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Technological Surveillance of Lithium Extraction Methods: A Critical Assessment

Policy Brief N° 3 | July 2025

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The Andean Wetlands Alliance brings together civil society organizations, local communities, and socio-environmental movements in Argentina, Bolivia, and Chile, with the aim of protecting, conserving, and defending Andean wetlands in peasant and Indigenous territories. The Alliance's work focuses on environmental conservation, respect for human rights, and environmental justice in the face of the ecological and climate crisis.



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ABSTRACT

This paper examines the current state of technological monitoring in relation to lithium extraction from mineral-rich salt flats. The primary objective is to identify and critically assess the development of direct lithium extraction (DLE) technologies, in contrast to the traditional method based on brine evaporation. To this end, the paper offers a critical review of conventional techniques and their associated environmental impacts. Moreover, it provides an in-depth analysis of emerging technologies that have achieved higher levels of technological maturity.

The discussion outlines the principles of operation, technical limitations, and environmental risks linked to the main methods of direct lithium extraction. Furthermore, the study evaluates whether these novel technologies hold the potential to substantially transform lithium carbonate production in the Andean salt flats, and whether their implementation is both viable and sustainable in the long term. In conclusion, the paper advances recommendations aimed at strengthening independent scientific knowledge in order to support institutional and community decision-making processes. Such processes are essential to safeguard territories characterized by high climate vulnerability and significant biodiversity loss.

ABSTRACT

This document analyzes the current state of technology monitoring related to lithium extraction in salt flats rich in this mineral. The primary objective is to identify and assess the development of direct lithium extraction (DLE) technologies in comparison to the traditional method based on brine evaporation. A critical review of conventional techniques and their environmental impacts is presented, followed by an analysis of emerging technologies that have reached higher levels of technological maturity. The operational principles, technical limitations, and environmental risks associated with the main direct lithium extraction methods are described. The study concludes by evaluating whether these new technologies have the potential to substantially transform lithium carbonate production in the Andean salt flats and whether their application is viable and sustainable in the long term. Finally, the document offers recommendations aimed at strengthening independent scientific knowledge to support institutional and community decision-making processes that ensure the protection of territories characterized by high climate vulnerability and biodiversity loss.

1. Introduction

1.1. The Global Context of Lithium and Its Strategic Relevance

Lithium has emerged as a strategic resource for the global economy due to its crucial role in the production of rechargeable batteries used in electronic devices, electric vehicles, and renewable energy storage systems. Its significance has grown within the framework of the global energy transition, driving an exponential increase in demand since the beginning of the twenty-first century. According to the International Energy Agency, this demand could increase fivefold over the next decade, primarily as a result of the expansion of electric mobility and clean energy¹.

Countries such as China, the United States, Japan, South Korea, and the European Union have developed strategies to secure access to lithium, a resource essential for both energy and technological security. This competition has stimulated investments in exploration and processing, while also triggering geopolitical tensions due to the geographic concentration of reserves.

Between 2014 and 2023, the share of lithium demand attributable to batteries rose from 35% to 87%, and projections suggest that by 2050 it could reach between 1.2 and 1.7 million tons². This growth has intensified pressure on the ecosystems where the mineral is extracted, particularly affecting water systems, biodiversity, and Indigenous communities inhabiting these territories. At the same time, producing countries face the pressing challenge of adopting more sustainable technologies that can ensure competitiveness without undermining social rights or ecological balance.

1.2. Environmental and Social Issues Associated with Its Extraction.

One of the main problems associated with lithium mining is the massive consumption of water, particularly in arid regions such as the Atacama Salt Flat in Chile. The traditional extraction method, based on solar evaporation, involves pumping brines from depths of around 30 meters below the salt flat, which are then deposited in large ponds to concentrate the lithium. This process not only consumes vast amounts of water in hyper-arid ecosystems but also generates saline waste that alters the chemical and physical balance of the salt flat³.

1 World Economic Forum. (2023). Lithium: Why Latin America is Key for the Global Energy Transition. Institutional Forum. Available at: <https://es.weforum.org/stories/2023/01/litio-por-que-america-latina-es-clave-para-la-transicion-energetica-mundial/>

2 Ministry of Economy, Government of Argentina. (2024). Value Chain Reports. Mining: Lithium. Available at: https://www.argentina.gob.ar/sites/default/files/informe_sectorial_litio_2024-2.pdf

3 Flexer V, Baspineiro C. & Galli C.I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Sci Total Environ.* 639:1188-1204. DOI: 10.1016/j.scitotenv.2018.05.223. Epub 2018 May 26. PMID: 29929287; Garcés, I. & Álvarez, G. (2020) Water mining and extractivism of the Salar de Atacama, Chile. *WIT Transactions on Ecology and the Environment*, 245, 189-199. DOI: 10.2495/EID200181.

Among the environmental impacts generated by the lithium industry is the net loss of water in systems already experiencing considerable hydric stress. To this is added the low efficiency of the evaporation method, which recovers only between 30% and 40% of the lithium contained in brine, and moreover requires between 14 and 18 months to complete a production cycle.⁴ Although its low cost—due to the use of solar energy and relatively simple technology—has facilitated its widespread adoption, the associated ecological and social costs are far from negligible. Recent scientific evidence, particularly publications from 2019⁵, has quantified these negative environmental impacts, and such findings have not been successfully refuted.

In light of these limitations, the last few years have witnessed the emergence of direct lithium extraction (DLE) technologies, hereinafter referred to as DLE. These approaches promise to be both more efficient and less environmentally harmful. They include processes such as adsorption, ion exchange, membrane separation, and electrochemical extraction, among the most prominent. Nevertheless, many of these technologies remain at the experimental stage or in pilot trials and continue to face significant technical and economic challenges before they can be implemented on a large scale.

South American salt flats due to uncertainties regarding its effectiveness and environmental impacts. Reported recovery rates range from 70% to 95%, while the method reduces brine use and shortens production times. However, it also requires freshwater and energy, and carries a significant environmental footprint. On the one hand, the reinjection of depleted brines could help mitigate the decline in groundwater levels and protect sensitive ecosystems, such as high-Andean lagoons. On the other hand, it may alter the geochemistry of the salt flat and disrupt the hydrological balance, due to substantial differences compared to the original brine⁶. There is also a risk that reinjection could dilute lithium concentrations and alter the stratigraphy of the system.

Despite its potential, DLE must be carefully evaluated in each context before large-scale implementation. Beyond the technical dimension, it is essential to question the economic development narrative tied to lithium, particularly within the framework of the energy transition. Although indispensable for batteries and electric vehicles, its growing demand risks exacerbating water scarcity and undermining the rights of local communities connected to salt flat ecosystems. The expansion of mining in sensitive territories requires a critical assessment of technologies such as DLE, which face not only

4 Kaunda, R. B. (2020). Social impacts of lithium mining: An institutional perspective from Chile. *Resources Policy*, 65, 101582.

5 Garcés, I. & Álvarez, G. (2020) Op. cit; Flexer, V., Baspineiro, C. & Galli, C.I. (2018). Op. cit.

6 Liu, W., Zheng, M., & Lu, X. (2021). Environmental implications of lithium extraction from salt lakes: A critical review. *Environmental Science & Technology*, 55(11), 7084–7097.

technical and economic challenges—such as the need for adaptation to each salt flat and the difficulties of achieving sustainable industrial scaling—but also broader socio-environmental concerns.

Beyond purely technical aspects, a critical reflection on the economic development model associated with lithium mining is required. While this mineral is central to the production of transition technologies, its extraction may reproduce patterns of overconsumption in high-income countries, while locally reinforcing extractivist models that have historically marginalized local communities—particularly Indigenous peoples, whose territorial rights and access to water are increasingly at risk⁷. Therefore, any public policy or administrative decision regarding lithium mining must consider not only technological efficiency but also strict compliance with existing regulations, with the aim of ensuring social equity as well as both global and territorial environmental sustainability.

In conclusion, lithium mining embodies the tension between advancing the energy transition and safeguarding fragile ecosystems and vulnerable communities. In sum, lithium mining faces a dilemma between the urgency of the energy transition and the need to safeguard fragile ecosystems and vulnerable communities. Technological innovations such as DLE may offer promising alternatives; however, their adoption must be accompanied by robust regulatory frameworks, informed community participation, and comprehensive, synergistic, and cumulative environmental impact assessments that take into account the socio-territorial complexity in which extractive activities are embedded across territories and watersheds.

1.3. Current State of Lithium Exploitation in the Region.

Salt flats are among the most complex natural systems in the world. Their formation is a process that requires very specific geological, geomorphological, and environmental conditions, as well as long periods of time. Throughout this process, interactions occur among the atmosphere, hydrosphere, and lithosphere. The life of this ecosystem—commonly referred to as a “salar”—depends on water, which over these long periods becomes enriched and interacts with the environment through a variety of chemical and biological reactions that unfold during its existence. Ultimately, this process leads to the formation of a brine enriched with different salts, depending on each basin. In summary, the formation of a saline ecosystem with lithium presence requires six factors: an arid climate; a closed basin; associated igneous and/or hydrothermal activity; subsidence due to tectonics (which creates space for continuous inflow and infill); adequate lithium sources; and sufficient time to concentrate lithium in the brine.

The South American salt flats that represent the richest and most

⁷ Zicari, J., Gudynas, E., & Alayza, A. (2022). Transición energética y extractivismos: dilemas del litio en América del Sur. *Revista de Ecología Política Latinoamericana*, 4(1), 45–63.

significant lithium deposits are located between 2,300 and 4,000 meters above sea level in the Andean region. The combination of altitude, solar irradiation, and aridity makes them some of the most extreme environments on Earth. These conditions give rise to unique flora and fauna, including microorganisms that form diverse and uncommon ecosystems, today associated with extremophilic communities. Around these ecosystems, Indigenous peoples have historically settled, maintaining close social and cultural relationships with the salt flats. For all users of the watersheds where these salt flats are located, water remains the essential element for livelihood and way of life.

The processing of lithium brine requires freshwater; therefore, as lithium exploration expands, accurate estimates of its availability in regions where water resources are extremely limited become essential for management decisions. Hydrological models employed to determine water availability, as well as to assess the environmental consequences of its extraction, often present errors and misrepresentations regarding the actual magnitude of freshwater resources. This issue has been evidenced by a recent hydrological study conducted by the University of Massachusetts⁸. This has placed the ecological health of the high-Andean lagoons—where lithium is found—at risk, as these ecosystems are fundamental for the survival of local and migratory fauna, as well as for flora in particular. Moreover, water is a vital element for Indigenous communities in the Circunpuneña Region or the Puna de Atacama, all of whom depend on the availability of freshwater at both surface and underground levels.

The search for more efficient alternatives to the brine evaporation method has therefore become a priority in recent years, with the governments of Bolivia, Chile, and Argentina strongly supporting the use of DLE technologies in new projects. Yet how promising are these technologies, and why have they not been widely adopted? The answer is not straightforward and relates to the inherent complexity of brines. Each brine is unique: while DLE may work experimentally at the laboratory scale, its performance under productive conditions differs significantly. Brines display complex chemical behavior in terms of quality, quantity, and variation of water types. Consequently, what proves effective for one type of brine in a given process cannot simply be replicated in another salt flat.

Each stage—extraction, processing, and reinjection of brines—presents technical challenges that must be overcome at scale, meaning that every brine requires an adapted approach. A DLE technology that performs successfully in one salt flat may fail in another. In addition, these technologies demand greater volumes of freshwater, while the entire operational infrastructure consumes more energy. Nevertheless, these methods extract lithium from the

8 Kirshen, A.B., Moran, B.J., Munk, L.A. et al. (2025) Freshwater inflows to closed basins of the Andean plateau in Chile, Argentina, and Bolivia. *Commun Earth Environ* 6, 177.

brine and, either in parallel or once extraction is completed, reinject the brine back into the salt flat. This practice generates impacts that remain insufficiently studied and could result in irreversible damage to the ecosystem, particularly considering the microbiota that exists below the Surface.

In Argentina, although DLE has been applied for some years in the Salar del Hombre Muerto, the traditional method continues to dominate. The operation begins with massive machines, pipes, evaporators, and purifiers that process brines extracted from beneath the salt flat, increasing their lithium concentration from 0.06% to 0.15%. The brine is then transferred to evaporation ponds, where after several months it is concentrated to about 6% lithium. The extraction efficiency of the evaporation process—known as the “lime-soda” method—does not exceed 30–40%, owing to the high solubility of lithium carbonate, even at 85°C (9.5 grams per liter)⁹. Freshwater consumption in this case is double¹⁰ the average concentration used in the Salar de Atacama and in the Salar de Olaroz (Argentina¹¹). The Centenario-Ratones Salt Flat, located at an altitude of 4,000 meters above sea level in the province of Salta, hosts a plant that recently began operations at the end of 2024 (operated by the company Eramet). The facility includes 19 wells that pump brines from depths of 400 meters—well below the water table—using a filter specifically designed in laboratories in France. Annual production is projected at 24,000 tons of lithium carbonate equivalent (24k LCE)¹² for 2025.

In northern Chile, the company CleanTech Lithium, through exploration licenses, intends to implement DLE in Laguna Verde and the Laguna del Negro Francisco Basin, both located in the Atacama Region. At the first site, the company has conducted experimental trials involving industrial-scale brine extraction; however, no public information on the results has yet been released. Similarly, although pilot plant operations have begun in the Maricunga Salt Flat, definitive results have not been disclosed. Nonetheless, preliminary reports suggest promising outcomes, even though no studies have yet been carried out that would allow for a reliable evaluation from an ecosystemic perspective¹³.

9 Calvo, E. (2022). Nuevos métodos de extracción directa de litio. Impacto en la explotación sustentable de los salares de la puna. Volumen 30 número 180 junio – julio. INQUIMAE, FCEN, UBA.

10 Por toneladas de carbonato de litio producido.

11 Vera, M.L., Torres, W.R., Galli, C.I., et al. (2023). Environmental impact of direct lithium extraction from brines. *Nat Rev Earth Environ* 4, 149–165 (2023). <https://doi.org/10.1038/s43017-022-00387-5>.

12 Carbonato de Litio Equivalente.

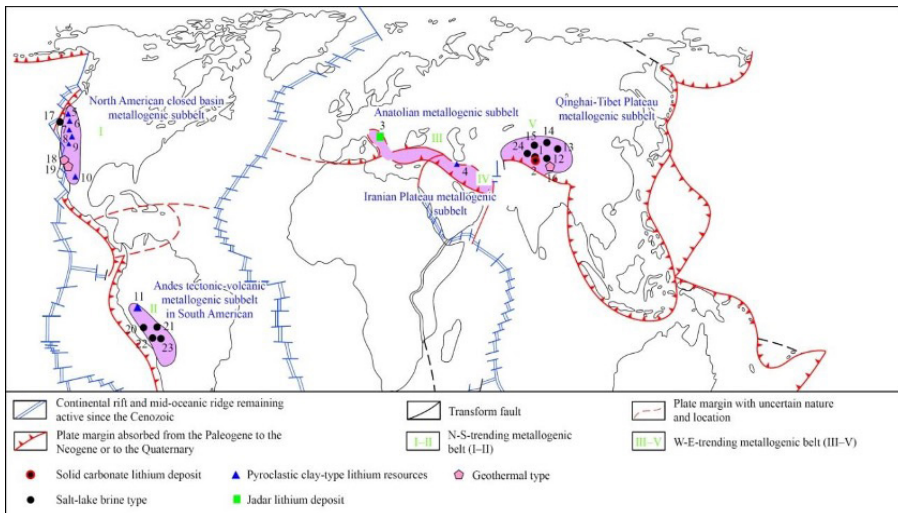
13 Bordeau, A. (2021). Sistema Hidrogeológico Salar de Maricunga-Quebrada de Paipote: Un aporte a la línea base de la comunidad colla El Bolo, Región de Atacama. Memoria para optar al Título de: Geólogo. Depto. De Geología. Facultad de Ciencias Físicas y Matemáticas. Universidad de Chile. Santiago de Chile.

2. Projected Lithium Extraction Methods: An Analytical Assessment.

According to deposit geology, lithium reserves derived from brines are classified as exogenous types. These include saline lakes, deep brines, geothermal waters, volcanic deposits (such as jadarite $[\text{LiNaSiB}_3\text{O}_7(\text{OH})]$), and clay-type deposits. These differ from endogenous lithium deposits, which consist of pegmatites, granite, and greisen, as well as magmatic-hydrothermal and crypto-explosive types.

The deposits in South America are mineralized and concentrated through the action of solar energy, by interactions among the lithosphere, hydrosphere, atmosphere, and biosphere, and under low temperatures and pressures near the surface. These conditions make the deposits complex and unique (Figure 1).

Figure 1. Map of the distribution of Cenozoic exogenous lithium resources. 1 – Solid carbonate deposit in the Zabuye Salt Lake; 2 – Brine-type lithium deposit in the Zabuye Salt Lake; 3 – Jadar lithium deposit; 4 – Iranian lithium resources; 5 – Big Sandy lithium resources; 6 – Silver Peak lithium resources; 7 – Northern Clayton lithium resources; 8 – Tonopah lithium resources; 9 – Thacker Pass lithium resources; 10 – Sonora lithium resources; 11 – Falchani lithium resources; 12 – Dangxiongcuo Salt Lake in Tibet; 13 – Qarhan Salt Lake in Qinghai; 14 – East and West Jinaier Salt Lakes in Qinghai; 15 – Yiliping Salt Lake in Qinghai; 16 – Semi in Tibet; 17 – Death Valley, United States; 18 – Brawley, California, United States; 19 – Salton, California, United States; 20 – Group of salt flats in Peru; 21 – Coipasa Salt Flat, Bolivia; 22 – Uyuni Salt Flat, Bolivia; 23 – Atacama Salt Flat, Chile; 24 – Chagcam Caka Salt Lake in Tibet.¹⁴



¹⁴ Zheng, M. P., Xing, E. Y., Zhang, X. F., et al. (2023). Classification and mineralization of global lithium deposits and lithium extraction technologies for exogenous lithium deposits. *China Geology de China*. Vol. 6(4), p. 547-56.

2.1. Traditional Brine-Based Lithium Extraction Method.

The industrial processes carried out in the Salar de Atacama (Chile), Salar de Hombre Muerto and Salar de Olaroz (Argentina), Clayton Valley (United States), Zabayu (or Zabuye) Lake, Dongtai Salt Lake, and Xitai Salt Lake (China) use evaporation ponds to concentrate brines into lithium, which is later purified in lithium carbonate refining and purification plants. Throughout several stages of the refining and/or purification process, chemical products and freshwater are required.

The communities surrounding these salt flats have brought to public attention the environmental and social impacts caused by the industry (e.g., the Atacameño people in the Salar de Atacama,^{15,16}, Salar de Hombre Muerto¹⁷, Salar de Olaroz,^{18,19}, and later other communities that have joined these claims)²⁰. The available data are still quite limited, and most are related to the Salar de Atacama and Clayton Valley, the latter being the first salt flat with productive extraction²¹.

2.2. Direct Lithium Extraction (DLE) Technologies: Principles, Methods, and Challenges.

There are several direct lithium extraction (DLE) methods; here we refer to the most commonly used ones currently under study. These can be summarized according to the extraction medium through which the brine flows, passing across a lithium-fixing material by means of processes such as adsorption, ion exchange, membrane separation, or solvent extraction, followed by purification solutions to obtain lithium carbonate or lithium hydroxide.

15 Espíndola, C. (2021). Testimonio de mi vida en Toconao y de la presencia de la minería en nuestro territorio licanantay. En Salares Andinos: Ecología de Saberes por la Protección de Nuestros Salares y Humedales. Observatorio Plurinacional de Salares Andinos. p. 37-39

16 OPSAL (2024). "Comunidades atacameñas mantienen posición en el salar de Atacama y comuneros visibilizan preocupación por impactos de la minería en el medio ambiente". Disponible en: <https://salares.org/comunidades-atacamenas-mantienen-posicion-en-el-salar-de-atacama-y-comuneros-visibilizan-preocupacion-por-impactos-de-la-mineria-en-el-medio-ambiente/>

17 OPSAL (2024). "Argentina: Medida cautelar presentada por Comunidad Atacameños del Altiplano logra detener nuevos permisos mineros en Salar del Hombre Muerto y ordena la medición de impactos acumulativos". Disponible en: <https://salares.org/medida-cautelar-presentada-por-comunidad-atacamenos-del-altiplano-logra-detener-nuevos-permisos-mineros-en-salar-del-hombre-muerto-y-ordena-la-medicion-de-impactos-acumulativos/>

18 Blair, J. (2021) Extractivismo del litio y el problema de la escala: acción climática global y justicia ambiental local. En Salares Andinos: Ecología de Saberes por la Protección de Nuestros Salares y Humedales. Observatorio Plurinacional de Salares Andinos. p.70-71.

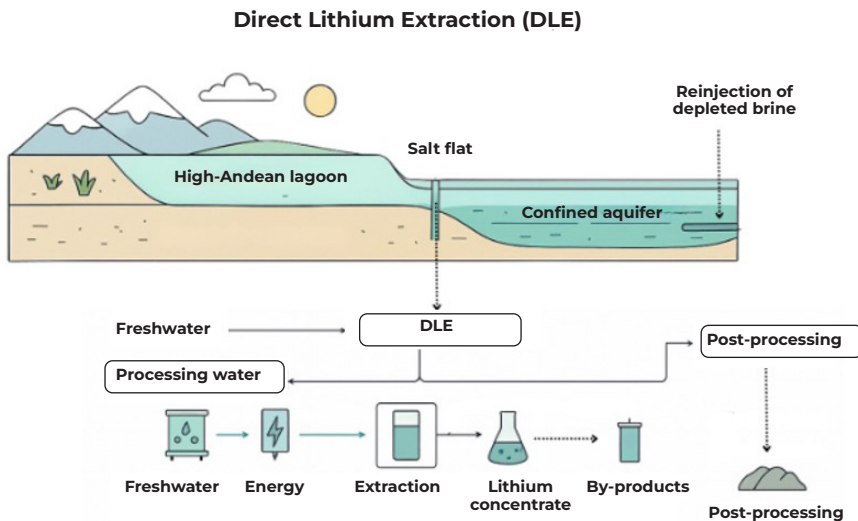
19 Jérez, B. (2021). Las desigualdades socioecológicas de la territorialidad extractivista del Triángulo del Litio en los Salares Altoandinos del Cono Sur. En Salares Andinos: Ecología de Saberes por la Protección de Nuestros Salares y Humedales. Observatorio Plurinacional de Salares Andinos. p. 108-109.

20 Jérez, B. (2021). Op cit., 109.

21 Garrett D.E. (2004). Manual de litio y cloruro de calcio natural Academic Press, Oxford, p. 1-47

The operational processes are based on pumping the brine into the processing unit, where it passes through a resin or other adsorptive material, thereby extracting only lithium. In this way, the lithium-depleted brine can be reinjected back into the aquifer basin. The DLE process is structured into three main stages: brine pre-processing, direct extraction, and post-processing (Figure 2).

Figure 2. Direct Lithium Extraction Scheme. Figure: Direct Lithium Extraction (DLE) Technology. Geological cross-section of a salt flat with lacustrine sediments, evaporites, and a confined aquifer; showing brine extraction and injection wells, the integration of process water in pre-processing, and the phases of direct extraction and post-processing. Own elaboration.



All of the technologies mentioned share this general scheme, although they differ in the mechanisms employed during the extraction phase:

2.2.1. Brine Pre-Processing: In this initial stage, the brine extracted from the salt flat is conditioned to optimize lithium recovery. This may include filtration to remove suspended solids, pH adjustments, and the removal of certain ions such as calcium and magnesium, which may interfere with subsequent stages. Although this phase generally does not consume large volumes of freshwater, it does require energy and chemical reagents, thereby contributing to the environmental footprint of the process.

2.2.2. Direct Extraction (Key Technology): Several technological pathways exist, all sharing the common objective of separating lithium from other elements present in the brine:

- i. **Ion Exchange:** This method uses resins that selectively capture lithium. After capture, a freshwater wash is required to release the lithium and produce lithium chloride (LiCl). The process generates lithium-depleted residual brine, which is either reinjected into the salt flat or treated as waste.
- ii. **Solvent Extraction:** Lithium is transferred from the brine into a selective organic solvent. It is then recovered through an aqueous washing stage. This process requires freshwater for washing and generates organic liquid waste; therefore, there is a dual waste stream: residual brine and spent solvent.
- iii. **Electro-Membranes:** This method uses selective membranes and electricity to extract lithium. Although it is less dependent on freshwater, the process produces a stream of residual brine. From an environmental standpoint, it entails high electricity consumption and the need to manage the resulting brine waste.
- iv. **Nanofiltration (NF):** Under applied pressure, NF membranes separate lithium from other ions. This technology requires water for membrane cleaning and leaves behind concentrated brine as a residual stream. Consequently, the process involves intensive use of both energy and water for cleaning, as well as the generation of saline concentrate waste.
- v. **Electrochemical Ion Pumping:** Lithium is captured in a solid, which is subsequently washed with freshwater to recover the metal. This method offers a high degree of selectivity but generates liquid waste and requires freshwater.
- vi. **Selective Precipitation:** By adding reagents such as phosphate, lithium precipitates in solid form, leaving behind residual brine as a byproduct to be managed.
- vii. **Thermally Assisted Methods:** Heat is employed to separate lithium. This approach has a high energy demand and also produces residual brine.

2.2.3. Post-Processing and Waste Generation: All technologies converge in the phase where the final lithium product (generally carbonate or hydroxide) is obtained, along with the generation of waste. This waste includes lithium-depleted brine, which may be reinjected into the salt flat or stored, water contaminated by washing processes, and solid residues such as precipitates or spent membranes. This step is critical, as poor management of residual brine can alter the hydrological and chemical balance of the salt flats, thereby affecting biodiversity and the local communities that depend on these ecosystems. En la Tabla 1 se pueden apreciar las diferencias generales entre el método de extracción de litio por evaporación y por extracción directa; la Tabla 2 resume la efectividad de los diferentes métodos de extracción directa de litio; mientras que la Tabla 3 muestra una comparación de los métodos de extracción de litio.

It is important to recall, however, that each salt flat constitutes a unique ecosystem with specific chemistry, which, in the case of lithium mining, requires differentiated extraction processes. The brines of Bolivia and China, for example, exhibit a high magnesium-to-lithium ratio, demanding a more complex treatment than the chloride-based brines exploited in Argentina and Chile. Variability in salinity and ionic composition prevents the application of a single technological solution in all cases.

At present, direct lithium extraction technologies remain at the pilot stage and have yet to be tested at large scale. Although they promise greater efficiency and a reduced environmental footprint compared to traditional methods, they still face significant challenges.

Among these challenges, the most significant are the high consumption of freshwater and the generation of residual brines, whose environmental and social impacts are not yet fully understood, particularly in ecosystems such as the high-Andean salt flats. The potential application of these technologies must take into account prior consultation with Indigenous peoples in accordance with international human rights standards, and must strictly comply with existing regulatory frameworks, rigorous environmental monitoring, and the rational and sustainable use of water within the basins. Moreover, it is essential to evaluate environmental impacts from the pumping stage to the production of the final solid lithium product and its preparation for export at ports. At the territorial level, cumulative and synergistic impacts must also be assessed.

2.3. Desafíos de la profundización de la extracción de litio

From a purely productive standpoint, the main advantage of DLE methods lies in the extraction time, which is reduced to only a few hours instead of the 12 to 18 months required by the evaporation method. To this is added the potential reduction in the volumes of brine that must be processed under the traditional method (for instance, the vast evaporation ponds covering the Salar de Atacama, exceeding 90 km² as of 2017)²². Producing one ton of lithium carbonate in the Salar de Atacama requires the evaporation of between 400,000 and 2 million liters of brine water, in addition to approximately 5,000 to 50,000 liters of freshwater for treatment plant operations²³.

Another relevant point from a strictly productive perspective is that these methods do not depend on climatic conditions or brine composition, thereby generating higher recovery rates (70%–90%). Ultimately, this translates into a lower environmental impact.

According to the standards under which the concept of DLE has been promoted, direct lithium extraction technologies offer a faster and potentially less harmful alternative to traditional evaporation methods. Nevertheless, their effectiveness at large scale has not yet been demonstrated in Chile, and uncertainties remain regarding their impact on the fragile ecosystems of the salt flats. In this context, it is urgent to establish specific environmental regulations that take into account the complexity and vulnerability of these ecosystems. Lithium extraction produces cumulative effects, particularly on hydrological systems, and therefore requires permanent and transparent environmental monitoring by companies. Moreover, the communities directly linked to these ecosystems must play an active role in the potential approval of projects as well as in the supervision and evaluation of impacts, contributing their knowledge and experience to the protection of ecosystems.

3. Concluding Recommendations.

The National Lithium Strategy promotes the implementation of DLE under the premise that this method is more sustainable and likely to reduce potential environmental impacts on salt flat ecosystems. However, environmental and social concerns persist regarding the mechanisms to ensure the availability of environmental information, as well as the political participation processes involved in public decision-making, such as Indigenous consultations and public participation mechanisms.

Moreover, given the absence of industrial-scale experiences implementing the proposed technologies and methods for new lithium and by-product extraction processes, there has been no review of the existing environmental regulatory frameworks to provide general guidelines on the impacts of public policy decisions.

22 Prieto, M. & Sandoval, G. (2018). Informe Expansión de la Extracción de Salmuera en el Salar de Atacama. Informe técnico.

23 Garcés, I. & Álvarez, G. (2020) Op. cit; Flexer, V., Baspineiro, C. & Galli, C.I. (2018). Op. cit.

In this regard, and in line with the foregoing, a set of guidelines is presented with the aim of strengthening governance in this area, thereby enabling decision-making processes that safeguard the territories and ecosystems affected by lithium mining:

3.1. Enhancing Research and the Development of Environmental Information Systems.

It is necessary to strengthen interdisciplinary and territorially grounded research in order to support institutional and community decision-making processes regarding the impacts on territories and ecosystems affected by lithium mining in its various stages and processes. Such research must be conducted in advance of the impacts and ensure the protection of vulnerable territories and biodiversity, thereby safeguarding minimum guarantees for the development of environmental information.

Furthermore, greater research is required on two essential issues. First, the establishment of public baseline studies, both for the implementation of the protected salt flats network and for the development of projects in salt flats declared strategic and those publicly tendered.

Second, it is indispensable to generate information on the potential impacts of reinjecting residual brines into salt flats, given the lack of available knowledge regarding modifications to the physicochemical properties of water bodies, which could cause irreversible damage to the ecosystem, including the subterranean microbiota. It is acknowledged that no studies currently exist that allow for a reliable ecosystem-based assessment of DLE operations, even at the pilot stage.

In this regard, high expectations are placed on the role that the National Institute of Lithium and Salt Flats may play in this area. Following its establishment, it will be essential to develop lines of work consistent with its mandate, aimed at generating, validating, and disseminating hydrological, geochemical, and biodiversity data, as well as qualitative information on socio-ecosystems. This would ensure the continuity of the observatory beyond the political cycles of the moment and make possible evidence-based public decision-making.

Furthermore, in line with compliance with the provisions of the Escazú Agreement, Articles 5 and 6, it is of high importance and feasibility to implement a public, open-access, interoperable, and real-time updated environmental information portal. This portal should contain georeferenced information, as well as historical series data on groundwater levels, salinities, and water consumption,

among other elements, covering both current and future lithium exploitation processes, for use by decision-makers, academia, and civil society.

3.2. Enhancing Environmental Assessment and Public Participation

The growing demand for lithium and the discourse surrounding new technologies such as DLE are often presented as legitimizing strategies which, if not accompanied by improvements in the regulatory standards of mining activities, risk remaining an empty or even contradictory narrative. It is therefore urgent to establish specific environmental regulations that address both the projected scale of intervention and the complexity and vulnerability of salt flat ecosystems. Such regulations should endow the system with the capacity to approach decision-making based not only on evidence, but also on the strengthening of environmental democracy, thereby incorporating intergenerational equity, socio-environmental justice, and territorial relevance.

In this sense, it is necessary to strengthen environmental impact assessment so that it is capable of addressing environmental interventions in an integral, synergistic, and cumulative manner, taking into account the historical and environmental complexity of the territories where various extractive activities are expected to be established.

These territories and basins are inhabited by both human and non-human beings who must be considered in decision-making processes, in order to truly identify the consequences that the expansion of lithium mining will have for the various life systems. To this end, it is essential to guarantee mechanisms of informed participation, whether through the implementation of Indigenous consultations under the standards of ILO Convention 169, or through the implementation of public participation processes in environmental matters, both in relation to public policies and to individual projects.

For the proper implementation of any form of exploitation, it is essential to evaluate environmental impacts from the stage of public policy design, through the development of infrastructure, up to the production of the final solid lithium product and its preparation for export at ports, as well as the closure of such projects and the condition in which these territories will be “vacated” by industrial activity. This must be accompanied by permanent and transparent environmental monitoring, particularly regarding water systems and their interactions with other environmental components.

Standardized protocols are also required for different areas, such as prior characterization (hydrological, geochemical, and geomechanical) according to each method of exploitation (adsorption, ion exchange, membranes). In addition, the criteria

of social and economic feasibility, as well as the environmental viability of projects, must include the generation and quality of environmental information, specific monitoring and contingency plans, their effective dissemination, and the adaptation of each project's elements to empirical evidence of the impacts generated by these projects.

Communities linked to these ecosystems must play an active role in project evaluation, moving from being considered mere observers to being recognized as bearers of indispensable knowledge for decision-making. This recommendation would allow them to contribute their knowledge of the territory and their experience in the functioning of ecosystems and associated life systems, as well as to access monitoring information in the event that particular projects are approved. It is crucial to ensure that mining expansion in sensitive territories does not compromise the rights of local communities—especially Indigenous peoples—nor their relationship with the environmental components present in their territories, such as access to water.

3.3. The Crucial Challenge of Protecting Water Ecosystems.

DLE technologies must ensure the rational and sustainable use of water within basins. Although DLE consumes less water than traditional methods, it still requires freshwater and energy. The reinjection of depleted brines, while promising as a way to mitigate falling groundwater levels, can alter the geochemistry of the salt flat and affect the hydrological balance.

Waste management must also be addressed, including residual brine, water contaminated by washing processes, and solid residues such as precipitates or spent membranes, since poor management can disrupt the hydrological and chemical balance of the salt flats.

Here we propose the creation of independent hydrogeological models to inform decision-making processes, making it possible to achieve proper water management that considers the specific characteristics of each salt flat and the interactions among water, communities, biodiversity, and extraction processes. In this regard, collaboration with universities, research centers, and civil society organizations can provide essential data and analyses for informed decision-making, thereby generating science in the service of people and their territories.

Table 1. Comparative chart of the conditions, advantages, and disadvantages of lithium extraction methods from a process ²⁴ perspective. Own elaboration..

Operating Conditions	Brine Evaporation Methods	Methods of Direct Lithium Extraction (DLE)
Rate of Evaporation and Precipitation	• High evaporation rate reduces process duration • In areas with high precipitation and low evaporation, the process is not profitable and becomes prolonged	• Does not depend on climate, allowing implementation under different environmental conditions
Concentration of Lithium in Brine	• High lithium concentration (2,100 ppm in the Salar de Atacama) improves efficiency. • Low concentrations require more time and resources, increasing costs.	• Effective for brines with low lithium concentrations. • Still experimental and not fully viable under industrial conditions.
Mg²⁺/Li⁺ Ratio	• Favors the formation of lithium chloride and reduces costs. • High magnesium concentrations increase reagent consumption and complicate the process.	• DLE technologies can efficiently separate lithium, even in the presence of high magnesium levels
Process Duration	• Under optimal conditions, the process lasts between 12-14 months • It may take up to 18 months in non-optimal areas	• Fast process (hours or days) compared to evaporation

24 Garcés, I. & Álvarez, G. (2020) Water mining and extractivism of the Salar de Atacama, Chile. WIT Transactions on Ecology and the Environment, 245, 189-199. DOI: 10.2495/EID200181

Environmental Impact	• High water consumption, generates saline waste, and affects local ecosystems	• Lower water consumption, lower waste generation • The long-term effects of brine reinjection are not yet fully studied
Cost	• Low operating costs in suitable areas • High costs in non-optimal areas due to the long duration of the process	• Potential to reduce operating costs in the future • High initial investment and operating costs at present
Climate Dependence	• Depends on the evaporation rate and local climatic conditions	• Does not depend on climate, can be implemented in diverse areas



Photograph: Aline Juárez.

Table 2. Effectiveness of the Different Direct Lithium Extraction Methods. Source: Taken from Garcés, 2017; Torres et al., 2020; Kelly et al., 2021; Murphy and Haji, 2022; Calvo, 2022.

Tecnology	Description	Lithium Recovery Rate (%)
Adsorbents	Sorbent-based adsorption process	80 – 99.9
Ion Exchange	Resin-, aluminate-, or ceramic-based ion exchange	80 – 99.9
Solvent Extraction	Solvent–brine mixing process for water extraction	99.9
Membrane Separation	Used in conjunction with ion exchange and adsorbents/ solvent extraction; promising processes include absorption or intercalation.	>99
Electrochemical Separation	Electrochemical lithium extraction from brines via adsorption	>90



Photograph: Aline Juárez.

Table 3. Comparison of Lithium Extraction Methods. Source: Modified from Goldman Sachs Global Investment Research, 2023; and other sources: Kelly et al., 2021; Murphy and Haji, 2022; Calvo, 2022.

Extraction Methods	Rock Mineral	Brine Mining	
	Conventional Mining	Evaporation	Direct Lithium Extraction (DLE)
Lithium Recovery	~60-80% (processing)	~40-60%	~70-90%
Process Duration	Weeks to months	11-18 months	Hours - days
Process	Spodumene (~5–6% Li ₂ O)	Lithium carbonate (Li ₂ CO ₃), lithium chloride (LiCl), lithium hydroxide (LiOH)	Lithium Carbonate (Li ₂ CO ₃) / Lithium Chloride (LiCl)
Costs	Medium – High	Low	Medium
Investment	Varied in grade / chemical conversion	~US\$23-34,000/tpa LCE	~US\$26-34,000/tpa LCE
Operating Costs		~US\$ 3, 300-4,900/t LCE	~US\$2 , 800 - 3,600/t LCE
Additional Treatment Requirements	Yes	No	No
Surface Area Requirements	High	Low	Low

Climate Dependency	Yes	Yes	No
Water Consumption	High	Medium – High	Low – Medium (subject to availability of reinjection)
Energy Consumption	High	Low (uses energy from the sun)	Medium
Emissions	High	Low	Low
Environmental Impacts	High	Medium	Low
Evaporation Rates	Independent	No specific requirement	Moderate to Low
Concentration Factors	Method applicable to any ore grade	Not economical for brines with concentrations below 30 ppm	More economical for low-concentration brines; applicable to natural geothermal brines.



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