalent {GLO}	5.40	1.22×10^{-2}	5.60×10^{-6}	1.44×10^{-2}	1.46×10^{-2}	1.34	1.55×10^{-1}	1.68×10^{-1}	2.81×10^{-2}
Quicklime, milled, loose {GLO}	1.22×10^2	5.23×10^{-2}	1.86×10^{-5}	9.37×10^{-2}	9.64×10^{-2}	1.53×10^1	1.22×10^{-1}	7.32×10^{-1}	2.99×10^{-2}
Soda ash, dense {GLO}	2.04×10^3	3.81	7.96×10^{-4}	4.41	4.50	6.04×10^2	4.39×10^1	5.95×10^1	1.69×10^1
V_NT, RO-treated water for 1 t Li ₂ CO ₃	5.28×10^2	7.85×10^{-1}	1.04×10^{-4}	4.60×10^{-1}	4.83×10^{-1}	1.89×10^2	1.03×10^1	4.22	1.71×10^{-1}

Table 2 (Contd.)

Subprocess or input	Global warming (kg CO ₂ eq)	Fine particulate matter formation (kg PM2.5 eq)	Stratospheric ozone depletion (kg CFC11 eq)	Ozone formation, human health (kg NO _x eq)	Ozone formation, terrestrial ecosystems (kg NO _x eq)	Fossil resource scarcity (kg oil eq)	Water consumption (m ³)	Land use (m ² a crop eq)	Mineral resource scarcity (kg Cu eq)
Heat, district or industrial, natural gas {ROW} heat production, natural gas, at boiler modulating >100 kW	9.21×10^1	8.76×10^{-2}	1.54×10^{-5}	5.74×10^{-2}	6.15×10^{-2}	3.34×10^1	2.04×10^{-2}	4.24×10^{-1}	2.73×10^{-2}
Electricity, medium voltage {CL}	3.36×10^1	3.00×10^{-1}	2.03×10^{-5}	1.45×10^{-1}	1.46×10^{-1}	9.52	8.63×10^{-2}	1.85	2.40×10^{-2}
Salt tailing from potash mine {GLO}	2.92	6.13×10^{-3}	1.89×10^{-6}	1.76×10^{-2}	1.80×10^{-2}	2.12	1.11×10^{-1}	1.09	1.11×10^{-2}
Dense soda ash	58.8%	58.6%	58.1%	49.5%	49.2%	47.9%	20.2%	18.2%	0.6%
Concentrated brine from solar evaporation	16.6%	19.9%	24.7%	39.3%	39.3%	29.1%	74.2%	78.4%	99.3%
Reverse osmosis-treated water	15.2%	12.1%	7.6%	5.2%	5.3%	14.9%	4.7%	1.3%	0.0%
Heat from natural gas	2.7%	1.3%	1.1%	0.6%	0.7%	2.6%	0.0%	0.1%	0.0%
Medium-voltage electricity	1.0%	4.6%	1.5%	1.6%	1.6%	0.8%	0.0%	0.6%	0.0%

categories. Lime primarily affects global warming (4%). Hydrochloric acid contributes to stratospheric ozone depletion (3%) and to (eco)toxicity-related indicators (2% in different corresponding categories). The main contributions of organic solvents are to stratospheric ozone depletion and fossil resource scarcity. The use of sodium hydroxide has almost no contribution on the indicators (at most 0.4%), consistent with the very low volumes required.

The core of the sustainability discussion concerning lithium brine mining centres on local impacts around mining sites (in this case, around Atacama). Operation 100 (Fig. 1) groups brine pumping, concentration in solar evaporation ponds, production of mixed salt tailings and transport of the highly concentrated brine to the coast (about 250 km from the main site). Panel (b) in Fig. 2 shows the relative contributions to 18 impact categories (see Table S14 in the SI). Results for this group of operations are quite different from those shown in panel (a) just above (see Table 2). There is no contribution from dense soda ash or any other chemical, since there are no chemical inputs to the ponds. Mixed salt tailings affect 17 of 18 categories, with contributions exceeding 65% in 16 of them. The two missing categories are dominated by the impacts of raw brine: mineral resource scarcity (100%) and water consumption (86%). Next, we observe contributions from the lorry transport (for the concentrated brine, salt tailings, and other operations around the ponds) in 16 of the 18 categories. The highest contributions are visible in (eco)toxicity-related categories. Medium-voltage electricity affects 15 of 18 categories, but never exceeds 13% in any category. Electricity is primarily used to pump brine from underground reservoirs and transfer it to different ponds as it becomes more concentrated.⁵⁴ Lorry transport involves transporting highly concentrated brine. The solar evaporation ponds contribute to only two categories: land use (32%) and mineral resource scarcity (3%).

We find it important to discuss the meaning of the impact of ionizing radiation. Given the chemical inputs defined for this process, the result can only be attributed to electricity generated by nuclear power. Chile has no nuclear power capacity.⁶⁴ Hence, a non-zero figure for impacts from ionizing radiation can only be attributed to generic impacts on energy consumption in the LCA database.

The model sensitivity is analyzed with respect to different soda ash excess rates (10%, 20% (base model), 30%, and 40%) and other consumptions. An excess rate for soda ash of 40%, water rejection rate at the RO plant of 50% (total needed treated freshwater $V_{NT} = 8.476 \text{ m}^3$), CaO purity of 54%, and 200 m brine well depth, with higher electricity consumption were the worst-case scenario (see Tables S7 and S15 in the SI). In the first analysis, only the soda ash excess rates had a significant influence on overall results. Therefore, the second step was performed on different soda ash excess values, coupled with the worst-case scenario of water rejection in RO, CaO purity and brine well depth. The results of the second sensitivity analysis show the lowest value deviation in comparison to the base model for marine eutrophication, and the largest distribution between the 10% soda ash excess scenario and the worst-case

scenario (96% to 119%, respectively) in fine particulate matter formation (see Table S15).

3.2 Comparative LCIA results

A comparison of existing studies must consider the approaches, assumptions, neglected values, and calculation methods used. Some model components must be modified or omitted to improve comparability across different processes and brine compositions. Some LCAs do not present a complete picture of a production site and instead focus on single impact categories, such as climate change or the characterization factor GWP, rather than the 18 categories included in the ReCiPe 2016 Midpoint assessment method. The recent study by He *et al.*, which uses a similar scope but differs in process simulation and optimization, attributes a significantly larger contribution to NaOH than to dense soda ash, unlike the present study, Stamp *et al.*, Chordia *et al.* and Mousavinezhad *et al.*,^{22,23,32,54,62} though soda ash remains a high contributor in both. However, the final results comparing the present study with He *et al.* show similar orders of magnitude,²² and once the NaOH-related contribution is excluded, water consumption results also become comparable, despite differences in the water assessment methods the two studies apply.

Fig. 3 presents all 18 indicators for different datasets compared with the present model (fifth bar, in blue). The highest impact per category across the five studies reported is scaled to 100% (see also Table S16). This allows relative comparisons within each category, but because categories are scaled separately and use different units, comparisons across categories are not necessarily meaningful. The categories are arranged from lowest (left) to highest (right) standard deviation to emphasize where the models vary the most. The individual LCIA results for the gravity analysis of some processes are available in the SI, as described below. Table S17 shows that, for the impact assessment of the Ecoinvent brine process and Chordia *et al.*'s processing, in 16 of 18 impact categories, dense soda ash is the main contributor.³² Only mineral resource scarcity and land use are principally attributed to the concentrated brine. In Table S18, both concentrated brine and processing are based on Chordia *et al.*'s data.³² The results attribute higher contributions to the concentrated brine. For mineral resource scarcity and three other categories, it is the main contributor, while the other 14 categories are also dominated by dense soda ash. Table S19 shows the LCIA results for Chordia *et al.*'s concentrated brine only, which is responsible for mineral resource scarcity and water consumption, whereas electricity and diesel are the only contributors to the 16 other categories.³² Mousavinezhad *et al.*, who did not include the brine's mineral content, attributed only the water consumption to it.³⁴ 16 categories are dominated by impacts from dense soda ash and fine particulate matter formation from electricity (see Table S20).

Based on the comparative LCIA results in Fig. 3, the underlying inventories of each model (Tables S8 and S9, in the SI), and the individual gravity analyses in Tables S17–S20 (in the SI), the first notable observation is the dominance of Chordia *et al.*'s study in 13 of the 18 impact categories.³² The input values for

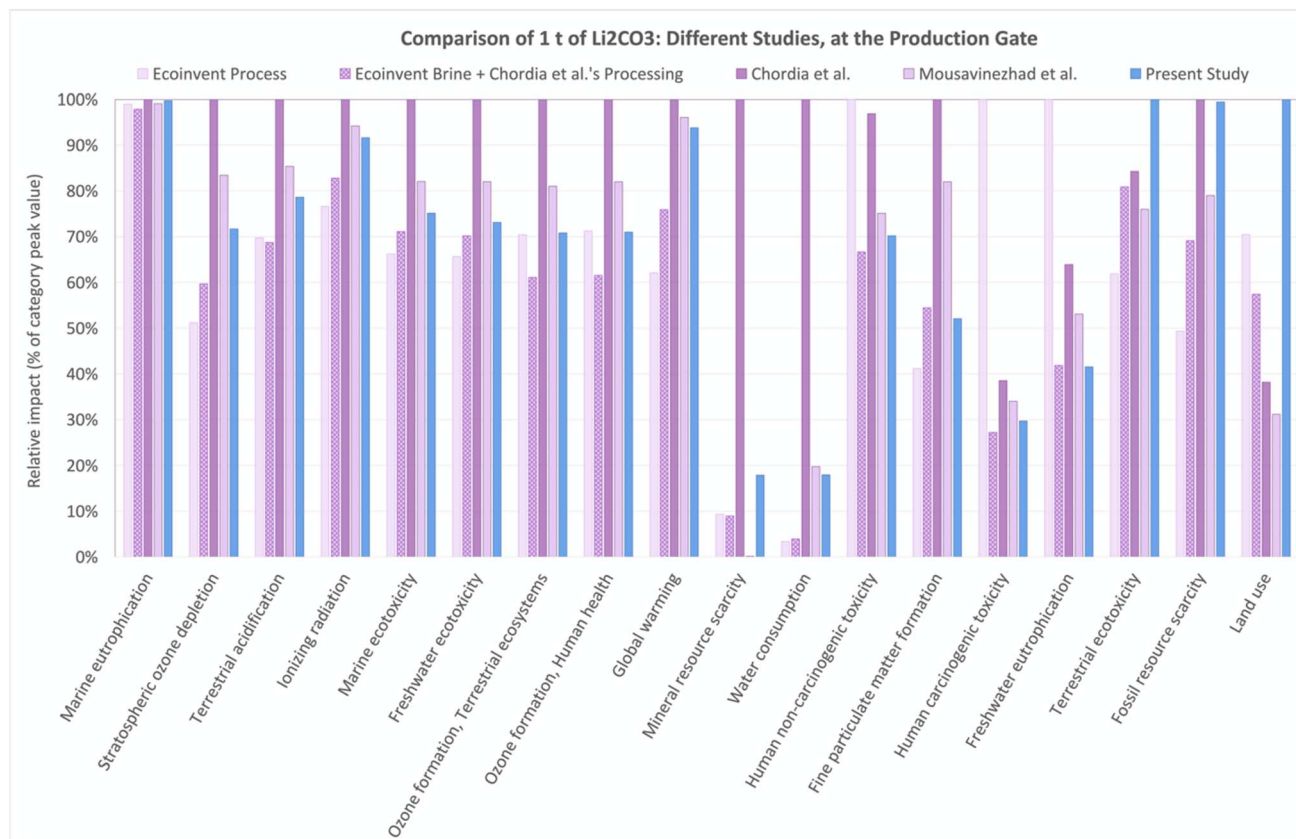


Fig. 3 Calculations based on the ReCiPe 2016 Midpoint method to compare the present model with the global Ecoinvent Li_2CO_3 from brines; a combination of the Ecoinvent brine production plus processing by Chordia *et al.* (2012, 2022); the total process by Chordia *et al.* (2022); and the total process modelled by Mousavinezhad *et al.* (2024); also see Table S16 (in the SI). The highest value in each category is scaled to 100% in order to compare the relative impact of each study per impact category.

the Li_2CO_3 production based on Chordia *et al.*'s data show significantly higher raw brine (920 t) and concentrated brine (4 t) consumption for the same final product amount (1 t Li_2CO_3).³² In comparison, Palacios *et al.* calculated the consumption of raw brine at 171 t and of concentrated brine at 3.25 t,⁵⁴ and these were the figures used in this work as well. The large difference in raw brine consumption is striking. The total Li content in the raw brine in Chordia *et al.* is the same as in the other studies analyzed; thus, it is difficult to understand how the authors arrive at such a large consumption. Palacios *et al.* carried out a thorough sensitive analysis for the required raw brine amount.⁵⁴ The largest raw brine input was calculated when considering a lower Li content in the Atacama brine and a considerably higher overall Li loss during processing (50%). In this limiting case, the total mass of brine was still 41% of the amount listed in Chordia *et al.* Furthermore, their electricity consumption is 4 times that in the present study (628.3 kWh *vs.* 155.2 kWh), which is likely related to the 5.2 times larger brine volume required to be pumped. In turn, Chordia *et al.* did not account for any waste.³² The considerably larger raw brine value used by Chordia *et al.* accounts for the large differences observed across most categories, especially in water consumption and mineral resource scarcity.³²

For human carcinogenic and non-carcinogenic toxicity and freshwater eutrophication, the Ecoinvent process, based on Stamp *et al.*'s data, yields the maximum value.^{23–25} This is due to the process decarbonising waste chosen as residual salt waste treatment, and the use of light soda ash.²³ We find that the current mixed salt tailings process is more realistic. The present study shows the highest results in the comparison for terrestrial ecotoxicity, predominantly related to explicit inclusion of the mixed salt tailings produced during the solar evaporation phase, which were not accounted for in other reports. In addition, this work identifies the largest land-use value, mainly attributed to the construction of the solar evaporation ponds, which is not considered in several of the studies compared.

Overall, this study found much larger impacts for land use and terrestrial ecotoxicity than previous studies, which we attribute to the clear acknowledgment and inclusion of mixed salt tailings in the calculations, and not only the land occupied by solar evaporation ponds. Except for land use, terrestrial ecotoxicity, and fossil resource scarcity, the present study shows slightly lower impacts than the recent study by Mousavinezhad *et al.*³⁴ and the study by Chordia *et al.*³² The reassessment of the study by Mousavinezhad *et al.* shows significantly high values for the categories ozone formation, ozone depletion, and fine particulate matter formation.³⁴ These results are generally

slightly higher than average in the comparison. However, for land use as well as fossil and resource scarcity, the present study shows more realistic values, as this information is lacking in the aforementioned study.

Concerning water consumption, the values show similar results, 240 m³ vs. 218 m³ in the present study. In both studies, the elevated values are due to lithium brine and the solar evaporation process, as water is lost to air by evaporation. The water consumption and land use categories correlate well with the sustainability issues listed above that have raised concerns among researchers and local populations, including declining water levels and their associated impacts, such as reduced vegetation or problems with fauna.

Regarding the specific areas where lithium brine deposits are found, it is also important to highlight isolated areas in the Andes Mountains, far from highway connections to the lowlands and large towns or cities. Not only must the final product and concentrated brine be transported from the facility to a port, but chemical reagents, grid electricity, and natural gas for heating must first be delivered to the isolated production site. Serpentine roads are frequented by trucks that slowly climb from the sea level to about 2500 meters (Atacama) or up to 4000 meters for other deposits. The transportation process in the LCA database does not account for these isolated, high-altitude locations (nor gravel roads often in poor condition), but only for mass and distance for a selected vehicle type. Thus, the results may significantly underestimate impacts associated with transportation, such as fuel consumption, emissions, and maintenance, which currently show low impacts on the overall results. Additionally, it has not been clearly established how transportation along these isolated desert highland roads affects biodiversity, ecosystems, or other specific environmental concerns.

The accuracy of life cycle assessments heavily depends on data quality. Enhancing transparency, sharing industrial data, and improving background databases, such as Ecoinvent, are crucial for achieving more reliable environmental assessments in lithium production.

3.3 Local vs. global impacts and the Atacama case study

Selected categories of LCA analyses measure impact to the environment on a global scale (*e.g.* climate change and ozone depletion), while the remaining categories assess impacts on a more regional or local level (*e.g.* water consumption and land use). As summarized in the Introduction, lithium brine mining, particularly around Atacama, has been associated with severe environmental concerns at the local level.^{35–43} In this context, it has been considered that more attention should be paid to selected impact categories. There is certainly no consensus in the scientific community as to how to weigh the impact of different categories.^{63–65} However, already measured water and desertification observations around lithium brine mining sites are a strong invitation to focus on results on water consumption, land use, terrestrial ecotoxicity, freshwater eutrophication and freshwater ecotoxicity. Indeed, for these 5 impact categories, the results presented here show relevant

differences with previous research. This study is focused on the specific mining site of Atacama, Chile. The discussion just above emphasizes that lithium brine mining environmental impacts seem to be particularly relevant at the local level. In addition, in our recent work,⁵⁴ we showed that several important inputs and outputs of the classical evaporitic process are strongly dependent on the Li content in the brine, and thus site specific. The Li content in the raw brine is the most sensible variable for brine volume input and evaporated water. In addition, the raw brine volume might also change within the same deposit, as exemplified by 3 different compositions presented for Atacama, as brine is pumped from different wells (varying locations within the same salar, depths, and even temporal variability as brine in the resource is temporally depleted). The total brine salinity, together with Li content determines the amount of salt mixed tailings,⁵⁴ and is thus also site dependent and as per the discussion above, will change results on several local impacts again. Overall, the results presented here are inherently site-specific, due to brine chemistry. The process modelling could still be transferred to other brine facilities, provided a very similar evaporitic process is used. The model should still be fed to the specific brine chemistry of the new site.

4 Conclusions

Process analysis and environmental assessment must be contextualized by considering various details related to the environment, the process, and all stakeholders. Lithium carbonate production from brine is carried out in arid regions, where water is scarce, and the production site is distant from populated areas yet close to nature and indigenous communities. The life cycle assessment of the lithium carbonate production from lithium-rich brines in the Salar de Atacama region of Chile was conducted to (1) identify and fill data gaps, (2) highlight influential aspects of the raw material exploitation in terms of environmental impact, and (3) compare the modelled process with existing data from previous research.

The production of the functional unit of one ton of lithium carbonate was evaluated using the main production process from cradle (raw brine originating from beneath the Salar) to the production gate (1 t Li₂CO₃). Prior to subsequent modelling in the LCA interface of SimaPro, the methodology included a material flow analysis to establish a detailed life-cycle inventory. This was followed by an impact assessment using the ReCiPe 2016 Midpoint method. Both the process itself and a comparison with other existing studies of Atacama production were analyzed. The results highlight several key environmental impacts associated with lithium production. Solar evaporation, which involves significant water consumption and extensive land use (25 m²a crop eq) per ton of concentrated brine, is a primary contributor to water- and land-related impact categories. Additionally, disposing of residual salts and using 2 t of dense soda ash during brine processing are important for several impact categories. Compared with previous studies, issues such as water consumption, land use, fossil resource

scarcity, and terrestrial ecotoxicity were found to be notably more pronounced than those reported in the literature.

Gaps remain in understanding the full life-cycle impacts of lithium mining infrastructure and the potential of emerging technologies to reduce these environmental burdens. Current limitations include insufficient data on local environmental variables, impact allocation, and industrial transparency. These constraints affect LCA model accuracy. This study underscores the urgent need for more detailed environmental assessments of lithium carbonate production, especially given its significant impacts on land use and (potential) impacts on water resources in sensitive regions like Atacama.

Future research should evaluate lithium mining in its local context, considering factors such as biodiversity and regional environmental analyses to provide a more comprehensive assessment. Precise data on lithium production operations and regional specifications, such as local transport conditions and mixed salt tailings, should be added to Ecoinvent and used in further LCAs. In this study, the facility itself, *i.e.*, plastic foil for evaporation ponds, construction machinery, infrastructure, and vehicles, among others, was excluded from the assessment as the information cannot be correctly attributed to the final product. Incorporating these elements would require detailed assumptions and inventories, as only very limited data on generic processes are available in Ecoinvent.

It is important to highlight that not all impact variables affect the sustainability at a local level. This is most likely the reason why previous LCA studies diverge so markedly from local field data showing severe impacts. In this context it is paramount to analyze the differences in impact categories when the whole production process is analyzed *vs.* brine concentration in solar ponds only. It is key to discuss if all impact variables should be analysed as of being of equal importance, since minor impacts in over 10 categories could be hiding severe environmental effects on land use, ecotoxicity and water scarcity as highlighted here.

Conflicts of interest

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

Data availability

Supplementary information (SI) associated with this article includes all calculations and tables with precise numerical data shown in graphs in the main manuscript. Further data will be made available on request to the corresponding authors. Specifically, we can provide a spreadsheet with detailed quantities for the model and the results of different calculations. Supplementary information: abbreviations: composition of the native and concentrated brines used in calculations. Material densities. Quantities of freshwater and treated water in the process. Detailed life cycle inventory. Assembly in the LCA model: lithium carbonate product, packaging, and transport. Information concerning the bulk container for one ton of

lithium carbonate. LCA model of the concentrated lithium brine production, in comparison to the description in several scientific articles. ReCiPe 2016 impact categories. LCIA to evaluate the production process of 1 t Li₂CO₃. Results of the sensitivity analysis. Results of the Comparative LCIA using the ReCiPe midpoint method for selected studies. See DOI: <https://doi.org/10.1039/d6su00137h>.

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