Public Policies, Salt Flats and Lithium Extraction Technologies: Challenges and Perspectives for Energy Transition in South America

Andrés Soto- Bubert[70], Rashmi Bhardwaj[71], Surbhi Sharma[72], Roberto Acevedo[73]

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Abstract

This paper analyzes lithium production routes from a process engineering perspective, focusing on brine-based extraction systems in South American salt flats within the Lithium Triangle (Chile, Argentina, and Bolivia). It examines the physicochemical characteristics of high-Andean brines, process design constraints, and the technological maturity of both conventional and emerging extraction pathways. A comparative review of peer-reviewed literature, institutional reports, and publicly available project data evaluates process configurations, lithium recovery efficiencies, water and energy consumption, and scale-up readiness. Results indicate that traditional solar evaporation remains industrially established but presents significant limitations, including long residence times, relatively low lithium recovery, high water losses, and limited operational flexibility. In contrast, Direct Lithium Extraction (DLE) technologies such as adsorption, ion-exchange, electrochemical, and membrane-based processes demonstrate reduced processing times, lower water consumption, and improved recovery, particularly in complex or low-grade brines. However, critical engineering challenges persist, including energy intensity, reagent regeneration, long-term material stability, impurity management, and integration with downstream refining at commercial scale. The study concludes that technical feasibility and sustainability depend on the coherence between brine chemistry, process design, and system-level integration rather than solely on resource quality. The findings provide guidance for technology selection, pilot-to-commercial scale-up, and process optimization in environmentally constrained salt-flat systems, supporting the development of resilient and sustainable lithium supply chains.

Keywords: lithium; salt flats; public policy; lithium direct extraction (DLE); sustainability
JEL Code: Q32, L72, Q56, O13, Q58

INTRODUCTION

[70] Associated professor, Facultad de Ingeniería. Universidad San Sebastián. Bellavista 7. 8420524 Santiago. E-mail: andres,soto@uss.cl. ORCID: 0000-0002-1127-6809
[71] Professor DRA, Fellow of the Institute of Mathematics & Applications UK, Department of Mathematics, University School of Basic and Applied Sciences, Head, Non-Linear Dynamics Research Lab, GGSIP University, Delhi, India. Email: rashmib@ipu.ac.in. ORCID 0000-0002-0502-762x
[72] Schoolar, Research Scholar, University School of Basic and Applied Sciences, Guru Gobind Singh Indraprastha University, Delhi, India, Email: surbhi.11540890024@std.ggsipu.ac.in. ORCID 0009-0009-8762-728x
[73] Professor PhD, Facultad de Ingeniería. Universidad San Sebastián. Bellavista 7. 8420524 Santiago. E-mail: roberto.acevedo.llanos@gmail.com. ORCID: 0000-0001-6847-0285

The strategic resource that has risen to the fore in the global energy transition is lithium, as the other indispensable component in the production of batteries in electric vehicles (EVs) and renewable energy storage systems. Following the fast development of clean energy technologies and the electrification of transportation, lithium is being considered as an important critical mineral to the 21 st -century economies. The lithium demand, mostly due to the development of the EV market, is driven by electromobility since lithium-ion batteries are needed to minimize the emission of greenhouse gases and to meet international climate targets. Simultaneously, the implementation of solar and wind power facilities will be extremely dependent on the effective lithium-based storage facilities to counter the intermittency of renewable energy sources (International Energy Agency, 2025).

There has been a significant growth in the global lithium output during the last decade, growing by around 200,000 tons of lithium carbonate equivalent (LCE) in 2016 to close to 983,000 tons in 2023. This growth is not only a symptom of the increasing demand but also an indicator of increased efficiencies of extraction and processing. Existing continental brine reserves already contribute approximately 48 percent of the world lithium production with Chile and Argentina jointly contributing almost 40 percent of the total lithium output. Chile presents one of the most strategic location positions of these producers with its large reserves, its developed mining industry, and its long-term operation on the Atacama Salt Flat, which is one of the most productive systems of lithium brine in the world (COCHILCO, 2025; USGS, 2025).

It is estimated that the lithium demand in the world would keep increasing at the rate of 15.5% per year in 2021-2035, with the automotive industry taking the major part of the demand. With this trend, the production would increase to 3.8 million tons in 2035 as compared to 508,000 tons in 2021, which is more than 650 percent. The Government of Chile has acknowledged the strategic and economic importance of this mineral and it introduced its National Lithium Strategy in 2023. The objective of the strategy is to use the lithium resources in Chile to enhance sustainable development, added value and development of technological and industrial capacities. Some of the main factors are the state leadership, via CODELCO and ENAMI, establishment of a National Lithium Company, public-private alliances, and efforts to have an environment and social sustainability. The strategic measures include being directly involved in major projects at the Atacama and other salt flats, the creation of a technological institute to research sustainable extraction, protecting the salt marsh ecosystems, regulatory modernization, exploration of new deposits in terms of sustainability criteria, and the promotion of innovation to make Chile a global leader in the lithium industry (COCHILCO, 2025; USGS, 2025).

In addition to Chile, lithium salt flats in Bolivia and Argentina make up the so-called Lithium Triangle (as indicated by figure 1), which along with Chile predominate in world lithium reserves. The Uyuni and Coipasa salt flats in Bolivia, and the Hombre Muerto, Olaroz and Cauchari-Olaroz in Argentina are the hubs of the new national approaches towards state regulation and technological development and environmental management. Further development of these projects is based on the new technologies of Lithium extraction, including Lithium Direct Extraction (DLE), to increase the recovery efficiency, decrease the water usage and to decrease environmental impact in accordance with the principles of sustainable mining and energy transition.

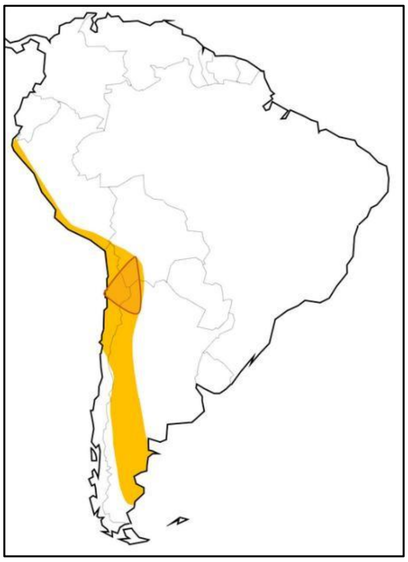


Figure 1. Lithium Triangle (*Source:* Wikipedia)

Project CODELCO - Rio Tinto

This is a strategic alliance between CODELCO (50.01%) and Rio Tinto (49.99%), and has an estimated investment of up to US 900 million. The primary goal of it is to create the world-class operation through the application of Lithium Direct Extraction (DLE) technology, which allows making the processes efficient and minimizing environmental footprint, especially the use of water. It was officially established in May 2025 and the operation is predicted to close through the first quarter of 2026. The manufacturing of the equivalent lithium carbonate shall be done according to stringent standards of environmental and community governance systems that enforce the social aspect of the project.

Project "Sales Production Maricunga" - Simco (Errázuriz Group)

This project, which is set to be launched with a capital of about US 600 million, will yield 22,000 tons of lithium hydroxide by the year 2028. It is currently undertaking the indigenous consultation and negotiation with the local communities especially the Colla Pai Ote people with the focus on sustainability and adherence to the water rights. The project is important in that, it is the first operation outside the Salt Flat “Atacama” to generate lithium in Chile hence making it to imply high diversification in the territory.

Dealer union led by RJR Lithium

This consortium operates in about 21,500 hectares, which is half of the salt flat. It aims at creating a unified operation which involves integration of new overseas partners, who are currently being negotiated with through a business group in China. Besides lithium, plans are underway to exploit potassium, boron and magnesium which are strategic minerals to the automotive and agricultural sector. The project lies in the phase of geophysical studies and drilling in accordance with the ideas of the National Lithium Strategy. The project portfolio in the Salt flat Maricunga depicts a structural transformation of the Chilean lithium sector, whereby the new strategy involves the use of modern technologies, geographical diversification and integration of sustainability standards and community involvement. This situation makes Chile a principal participant in the global chain of significant minerals, which will help in decarbonization and the move to clean energy. All in all, strategic significance of lithium in South America highlights why there should be all round policies, technological innovation and sustainable management of resources. Besides contributing to the global shift to a low-carbon energy system, these initiatives have a positive effect on the economic development of the region, the energy sovereignty of the countries, and on the role of Chile, Bolivia, and Argentina in the global lithium supply chain.

The three research questions that are addressed in this review are:

RQ1: How do the prevailing lithium extraction pathways in South American salars rely on brine, and what physicochemical limitations (e.g. Mg/Li ratio, ionic strength, precipitation of impurities, mass-transfer limitations) govern South American salar extraction?

RQ2: Which are the differences in recovery, water and energy intensity, processing time, and Technology Readiness Level (TRL) of solar evaporation systems and major Direct Lithium Extraction (DLE) technology families, assuming a clearly defined set of system constraints?

RQ3: What is the impact of governance and regulatory systems on technology choice and, hence, sustainability performance and cost competitiveness in the Lithium Triangle (Chile–Argentina–Bolivia)?

The objectives are:

1. Engineering Indicator Harmonization: To compare and then standardize recovery, water balance (brine depletion vs freshwater demand), energy intensity (kWh/kg Li or t LCE), processing time, and TRL using extraction routes through transparent secondary-data protocols.

2. Scale-Up Constraint Analysis: Scale-Up Constraint Analysis To determine the technical bottlenecks, as to commercial deployment, such as impurity management, sorbent/resin regeneration, energy integration, brine reinjection feasibility, and downstream conversion requirement.

3. Policy-Technology Interface Assessment: In order to take the implications of process-level trade-offs into water governance (permitting, environmental risk management and social license to operate), it is important to allow trade-offs to be translated at the policy-technology interface.

Limitations: The analysis will rely on heterogeneous secondary information (peer-reviewed literature, institutional reports, and company disclosures) whose reporting standards and system boundaries are variable. Reporting of performance metrics is thus in the form of ranges. Pilot data as reported by the company are clearly so identified and cross-source comparability is taken care of by trying to normalize indicators and harmonizing boundaries (Section 3).

2. THEORETICAL BACKGROUND

2.1 Comparative Assessment of South American Salt Flats

The South American region has established itself as the global lithium resource epicentre, with three dominant countries: Argentina, Chile and Bolivia. The analysis of the main salt flats reveals significant differences in terms of resources, production levels, technologies employed, and projections for the coming years.

2.2 Distribution of Resources and Development Projects

Argentina has the highest level of concentration of projects in operation and development with salt flats like Cauchari-Olaroz (4.9 million tons of LCE) and Olaroz of which production is already stable. Other ones like Centenario-Ratones, Sal de Oro and Mariana are undergoing first stages yet with some pertinent forecasts in 2025.

In Chile it retains its historical leadership owing to Salt flat Atacama, and the resources at the Salt flat are estimated at 6.3 million tons of LCE and the consolidated production is estimated at 150,000 tons in 2024 (and is projected to increase moderately in 2025). Maricunga is a project in the pipeline that is being built and enhancing the position of the Chile market. In Bolivia, it has a small amount of production (1,000 tons in 2024) despite having the largest resource discovered in the world in the Salt flat Uyuni (21 million tons of LCE), as it makes use of pilot projects and new technologies to transition to industrialization.

Solar evaporation technology is still the major one in the area as it is extensively employed in Argentina and Chile because of its low operating cost. There are however time and water restrictions. Direct Lithium Extraction (DLE) is gaining momentum and is especially being used in Bolivia and new projects in Argentina because it is more efficient and less environmentally harmful. More innovative technologies also appear in the Golden Salt project including ion absorption.

Chile is the unquestioned leader, and the output will increase by 150,000 tons to 160,000 tons. A sustained growth can be observed in Argentina as it is caused by the growth of the existing projects and the opening of new plants which will enable the country to achieve the figures in the middle term similar to the ones in Chile. It is not only the technological and investment challenge that Bolivia faces, but even with such massive reserves Bolivia will be only able to raise the production over 1,000 to 3,000 tons in 2025.

The center of the lithium industry is turning out to be South America where Chile and Argentina are the biggest producers and Bolivia is rising above the pilot stage. Technological trends are inclined to the use of more sustainable practices like Direct Extraction that will save time and minimize the harm to the environment. Nonetheless, there are still major problems: Bolivia is in need of a lot of investment and technology transfer in order to utilize its heavy resources. Meanwhile, Argentina needs to be stable in the regulations and expedite technological diversification, and Chile needs to be pressured to enhance sustainability and introduce new tenders.

To sum up, the region will not only play a central role in providing the increasing global demand caused by electromobility, but will also serve as the center of lithium mine technological advancement and sustainability. The salts flats of Argentina are important as illustrated in figure 2 and the resources and the production of salt shown in the table 1.

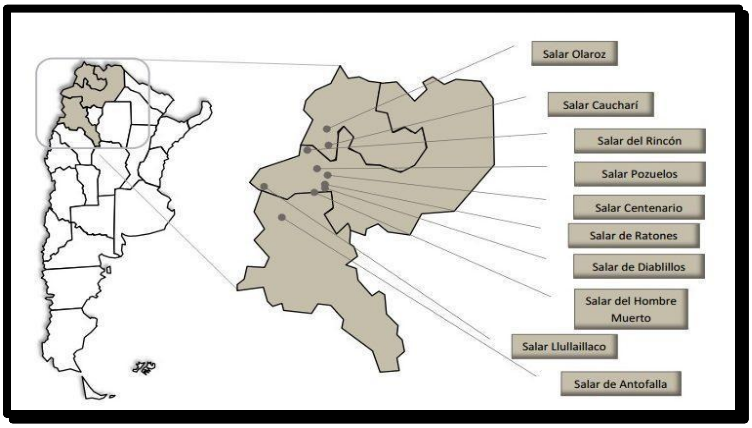


Figure 2. Most important salt flats in Argentina (compiled from published geological and mining literature).

Table 1. Resources and salt production.

Salt		**Resources LCE (t)**	**Production 2024 (t)**	**Situation 2025**	**Technology**	**Estimated Production 2025 (t)**
Hombre Muerto	Argentina	360,000-400,000	30,000	Operation	Solar Evaportion	50,000
Olaroz	Argentina	990 ppm salmuera	42,000	Operation	Solar Evaporation	50,000
Cauchari-Olaroz	Argentina	4,900,000	30,000	Operation	Solar Evaporation + hybrid DLE	35,000
Centenario-Ratones	Argentina	N/D	0	Operation	Direct ex-traction (DLE)	24,000
Sal de Oro	Argentina	N/D	0	Operation	Ionic Absorption	25,000

Mariana	Argentina	N/D	0	Operation	Solar evaporation	20,000
Atacama	Chile	6,300,000	150,000	Operation	Solar evaporation	160,000
Maricunga	Chile	1,300,000	0	Construction	Solar evaporation + DLE	10,000
Uyuni	Bolivia	21,000,000	1,000	Pilot/Expansion	Direct extraction(DLE)	3,000
Coipasa	Bolivia	N/D	0	Pilot	Direct extraction (DLE)	500

Source: COCHILCO (2025). Report. Lithium Market. Projections: 2025-2026-2027-2028)

2.3 Risks and Challenges for Chile in Lithium Production

In spite of such a favorable situation, critical analysis of the situation shows that the Chilean lithium market share in the world market had been dropping over the years. In part, this erosion can be attributed to the inflexibility of the regulatory and contractual framework especially the restrictions which are provided by the fixed quotas established in the Special Lithium Operation Contracts (CEOL). By failing to include the mechanisms of flexibility to adapt to the demand or technological advancement, these contracts inhibit significantly the capacity of Chilean producers to respond to the increasing and dynamic global demand of lithium, Holding back the growth required to continue to lead.

This rigidity in regulations makes matters of competitiveness worse compared to other producer nations. Countries like Australia whose spodumene mining model has intensified and Australia with its salt marshes in the Lithium Triangle as well as a more relaxed regulatory regime that is more responsive to investment are putting on a speedy rise to their output. Failing or reluctance to adapt effectively by Chile may result in being pushed to a minor position in the global value chain not only losing possible revenue but also strategic power in a market that is essential in the energy transition.

There is an extreme necessity to introduce DLE technologies to preserve and even confirm the leadership of Chile. The existing window of opportunity based on the growing need of electric cars and energy storage is limited. These are the dangers of inaction in the rapid adoption of new technologies, which are manifold: the obsolescence of the existing practices, the lack of any productive efficiency, the tightening of environmental laws and the increasing social pressure on more environmentally friendly mining. Every day lost is a loss of the possibilities of exploiting the added value, diversify the economy and create own technological knowledge.

Competitiveness and sustainability are an inherent problem. Although sustainability is a necessary pillar in the future of mining, this should not be done in a manner that compromises the competitiveness of the country. The trick is in the flexibility of regulations that enable the existence of environmental protection and the required flexibility to respond to changes in the market and other technological advances, stimulating investment and not deteriorating the socio-environmental norms.

Lack of activity in these strategic issues is one of the primary dangers of missing the historic chance that the energy transition provides to Chile. The fact that they can strike a balance between effective utilization of their resources and their unswerving commitment to sustainability with the help of a flexible regulatory framework and innovation enabler will be critical in making Chile an undisputed leader in the mining of the future and in a major driver of decarbonization around the globe.

2.4 Global Overview and Lithium Extraction Technologies

This section provides the global and technological background necessary to contextualize the results presented in Section 4.

2.4.1 Sources and Global Distribution of Lithium

There are three major types of geological deposits of lithium namely pegmatites (hard-rock deposits), continental brines and sedimentary/clay-hosted formations. Globally, Brine resources are still dominant, especially in the Lithium Triangle (Argentina, Bolivia and Chile) which harbors over 55 percent of all known world lithium reserves.

Such elevated altitude salars have high levels of lithium and favourable evaporation. The spodumene-carrying ores and pegmatite deposits are also at strategic positions as they are widely distributed all over Australia, China, Canada, and Africa. The hard-rock operations offer supply diversification and reduced development times as opposed to the salar based projects.

By 2025, the lithium market in the world is structurally oversupplying, and the price is more stable at a cost around USD 12,000 per ton, which is about 82% of the 2022 rate. The structural strength of demand is high with price corrections, and with the electrification of transport and grid-scale energy storage, the demand is projected to rise by about 22.9% in 2025.

2.4.2 Technological Innovations in the Lithium Industry

2.4.2.1 Lithium Direct Extraction (DLE): Concept and Advantages

Lithium production in South America has historically relied on solar evaporation of high-purity brines. This method benefits from arid climatic conditions but is constrained by:

- Long processing times (12–18 months)
- Lithium recovery rates typically between 40–60%
- Significant evaporative depletion within salar hydrological systems

- Land-intensive pond infrastructure

While mature and commercially proven, the method faces increasing scrutiny due to environmental and water-balance concerns in fragile High-Andean ecosystems.

2.4.2.2 Emerging Technologies: Lilac Solutions, Lithios, AMeLi

Lithium Direct Extraction (DLE) technologies are emerging as process-intensified alternatives to evaporation. DLE systems selectively extract lithium from brine using physicochemical separation mechanisms, reducing residence time and minimizing brine loss.

Core advantages include:

- Processing times reduced from months to hours or days
- Higher lithium recovery rates (often >80%)
- Reduced evaporative brine depletion
- Smaller physical footprint
- Potential reinjection of treated brine

DLE technologies are particularly relevant for complex brines with high Mg/Li ratios or lower lithium concentrations.

2.4.2.3 DLE Technology Comparison: Maturity, Water and Energy Consumption

Representative technological approaches include:

- **Lilac Solutions (Gen 5)** – Ion-exchange technology capable of operating at lithium concentrations as low as ~70 mg/L; validated in pilot projects across Argentina, Chile, USA, and Europe.
- **Lithios (MIT)** – Electrochemical lithium capture system avoiding evaporation ponds and aggressive reagents.
- **AMeLi (AMTC, Chile)** – Membrane-based hydrometallurgical platform producing high-purity lithium hydroxide with reduced downstream refining.

A quantitative, maturity-based comparison of these technologies is presented in Section 4.

3. METHODOLOGY

3.1 Research Design

This study uses comparative, integrative and multi-scale research design to compare lithium extraction pathways, level of technological development, environmental effects, and dynamics of the market in the major producing regions, with a special emphasis on South America. The research design is designed as a qualitative-quantitative synthesis, which incorporates physicochemical analysis of systems of brine, techno-economic analysis of extraction technologies, and policy-market analysis.

The comparative design can be explained by the heterogenic character of lithium resources that vary greatly in terms of geological setting, the brine chemistry, the climatic conditions, the regulatory regimes, and the technological implementation. Instead of using a single case study, the study compares several countries (Chile, Argentina, Bolivia and several global producers) and several technological paths (solar evaporation, adsorption-based DLE, ion exchange, electrochemical process and membrane process). The method enables acknowledging the structural benefits, bottlenecks and trade-offs, which are not easily seen when they are individually analyzed. The analysis is based on a descriptive-analytical process. To start with, it describes the nature of lithium resources and mining operations, such as physicochemical limitations of evaporation and precipitation in multicomponent brines. Second, it evaluates technologies on extraction based on standardised indicators concerning the efficiency of recovery, water and energy usage, time of processing, technology level readiness (TRL), and the costs per ton of lithium carbonate equivalent (LCE). Third, it incorporates the aspects of the environment and society as a whole and pays attention to the use of water, ecosystem sensitivity, and operational risks. Lastly, the outcomes are discussed within the framework of the global market forces, lithium technology development, and country-level strategies towards lithium, specifically in Chile.

3.1.1 Review protocol and reporting transparency.

Search strategy and screening were performed based on principles and in line with PRISMA 2020 reporting principles of systematic review (Page et al., 2021). Search in Scopus and Web of Science Core Collection was done, with the addition of Google Scholar where institutional publications and technical reports up to the project level were sought and could not be located on the larger databases. Search terms consisted of the family of direct lithium extraction (DLE) technologies; adsorption/sorption, ion exchange, membrane separation, electrodialysis/electrochemical and solvent extraction with brine and salar.

Inclusion criteria included: (i) peer-reviewed research articles and review papers; (ii) reliable institutional and intergovernmental reports (ex: COCHILCO, USGS, IEA) and (iii) project-level technical disclosures with quantitative performance indicators (e.g. recovery rate, water intensity, energy intensity, processing time, production capacity or cost measures). We excluded sources that did not have traceable quantitative data, were not sufficiently methodologically transparent, or were so poorly described technically that it would be impossible to extract and compare indicators. Uncertainty Treatment and Indicator Harmonization. Lithium carbonate equivalent (LCE) was used where necessary to harmonize reported quantities across heterogeneous sources. Water accounting was broken down into (i) net brine withdrawal and evaporation depletion in the salar hydrological system and (ii) supplementary freshwater demand to perform plant operations, i.e. washing and regeneration. Energy intensity is reported as electrical demand (kWh per kg Li or per tonne LCE), with explicit indication when downstream conversion to Li_2CO_3 or LiOH is included within system boundaries.

Where discrepancies were identified across credible sources, performance metrics are reported as ranges rather than single-point estimates. The nature of the source (peer-reviewed publication, institutional assessment, or company disclosure) is indicated in accompanying table notes to enhance transparency and allow readers to evaluate evidentiary strength and associated uncertainty.

3.2 Data Sources

The analysis is based exclusively on secondary data, ensuring transparency, reproducibility, and consistency with international reporting standards. Data sources were selected based on institutional credibility, methodological rigor, and relevance to lithium production, technology, and markets.

3.2.1 Institutional and Governmental Sources

Primary macro-level data on lithium production, reserves, prices, and demand projections were obtained from:

- **COCHILCO (Chile)**: lithium market projections, national production statistics, cost structures, and demand scenarios.
- **USGS (United States Geological Survey)**: global production and reserve estimates.
- **IEA (International Energy Agency)**: electric vehicle and battery demand projections.
- **SONAMI and national mining agencies**: regional and country-level assessments.

These sources provide standardized datasets that enable cross-country comparison and temporal consistency.

3.2.2 Industry and Project-Level Sources

Project-specific and technology-specific data were collected from:

- Technical reports, sustainability disclosures, and investor presentations of companies such as SQM, Albemarle, Eramet, Livent, Lilac Solutions, Rio Tinto, Sunresin, and Cleantech Lithium.
- Public information from pilot plants and commercial operations in Argentina, Chile, China, the United States, and Europe.

These data were used to assess operational parameters, recovery rates, water and energy consumption, and scaling potential of extraction technologies.

3.2.3 Scientific Literature and Patents

Peer-reviewed articles, technical monographs, and patent documents were reviewed to support:

- Physicochemical modelling of brine evaporation and ionic equilibria.
- Performance assessment of Lithium Direct Extraction (DLE) technologies.
- Environmental and social impact analysis.

The literature review covers the period 2010–2025, with emphasis on post-2020 developments reflecting rapid technological and market changes.

3.3 Analytical Framework

The analytical framework integrates three complementary dimensions: physicochemical analysis, techno-economic evaluation, and environmental–social assessment.

3.3.1 Physicochemical Analysis

Brine system is studied as a multicomponent solution of electrolyte, in which ionic activities, activity coefficient and product of solubility control the sequence of precipitation. Evaporation paths, fractional precipitation, and the constraints of solar evaporation in high-magnesium or high-sulphate brines are related using classical chemical equilibrium relationships. This model assists in comparing traditional evaporation ponds and other extraction paths by circumventing the equilibrium-based precipitation.

3.3.2 Techno-Economic Evaluation

Lithium extraction technologies are compared using a set of standardized indicators, including:

- Lithium recovery efficiency (%)
- Processing time (months vs hours/days)
- Water consumption (m^3/t LCE)
- Energy consumption (kWh/kg Li or LCE)
- Technological readiness level (TRL)
- Estimated production cost (USD/t LCE)
- Scalability and modularity

These indicators allow consistent comparison across technologies such as solar evaporation, adsorption-based DLE, ion exchange, solvent extraction, electrochemical separation, and membrane-based processes.

3.3.3 Environmental and Social Assessment

Water consumption, land use, and ecosystem sensitivity are the main parameters taken into consideration in evaluating the environmental performance, and the analysis will be focused on High-Andean salt flat environments. Social factors comprise operational risks, occupational hazards, effects on local community and social license to operate. The discussion indicates trade-offs of rapid production growing and the constraints of sustainability.

3.4 Comparative and Interpretative Approach

The last part of the methodology is cross-regional and cross-technological comparison which summarizes findings of the analytical steps carried out. The prevailing trends, relative advantage and structural risks are identified by the utilization of comparative tables and figures. The interpretation specifically attributes the technological performance on the market conditions, regulatory frameworks and future demand of batteries, which allows making policy-relevant conclusions among countries that produce lithium, especially Chile. **Methodological Contribution**

This approach can be useful as it helps to bridge the gap between the physics-chemical principles, industrial technology and market forces towards a single comparative system. In contrast to technical or more economic research, it offers a synthesized view that is required to assess lithium extraction plans in a scenario of a rapid energy transition and growing sustainability limits.

This paradigm allows a comparative approach to be systematic across both technologies and regions with consistency and consistency between theoretical constructs and empirical testing.

4. RESULTS AND DISCUSSION

4.1 Global Overview and Lithium Extraction Technologies

4.1.1 Sources and Global Distribution of Lithium

Argentina leads regional growth, with projected production of 131,800 t LCE in 2025 (77% increase year-on-year), while Chile maintains stable output and Bolivia remains constrained by infrastructure limitations.

Market oversupply conditions in 2025 reflect rapid capacity expansion, particularly from brine and hard-rock operations.

4.1.2 Technological Innovations in the Lithium Industry

By 2025, Lilac Solutions' Gen 5 ion-exchange platform represents one of the most advanced DLE systems commercially validated.

Reported performance characteristics include:

- Recovery rates exceeding 87%
- Impurity rejection above 99.9%
- Water consumption up to ten times lower than conventional evaporation (within defined system boundaries)
- Modular, scalable system architecture
- Elimination of evaporation ponds

Seven pilot and demonstration plants are currently operational, with commercial scale-up plans from 5,000 to 20,000 t/y LCE by 2027.

A structured comparison of DLE platforms (recovery, energy intensity, water balance, maturity level, and cost positioning) is provided in Table 2.

4.1.2.3 DLE Technology Comparison: Maturity, Water, and Energy Consumption

In 2025, the Lilac Solutions integrated its technology leadership in DLE technologies by introducing its fifth-generation (Gen 5) ion-exchange systems. The major benefits are the ability to consume up to ten times less water than traditional methods, scalable design and modularity, high efficiency in complex brines with low lithium concentrations and proven by international pilot projects. The recovery is more than 87% and the impurity rejection is more than 99.9%.

This technology allows operation without the use of evaporation ponds, lowers the project start-up times, and locates South American projects at the first quadrant of the global cost curve. Lilac Solutions has seven pilot and demonstration plants in Argentina, Chile, USA and Europe with the aim to increase commercial production to 5,000 to 20,000 t/y LCE by 2027.

4.2 Physicochemical Aspects of Evaporation Processes

4.2.1 Ionic Activities and Chemical Equilibrium

In concentrated brines, the calculation of ionic activities is essential to predict salt precipitation sequences and design evaporation routes. Neglecting non-ideal interactions generates significant errors, particularly in multicomponent systems such as the Atacama Salt Flat.

The concentration of a pure salt is determined by the chemical balance between the solid and the ions in solution. A typical example is sodium chloride dissolved in water:

$$NaCl_{(s)} \leftrightarrow Na^{+}_{(ac)} + Cl^{-}_{(ac)}$$

The solubility product constantly describes this equilibrium:

$$K_{ps} = a_{\mathrm{Na}^+} \times a_{\mathrm{Cl}^-}$$

Where the activity of each ion is expressed as:

$$a_x = \gamma_x[X]$$

being the coefficient of activity γ_x and [X] the molar concentration. This coefficient reflects the ion's interaction with its environment and represents deviations from ideality.

Figure 3. Process via solar pools.

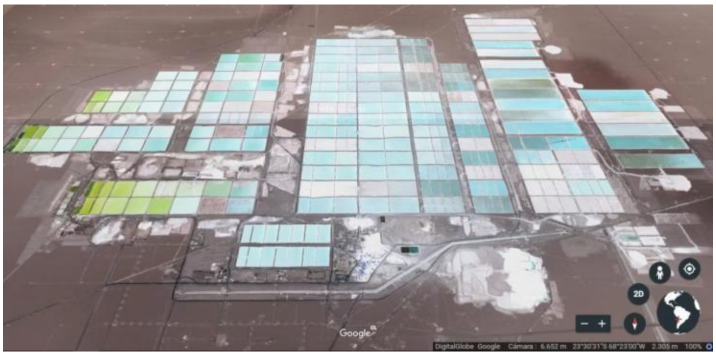
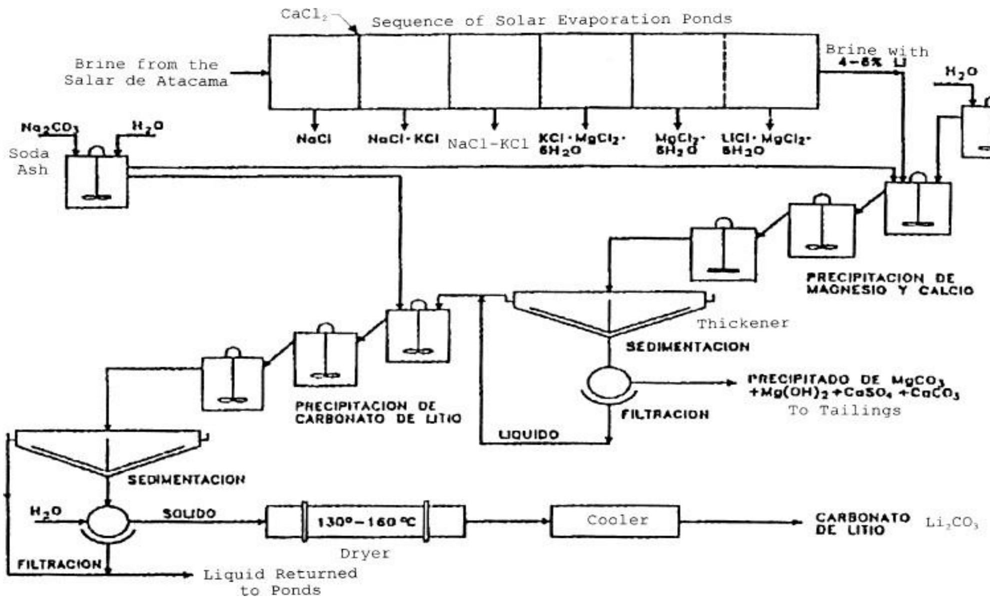


Figure 3 shows the process for obtaining lithium carbonate and chloride from brine, such as that used by Rockwood Holding, which starts with a brine containing 0.2% lithium and reaches up to 6%.

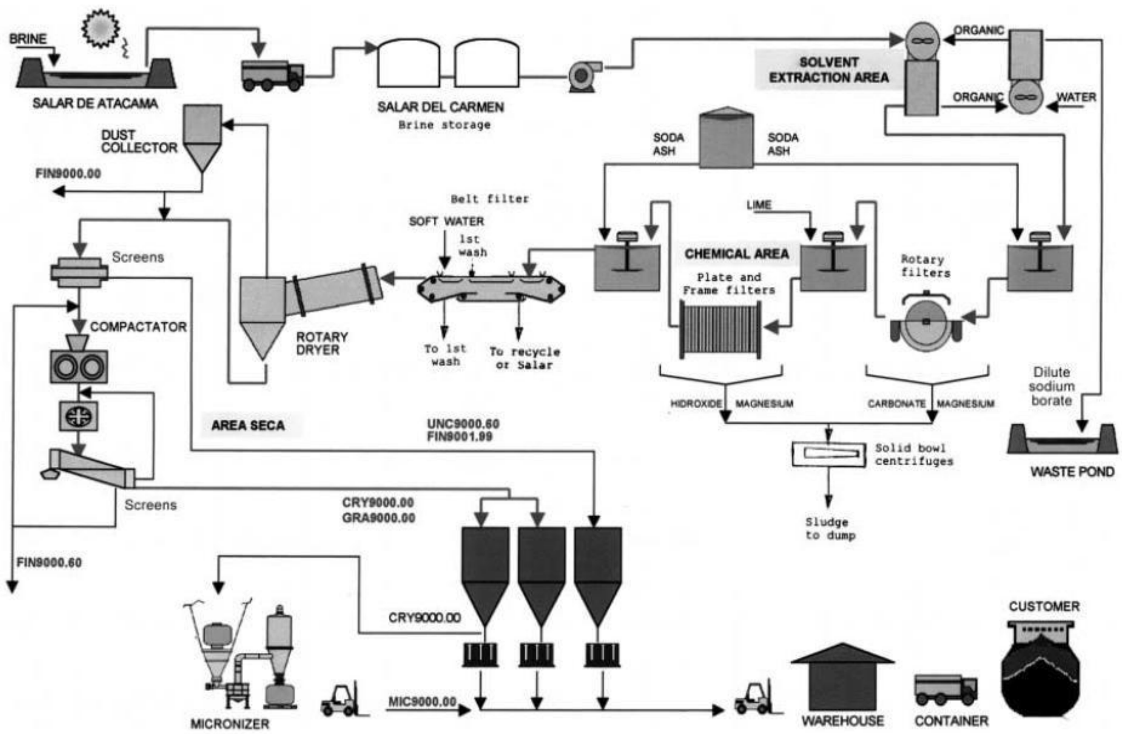
The block diagram of the extraction process of a typical brine found in the Atacama Salt Flat is indicated in figure 4. The process follows with the pumping of brine through several wells and the process is followed by chemical conditioning in order to attain the desired composition. This brine is then pumped into a number of solar evaporation ponds where consecutive precipitation is used to concentrate lithium. The figure highlights the following chemical reactions towards the formation of lithium carbonate. Figure 5 in its turn represents the particular process, which SQM applies to the Atacama operations. The industrial arrangement shown in this flowchart is to maximize the evaporation process and the chemical treatment, to obtain high-purity lithium carbonate. The design of SQM incorporates proprietary modifications to control chemistry of the brine and increase its efficiency over traditional designs.

Figure 4. Flow diagram for lithium carbonate extraction from the Salt flat Atacama.



Source: Wilkormisky (1998)

Figure 5. Flow diagram for obtaining carbonate from the Salt flat Carmen plant.



Source: SQM (2002)

4.2.2 Evaporation Routes and Fractional Precipitation

In multicomponent brines, ionic interactions and solubility constants determine the sequence of salt precipitation. Factors such as temperature, pressure, and ionic activities define the evaporation route.

Typical precipitated salts include halite, sylvite, gypsum, anhydrite, carnallite, lithium sulphate monohydrate, bischofite, lithium carnallite, and sassolite.

The aqueous speciation includes:

- **Anions:** Cl^-, SO_4^{2-}, OH^-, BO_2^-, $B_4O_7^{2-}$
- **Cations:** Na^+, H_3O^+, K^+, Mg^{2+}, Ca^{2+}, Li^+
- **Neutral species:** H_2O, H_3BO_3

Evaporation routes are designed to adjust solar pond chemistry and obtain lithium-enriched brines through controlled fractional precipitation.

4.3 Environmental and Social Impacts

4.3.1: Recovery of lithium with solar evaporation is normally between 40 and 60 percent with big losses associated with coprecipitation of lithium-bearing phases during sequential salt precipitation. Certain processing times (12-18 months) also limit the flexibility and responsiveness to market conditions. The reported losses of water over 170,000 litres per ton of LCE in the Atacama Salt Flat are expected to be measured within a specific system boundary: these values are mostly the net loss of brine and evaporation losses which can be attributed to the operation of the pond to the salar hydrological system. This is an independent component of freshwater demand that is not related to plant operations, like washing, making of reagents, and regeneration of resin during direct lithium extraction (DLE) operations. Reporting of evaporative brine depletion and freshwater consumption are to be reported separately because of the avoidance of conflation and to allow better representation of hydrological effects of fragile High-Andean ecosystems.

4.3.2: Lithium is a high-level toxic substance. Lithium hydroxide is very corrosive and occupational hazardous. The exploitation of brine changes the hydrological equilibrium, as they could cause the decrease of the lagoon levels and the impact on fauna and the local population, especially in Bolivia.

4.4 State of the Art and Evidence of Implementation

4.4.1 Commercial Plants and Pilots

Conventional solar evaporation requires extensive land use, depends on climatic conditions, and consumes up to 2,000 m^3 of water per ton of LCE. Processing cycles may reach 24 months. In response, DLE technologies have expanded rapidly, with a 163% increase in related academic publications between 2012 and 2023.

4.4.2 Lithium Direct Extraction Technologies

DLE technologies selectively separate Li^+ from complex brines without evaporation, achieving recoveries above 90% and product purities exceeding 99.5%. Techniques include adsorption, ion exchange, solvent extraction, electrochemical separation, and membrane-based processes.

4.4.3 Projects in Chile, Argentina, Bolivia, and Worldwide

Operational and pilot projects include Eramet Centenario (Argentina), Sunresin (China), Lilac Solutions (USA), Livent (Argentina), ENAMI Alto Andinos (Chile), and Cleantech Lithium.

4.4.4 Technical and Economic Challenges

Key challenges include long-term validation, high capital costs, waste management, and energy demand. Future trends emphasize modularity, hybrid systems, artificial intelligence integration, and coupling with renewable energy sources.

4.5 Future Perspectives: Batteries and Global Demand

4.5.1 Solid-State Batteries and Li–Al Alloys

Solid-state batteries offer improved safety and energy density. Lithium metal remains attractive due to its high specific capacity, while Li–Al alloys provide improved mechanical stability, lower volumetric expansion, and reduced reliance on metallic lithium.

4.5.2 Technological Projections

Short-term developments focus on interface optimization (2025–2027), medium-term on initial commercialization (2027–2030), and long-term on mass deployment with energy densities exceeding 900 $Wh \cdot L^{-1}$.

4.5.3 Market Trends

Lithium-ion batteries dominate the market in 2025, with solid-state technologies expected between 2026 and 2028. Sodium-ion batteries gain relevance for cost-sensitive applications.

4.6 Lithium Market and Regional Perspectives

The market is restructuring due to global lithium production, price volatility, oversupply, the growth of EV and the light pace of African producers. Africa, spearheaded by Zimbabwe and the Democratic Republic of the Congo is becoming a serious supplier, whereas Chile is still a strategically important but competitive country. The comparative merits and drawbacks of modern DLE technologies are comparatively tabulated in Table 2 and a comparative summary of exemplary DLE projects and industrial initiatives, including their geographical location, technological methods, production and approximated cost is in Table 3s.

Table 2. DLE Technology Comparison (2025)

Technology	**Operating plants / pilots**	**Maturity level**	**Main limitations**	**Requires fresh water**	**Power demand**
Selective adsorption	Pilots in Bolivia, China	High (TRL 7–8)	Sensitive to Ca^{2+}/Mg^{2+}; adsorbent regeneration	Yes (washing)	Medium (pumps)
Ion exchange	Lilac Solutions (USA); projects in Argentina	High (TRL 7)	Resin cost; brine pre-treatment	Yes	Medium
Solvent extraction	Adionics (France); pilots in Uyuni	Medium (TRL 6)	Solvent handling; potential environmental impact	No	Low
Electrodialysis	EnergyX (USA); tests in Chile	Medium (TRL 6)	High energy consumption; expensive membranes	Yes	High (3–5 kWh/kg Li)
Capacitive deionization (CDI)	Laboratory (China, USA)	Low (TRL 4–5)	Scale-up; electrode degradation	Yes	High
Nanofiltration / reverse osmosis	Integrated in hybrid processes	High (TRL 7)	Pre-treatment; membrane fouling	Yes	Medium

Key observations:

All DLE technologies reduce the water impact on the salt flat but require fresh water for regeneration and washing.

Power consumption varies electrochemistry and electrodialysis are the most intensive.

Adsorption and ion exchange are the most mature and close to industrial scaling.

Bolivia and Argentina already operate pilots with DLE, while Chile advances in integrated tests.

Table 3. Comparison of DLE projects

Project / company	Location (country)	Salar / region	Status	Capacity (t/y LCE)	Main technology	Estimated cost (USD/t LCE)	Notes
Livent (Arcadium Lithium)	Argentina	Salar del Hombre Muerto	Operating	~21,000	Adsorption + evaporation	4,000–5,000	Operating since 1996.
Centenario (Eramet)	Argentina	Salar Centenario-Ratones	Operating (2024)	24,000	Selective adsorption	4,500–5,500	Industrial-scale DLE plant commissioned in 2024.
Summit Nanotech	Pilots in Canada / Andes	High-Andean salar (Chile/Argentina)	Development	10,000–20,000 (proj.)	Selective adsorption	5,000–6,000	Testing in High-Andean salars.

Lilac Solutions	USA / Pilots	Salar de Atacama (Chile)	Development	20,000–30,000 (proj.)	Ion exchange	5,500–6,500	Pilots in Argentina and Chile.
Adionics / Eramet JV	France / Argentina	Salar Centenario-Ratones	Development	24,000 (proj.)	Molecular adsorption	4,500–5,500	Hybrid technology under testing.
Rio Tinto	Australia / Pilots	High-Andean salar	Development	20,000–35,000 (proj.)	Hybrid DLE + evaporation	4,000–5,000	Integration with conventional processes.
Watercycle Technologies	United Kingdom	Pilots (Europe)	Pilot	5,000–10,000 (proj.)	Membranes + electrochemical	6,000–7,000	Advanced electrochemical processes.
Cleantech Lithium	Chile	Salar Laguna Verde / Francisco	Development	20,000–30,000 (proj.)	Adsorption + reinjection	4,500–5,500	Connected to renewable energy.

Findings in Section 4.1- 4.6 show that the development of lithium in South America largely depends on the complex interaction between the endowment of geology, technological capacity, regulatory environments, and sustainability issues. Though the Lithium Triangle is structurally dominant with regards to global lithium resources, the outcomes between countries differ considerably with the variation in institutional ability, policy formulation and in the adoption of technology.

The strong leadership of the Chile is backed by excellent quality of brines, a history of operational experience, and industrial infrastructure present in the Atacama Salt Flat. The analysis however reveals that regulatory rigidity especially the fixed production quotas and contractual constraints has decreased adaptive capacity to an ever changing and competitive global market. Conversely, the Argentina regulated environment has been relatively flexible to enable faster deployment of projects and increase production although at the expense of increased vulnerability to environmental and water-use risks. The situation in Bolivia demonstrates that even an abundance of resources is not enough; lack of industrialization, technological underdevelopment, and execution issues remain to halt the large-scale commercialization.

Technologically speaking, the shift of the traditional solar evaporation technique to the Direct Lithium Extraction (DLE) appears as a turning point in technology. As it can be seen in Table 2 and Table 3, DLE technologies have significant benefits in the form of less water usage, less time on processing, and better lithium recovery. However, the findings also prove that DLE is not a universal solution. Demand of energy, management of reagents, long-term stability of materials, and scale-up uncertainty is also a major limitation that needs to be mitigated by pilot-scale validation and integration of a system. Notably, sustainability should be viewed as a complex constraint and not an environmentally related measure. Water balances, resilience of the ecosystem, social license to operate, and regulatory credibility are highly related. The data indicate that the strategies focused on quick development of production without a strong environmental regulation can lead to the deterioration of the stability in the long-term perspective, and also excessively strict regulations can weaken the competitiveness and topicality in the world lithium markets. In general, the combined evaluation shows that technological performance, the environmental impact, and design of the policies cannot be judged separately. Their coherence in consistent national and regional strategies is the key to long-term sustainability and competitiveness.

5. CONCLUSIONS

This paper offers a combined evaluation of extraction technologies, governmental policies, and sustainability issues of lithium mining in South America and especially in the Lithium Triangle. The findings substantiate that the area will continue being an epicenter of the global lithium supply during the energy transition, and the competitiveness of the future will be based on the strategic technological and regulatory decisions. Three key findings are drawn that are, first, diversification of technology and specifically to mitigate environmental stresses and increase operational flexibility, there must be the selective implementation of the Direct Lithium Extraction technologies. Second, the regulatory frameworks should move toward adaptive frameworks oriented towards the balance between the environmental protection and community engagement with investment incentives. Third, core areas of national strategies should focus on knowledge creation, pilot-scale testing and institutional capacitybuilding in order to prevent technological dependence and bottlenecks in implementation. In the case of Chile, implementing DLE technologies into a flexible, but enforceable regulatory environment will be a strategic move that will allow concentrating leadership and unify the development of lithium with the goals of sustainability. In the case of Argentina and Bolivia, the dilemma is how to convert resource endowment to long term industrial capacity without damaging delicate high-Andean ecosystems. In general, it is shown in this research that the geology or technology alone does not define sustainable lithium development, but rather, the consistency of policy formulation, the maturity of technologies and environmental management. The integrated outlook is necessary to make sure that lithium can be a valuable addition to the global energy transition and provide the long-term socio-economic value to the region of production.

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