Lithium, Environmental Impacts and High Andean Salt Flats in Argentina, Bolivia and Chile. An Integrative Review of Scientific Literature

Manuel Olivera-Andrade[1], Mauricio Lorca[2], Araceli Clavijo[3], Ingrid Garcés[4]

Abstract

This article reviews scientific literature on lithium mining's environmental impacts in Argentina, Bolivia, and Chile's salt flats, analyzing the period 1975-2024. The literature splits into two views: an optimistic one promoting lithium as vital for energy transition and global markets, and a critical one warning of irreversible damage to fragile ecosystems and local lifestyles. Despite growing socio-environmental interest over 50 years, knowledge gaps persist, the information on socio-environmental impacts is dispersed, with different levels of depth and rigor, and with uneven data distribution and capabilities among these countries. Chile's *Salar de Atacama*, heavily researched due to mining influence, shows major impacts on water, biodiversity, and communities, yet lithium extraction continues despite insufficient data for responsible management. Additionally, much of this information does not reach local territories, and the treatment of impacts perceived by local communities remains limited, exacerbating inequalities. Unless significant innovations are made, the extraction of lithium salts from high Andean salt flats is paradoxically accelerating the socio-environmental degradation of these fragile ecosystems.

Keywords: lithium triangle; environmental impacts; socio-environmental conflicts; lithium mining; salt flats.

[1] Candidato a Doctor en Política, sociedad y cultura (Universidad Mayor deSan Andrés, Bolivia). Magister en Desarrollo Económico (Universidad Mayor de San Andrés). Biólogo. Profesor en Postgrado en Ciencias del Desarrollo, CIDES, Universidad Mayor de San Andrés, La Paz, Bolivia. Orcid: 0000-0003-3291-2488. Email: manuel.olivera@cides.edu.bo

[2] Doctor en Gestión de la cultura y el patrimonio (Universidad de Barcelona, España). Profesor asociado Instituto de Estudios Humanísticos Juan Ignacio Molina, Centro de Documentación Patrimonial, Universidad de Talca, Chile. Orcid: 0000-0003-3490-8212. E-mail: mauricio.lorca@utalca.cl

[3] Doctora en Ciencias (Universidad de Buenos Aires, Argentina). Investigadora asistente en Instituto de Investigaciones en Energía No Convencional, INENCO, del Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Argentina. Orcid: 0000-0001-8370-6073. E-mail: a.clavijolara@gmail.com

[4] Doctora en Ciencias (Universidad de Zaragoza, España). Ingeniero Civil Químico de la Universidad Católica del Norte. Investigadora de proyectos Universidad de Antofagasta y Universidad Católica del Norte. Orcid: 0000-0002-8889-8374. E-mail: ingrid.garces@uantof.cl

Within the framework of the Paris Agreement (2015), measures aimed at reducing greenhouse gas emissions have been promoted[5]. In this context, a number of regional programs and financial incentives have been formulated to shape and replace fossil energy source generation and storage infrastructures with zero-carbon footprint technologies[6,7,8,9]. In this context, lithium has become a critical and strategic material for the production of lithium-ion batteries and the replacement of the conventional automotive fleet with an electric one.

The current energy paradigm shift, as has occurred in other stages of technological revolution, requires the intensive use of low-cost and highly available raw materials that are synonymous with global territorial reconfigurations[10,11]. Indeed, the growing demand for strategic critical elements for the energy transition, is paradoxically accelerating the environmental degradation of the territories that provide these "critical resources"[12,13]. In this context, the expansion of extractive frontiers to the salt flats shared by Argentina, Bolivia and Chile (ABC), transforms these still rich and fragile wetlands into mere "producing regions" of natural resources[14,15,16].

It is estimated that the intensive use of materials, such as lithium, will increase as the decarbonization process progresses[17]. About 70% of the world's lithium comes from hyper saline waters that, due to the high content of dissolved solids, are present

[5] Harpreet Kaur Paul, "The Green New Deal and global justice," Renewal (0968252X) 28, no. 1 (2020).
[6] Usman W. Chohan, "A green new deal: Discursive review and appraisal." Notes on the 21st Century (CBRI) (2019).
[7] EC-European Commission. "The European Green Deal, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee of the Regions (COM (2019) 640 final)." European Commission. Brussels 11 (2019).
[8] United Nations, "Paris Agreement on Climate Change", United Nations Framework Convention on Climate Change, accessed on July 2025, https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[9]United Nations, "Transforming our world: the 2030. Agenda for Sustainable Development A/RES/70/1", Department of Economic and Social AffairsSustainable Development, accessed on May 2025, https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf
[10] Gavin Bridge, and Ludger Gailing, "New energy spaces: Towards a geographical political economy of energy transition," Environment and Planning A: Economy and Space 52, no. 6 (2020): 1037-1050.
[11] Carlota Perez, Technological revolutions and financial capital: The dynamics of bubbles and golden ages (Cheltenham UK, Northampton USA: Edward Elgar Publishing, 2002).
[12] Vysetti Balaram, "Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact," Geoscience Frontiers 10, no. 4 (2019): 1285-1303.
[13] Alireza Dehghani-Sanij et al., "Study of energy storage systems and environmental challenges of batteries," Renewable and Sustainable Energy Reviews 104 (2019): 192-208.
[14] Audrey Sérandour, "Le «triangle du lithium» existe-t-il? Géographie politique d'une régionalisation andine (Argentine, Bolivie, Chili)." Belgeo. Revue belge de géographie 4 (2020).
[15] Maristella Svampa, Las fronteras del neoextractivismo en América Latina: conflictos socioambientales, giro ecoterritorial y nuevas dependencias (Germany: CALAS and Bielefeld University Press, 2019).
[16] Jason W. Moore, "El auge de la ecología-mundo capitalista (I)," Laberinto 38 (2013): 9-26.
[17] Kirsten Hund, et al., Minerals for climate action (Washington: World Bank, 2020).

in the salt flats located in the Puna and the Atacama Desert. The extraction and separation of lithium from this brine is carried out by a method consisting of pumping and concentration of the brine by solar evaporation. This process means the release of considerable volumes of water into the atmosphere which makes this extraction method environmentally inefficient. That is to say, if the technology to obtain lithium does not change, water consumption will increase, regardless the agreements that may be reached by the social actors at stake[18,19].

The academic community has been concerned with the growing impacts and conflicts of mining activities associated with lithium from brine. The first studies from the social sciences are based on the impacts perceived by local communities and experts and the conflicts that emerge from those impacts. However, the studies that articulate the monitoring of ecosystems with ethnographic data and the territorial transformations being generated by lithium mining in salt flats are still limited, dispersed and poorly systematized. This may be due to the scarcity of empirical evidence, the dispersion of information and the weak interdisciplinary interaction between researchers from the social sciences, natural sciences, engineering and other fields of knowledge.

This article compiles and analyzes the gathered scientific knowledge on environmental impacts, concerning lithium brine mining, with the aim of answering questions such as: how has scientific research on mining been organized in ABC? What are the main scientific perspectives on the socio-environmental impacts and conflicts produced by lithium mining in the countries of interest? Are they divergent or convergent? The paper is structured as follows: first, an overview of the scientific production on lithium in ABC is presented through a bibliometric review. Next, the main scientific contents proposed by this literature on the socio-environmental impacts related to lithium mining in salt flats are reviewed and, finally, a reflection on the

[18] Hans Gundermann, and Barbara Göbel, "Comunidades indígenas, empresas del litio y sus relaciones en el Salar de Atacama," Chungará (Arica) 50, 3 (2018): 471-486.
[19] Mauricio Lorca et al., "Mining indigenous territories: Consensus, tensions and ambivalences in the Salar de Atacama," The Extractive Industries and Society 9 (2022): 101047.

current scientific debate and arguments on the environmental sustainability of lithium mining is presented.

METHODOLOGY

This article addresses an integrative or critical review as a synopsis of the research, views and scientific arguments related to lithium mining in an orderly, precise and analytical manner. The integrative reviews synthesize both empirical and theoretical information in order to contribute to a deeper understanding of the topic discussed through global conclusions[20]. A review of the scientific literature on this topic, between 1975 and 2024, is presented, in order to account for the main data and ideas that the scientific production provides on lithium and the socio-environmental impacts (hereinafter impacts) and socio-environmental conflicts (hereinafter conflicts) in the countries of study.

Three documentary information analysis filters or screens were applied (Table 1). The information was then analyzed by applying three prioritization screens of publications, authors and data. Thus, was established as a proxy variable for the diversity of ideas that the academic world has put forward on the subject of lithium between 1975 and 2024. Regarding the impacts and conflicts related to its exploitation, the work emphasizes four key aspects: a) the gaps in scientific production and knowledge about the main salt flats in the region; b) the degree of relevance of socio-environmental issues in scientific production; c) the most influential publications in the knowledge domains of impacts and conflicts and d) the weak interrelation between them.

The review was complemented with a historical account of academic production based on statistical data available in the repositories of public universities and research institutions, and other published information, in each country for the period 2000-2024. Finally, information provided by recent socio-environmental studies was incorporated, in order to analyze the sustainability of lithium mining operations in the

[20] Silamani A. Guirao Goris, "Utilidad y tipos de revisión de literatura." Ene 9, 2 (2015): 0-0.

countries of interest. In other words, the conclusions of studies analyzing multiple reported impacts of the extraction of lithium in high Andean salt flats, are included.

Table 1: Screening of documentary information analysis.

Screen 1	Mentions in text and title were reviewed in Google Scholar for the period 1975-2024 (organized by lustrums). A total of 162 information search codes in English and Spanish were applied. These keyword combinations used as corpus the mentions of the code: Lithium + Argentina + Bolivia + Chile. The reflection was organized into two knowledge domains: impacts and conflicts. Eight root codes were used, which were combined with the geographical location (lithium triangle, country, region/province, name of the salt flat).[21]
Screen 2	The historical production of scientific articles in Web of Sciences (WoS), through its Open-source resource Plubons, on the Atacama and Maricunga salt flats in Chile; Uyuni, Coipasa and Pastos Grandes in Bolivia, and Hombre Muerto, Olaroz, Salinas Grandes and Laguna Guayatayoc in Argentina, distributed in 23 areas of knowledge, were reviewed.
Screen 3	The main ideas and informative content related to the socio-environmental impacts of lithium mining in salt flats were analyzed, organized by country, in a sample of the most cited publications from the period 2015-2024, using Google Scholar platform and Semantic Scholar IA resource, focused on Environmental Science field.

Source: own elaboration.

SCIENTIFIC PRODUCTION ON LITHIUM IN ABC (1975-2024)

Worldwide, the scientific knowledge in brines began to develop in the 1960s, in the dry bed of Clayton Valley Lake, near the town of Silver Peak, Nevada, USA, at the operations of Chemetall Foote Minerals Co. In 1975, this company signed the first agreement with the Chilean State to study the feasibility of producing lithium in the Salar de Atacama. In 1980 the Sociedad Chilena de Litio Ltda. (SCL, currently Albemarle) was created and in 1984 lithium carbonate production began. Since then, interest, production and scientific dissemination of this mineral have progressively increased.

[21] The eight root codes are: Lithium; Lithium triangle; Lithium + "environmental impacts"; Lithium + "socio-environmental impacts"; Lithium + "socio-ecological impacts"; Lithium + "environmental conflicts"; Lithium + "socio-environmental conflicts"; Lithium + "socio-ecological conflicts". Contrast code: "Nuclear" AND "geological study".

Scientific research on the subject and countries of study extends over 50 years (1975-2024). According to the record of publications indexed in the Web of Science platform (WoS), up to July 2022, 1,511 scientific articles were registered in a total of 23 areas of knowledge, excluding the field of physics (Table 2). Seventy-five percent of these publications were in the Salar de Atacama, followed by the Salar de Uyuni with only 2%. The Maricunga (Chile) and Pastos Grandes (Bolivia) salt flats have only four publications in the field of geosciences. In this group of publications there is a clear predominance of geosciences (31%), followed by social sciences (15%), plant and animal sciences (12%) and environment and ecology (12%).

Through an analysis of the level of popularity or number of appearances of the main salt flats in mentions and citations in the scientific literature related to lithium, it was estimated that the lithium-salt flats theme has multiplied by about 4,000% between 1975 and 2024 (Fig. 1A). However, scientific concern about the salt flats that host this raw material, as well as the possible environmental and social costs of its extraction on these wetlands, only appears in the scientific literature from the decade of 1990, being marginal compared to the debate on lithium in other sciences, with just over 5% of the total mentions, the last half decade. As shown in figure 1, since the 1990s, the popularity of lithium in the scientific literature has increased and the academic concerns on socio-environmental issues grew exponentially since 1990 onwards, reaching about 25% and 30% of the total number of mentions of lithium between 2020 and 2024, in ABC, respectively (Fig. 1A and 1B).

Table 2: Number of scientific publications in Web of Sciences (WoS), according to area of knowledge, salt flat and region.[22]

KNOWLEDGE AREA	ATA	MAR	ANT	CHL	SG/LG	OLA	HMT	CAT	JUJ	ARG	UYU	COI	SPG	LIP	BOL	ABC
Geosciences	358	4	38	400	2	3	0	26	20	51	15	2	4	3	24	475

[22] The knowledge areas are 23 ESI (Essential Science Indicators Research Areas), for the categorization of scientific journals. "Other sciences" includes seven knowledge areas: Neuroscience and Behavior, Psychiatry and Psychology, Immunology, Mathematics, Cross-Field, Economics and Business, and Computer Science. ATA = Atacama Salt Flat; UYU = Uyuni Salt Flat; MAR = Maricunga Salt Flat; HMT = Hombre Muerto Salt Flat; COI = Coipasa Salt Flat; OLA = Cauchari-Olaroz Salt Flat; SG/LG = Salinas Grandes y Laguna de Guayatayoc; SPG = Salar de Pastos Grandes; ANT = Antofagasta Region; CAT = Catamarca Province; LIP = Lípez Provinces; JUJ = Jujuy Province; ARG, BOL, CHL = Total publications recorded for the salt flats and regions in the table, summed in each country; ABC = Total publications recorded in the lithium triangle. In Atacama more than 3,600 publications are registered, only for the field of Physics.

Social Sciences	143	0	22	165	3	0	0	33	26	62	1	0	0	3	4	231
Environment and Ecology	129	0	27	156	1	0	1	4	3	9	4	0	0	1	5	170
Space Sciences	119	0	0	119	0	0	0	0	0	0	0	0	0	0	0	119
Plant and Animal Science	125	0	19	144	0	0	0	15	17	32	0	0	0	0	0	176
Microbiology	94	0	0	94	0	0	0	0	2	2	2	0	0	0	2	98
Multidisciplinary	58	0	5	63	1	0	0	0	2	3	1	0	0	0	1	67
Agricultural Sciences	24	0	1	25	0	0	0	8	4	12	0	0	0	0	0	37
Engineering	25	0	4	29	0	0	0	0	1	1	0	0	0	0	0	30
Chemistry	16	0	1	17	0	0	0	0	1	1	1	0	0	0	1	19
Biology and Biochemistry	16	0	6	22	0	0	0	2	1	3	3	0	0	0	3	28
Molecular Biology and Genetics	8	0	1	9	0	0	0	0	1	1	0	0	0	0	0	10
Clinical Medicine	7	0	3	10	0	0	0	2	16	18	0	0	0	0	0	28
Pharmacology and Toxicology	6	0	2	8	0	0	0	1	1	2	0	0	0	0	0	10
Material Science	2	0	0	2	0	0	0	1	0	1	4	0	0	0	4	7
Other sciences (excepting Physics)	2	0	2	4	0	0	0	1	1	2	0	0	0	0	0	6
Total	**1.132**	**4**	**131**	**1.267**	**7**	**3**	**1**	**93**	**96**	**200**	**31**	**2**	**4**	**7**	**44**	**1.511**

Source: Own elaboration based on data from the WoS public access platform[23].

Through an analysis of the level of popularity or number of appearances of the main salt flats in mentions and citations in the scientific literature related to lithium, it was estimated that the lithium-salt flats theme has multiplied by about 4,000% between 1975 and 2024 (Fig. 1A). However, scientific concern about the salt flats that host this raw material, as well as the possible environmental and social costs of its extraction on these wetlands, only appears in the scientific literature from the decade of 1990, being marginal compared to the debate on lithium in other sciences, with just over 5% of the total mentions, the last half decade. As shown in figure 1, since the 1990s, the popularity of lithium in the scientific literature has increased and the academic concerns on socio-environmental issues grew exponentially since 1990 onwards, reaching about 25% and 30% of the total number of mentions of lithium between 2020 and 2024, in ABC, respectively (Fig. 1A and 1B).

According to the WoS database, Chile concentrates 84% of the scientific production in ABC (Table 2), and the Salar de Atacama has received most research attention. Most of that production was led by the natural sciences, possibly due to the

[23] https://publons.com/publon/?order_by=date Access: July 2022. Since 2023, Plubons was incorporated in WoS platform, which was no longer an Open-Source resource.

importance of this salt flat in terms of its geological, mineralogical and hydrogeological scientific interest. Furthermore, the strong prevalence of Chile and the Atacama salt flat for scientific research is probably explained by the disparities in the scientific development of each country but, above all, by the presence, magnitude and interest of mining capital in those places. Indeed, for science and capital, the identification and quantification of existing resources and their applied research (geological prospecting, nuclear research, materials science, among others) is of special interest. In this regard, the study of the impacts and conflicts associated with lithium in the area have been recently integrated into the productive cartography and academic debate, being the most representative case, as mentioned above, that of the Salar de Atacama (Fig. 1b). The problem of the impacts caused by lithium mining in this salt flat coincides with the establishment of Chilean environmental regulations through the enactment of Law 19,300 or Ley sobre Bases Generales del Medio Ambiente in 1994. The study of conflicts caused by lithium mining is addressed by science from the first and second half of the 2000s, coinciding with the beginning of the judicialization of disputes between mining companies and Atacameño indigenous organizations[24,25].

The lithium research began in Chile in 1969, when the Corporación de Fomento a la Producción (CORFO) commissioned the Geological Research Institute to carry out a study of the Salar de Atacama. The results, presented in Moraga and collaborators[26], established the potential to produce lithium in that salt flat at a lower cost than the brine deposits located in the USA. During the 1970s and 1980s, and in spite of the high interest generated by the salt flats, few studies were published at that time and those that were mainly aimed at experimental tests to quantify resources and obtain salts. Most of the research was conducted by the Universidad de Antofagasta and the Universidad Católica del Norte, under the supervision of Sociedad Minera Salar de

[24] Héctor Morales, and Rodrigo Azócar, "Crónica analítica de un triunfo etnoambiental en el Salar Atacama: Pampa Colorada," Revista Chilena de Antropología 39 (2019).
[25] Paola Bolados García, "Los conflictos etnoambientales de “Pampa Colorada” y “el Tatio” en el salar de Atacama, norte de Chile: Procesos étnicos en un contexto minero y turístico transnacional," Estudios atacameños 48 (2014): 228-248.
[26] Gustavo Lagos, El desarrollo del litio en Chile: 1984-2012 (Santiago de Chile: Centro de Minería, Pontificia Universidad Católica de Chile, 2012).

Atacama Limitada (MINSAL Ltda., now SQM), the company that had been granted the exploitation rights for the Salar de Atacama[27].

It is relevant to note that since 1981, Chile has had the Fondo Nacional de Desarrollo Científico y Tecnológico (Fondecyt), which today depends on the Agencia Nacional de Investigación y Desarrollo (ANID), which is the service responsible for promoting, encouraging and developing research, technological development and scientific and technological innovation in that country. Between 2005 and 2011, 24 lithium research projects were recognized by Fondecyt. 71% of these projects were on battery materials and 54% of them were carried out by the Universidad de Santiago and the Universidad de Chile (Fig. 2a). Only from 2008 onwards research addressing the socio-environmental impacts generated by lithium mining in the Atacama and Maricunga salt flats (Fig. 1b) was detected.

Since the launching of the Estrategia Nacional del Litio (ENLi) in April 2023, the State of Chile, through ANID, has invested significant sums of money with the objective of generating knowledge on salt flats in all fields of knowledge. This has been done through public competitions aimed at producing information through the financing of research projects, training of advanced human capital, strengthening of international academic linkage networks, creating associative research centers and even a research fund aimed at studying three specific salt flats (Aguilar, Grande and de la Isla). However, his has not reversed research interest in lithium applications, as an input for batteries. Finally, as part of the strategy, the Instituto Nacional del Litio y Salares (INLiSa) began operations in 2025. This organization focuses on ; research and characterization of salt flats, evaluation and development of salt flat exploitation technologies and new products, study of the socio-cultural impacts of lithium mining and development of citizen science.

On the other hand, in Argentina, highlights the role of the Dirección General de Fabricación Militar (DGFM) and the Comisión Nacional de Energía Atómica (CNEA) which, between 1969 and 1974, within the framework of the Plan *Salares*, investigated

[27] Aldo B. Moraga et al., "Estudio Geológico del salar de Atacama, Provincia de Antofagasta," Boletín IIG, 29 (1974).

the field of atomic energy[28]. Despite the high interest the salt flats generated at that time, during 1973 and 1992, few publications are detected, mainly aimed at conducting experimental tests to quantify resources and obtain salts. Since 1958, the Argentinean scientific research is promoted by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). Between 2000 and December 2024, the CONICET repository reports a total of 233 studies related to lithium, published mainly as scientific articles, of which most correspond to social sciences (42%) and natural and exact sciences (17%), being relevant that 95% were published after 2010 (Fig. 2b). Indeed, since that year, the highest productivity on lithium in that country is found, which coincides with, first, the interest that this mineral awakens as a critical strategic component of the energy transition and, second, with the interest generated by the socio-environmental conflicts that emerge from the expansion of lithium mining in that country. Argentine research, unlike that produced in the other two countries studied, stands out for the significant presence of works from the field of social sciences.

Meanwhile, in Bolivia, the first studies are recorded since 1974 and were carried out by the Universidad Mayor de San Andrés (UMSA) through an agreement with the Office de la recherche scientifique et technique outre-mer (ORSTOM) of France and since 1976 through an agreement between the Servicio Geológico y Minero de Bolivia (SERGEOMIN) and the United States Geological Survey (USGS). That collaboration focused its main interests on Quaternary geology, limnology of altiplano wetlands and geology of salt flats[29,30]. Starting in 1989, after the attempt to award the exploitation of lithium from the Salar de Uyuni to the company FMC Lithium (then Livent Corp.), lithium research in Bolivia was led by UMSA, Universidad Técnica de Oruro (UTO) and the Universidad Autónoma Tomás Frías (UATF)[31]. Since 2005, Bolivian public universities began to receive resources for research from the Direct Tax on Hydrocarbons (IDH), although most of these resources have been allocated to infrastructure and equipment. In the last 12 years, coinciding with the period of the

[28] Lagos, "El desarrollo del litio en Chile: 1984-2012"
[29] Goerge E. Ericksen et al., "Lithium-rich brines at Salar de Uyuni and nearby salars in southwestern Bolivia," US Geological Survey, (1977) 77-615.
[30] Manuel Olivera Andrade, La industrialización del litio en Bolivia: un proyecto estatal y los retos de la gobernanza, el extractivismo histórico y el capital internacional (La Paz: CIDES-UMSA, 2017).
[31] Ibid.

state lithium industrialization program, interest in this mineral has increased: between 2015 and 2020 the UMSA executed five research projects linked to lithium.[32]

Apart from these initiatives, each Bolivian university still have to raise their own funds for research, usually in the context of agreements with foreign programs. Between 2000 and December 2024, 48 documents (degree projects, bachelor's theses and master's theses) on topics directly related to lithium industrialization were registered in the UMSA repository. Of these, 81% studies belong to the fields of engineering, technology and chemical sciences (Fig. 2c). Additionally, UMSA Research Outputs Database and SciELO Bolivia Repository report 30 published scientific articles related to salt flats and lithium, 37% of which are related to material sciences, chemistry and mineral processing. In 2024, Bolivian government launched the first call from the Fondo de Fomento al Desarrollo de Ciencia y Tecnología (FONDECyT) for Universities and Technical and Technological Institutes, based on the needs identified by entities and companies in strategic sectors, including eight projects related with lithium sector.

In summary, research priorities in ABC have been focused in the field of geosciences and engineering and are associated with the consumption cycles and technical needs of lithium as a raw material for the energy transition (Fig. 2). In fact, between 1985 and 1999 (Fig. 1B), research promoted by universities and state agencies was used and deepened by mining companies such as, in Chile, Foote and MINSAL Ltda. and, in Argentina, FMC, to facilitate the extractive processes and their international insertion. Today, despite that the emergence of the impacts and conflicts associated with lithium mining are recent and capture the growing attention of many researchers, most studies on lithium are still focused on the characterization of the resource and on applied research framed in the needs of the transition energy, materials manufacturing and new technologies for salt extraction. This leads to the persistence of important information gaps for decision-making in terms of conservation and environmental management, hydrogeology, ecological functions and biodiversity, among others. Moreover, comparison between the three countries should be cautiously interpreted, due the different forms of research output registration in the ABC.

[32] UMSA, Potencial científico tecnológico Universidad Mayor de San Andrés (2015-2020), (La Paz: UMSA, 2020).

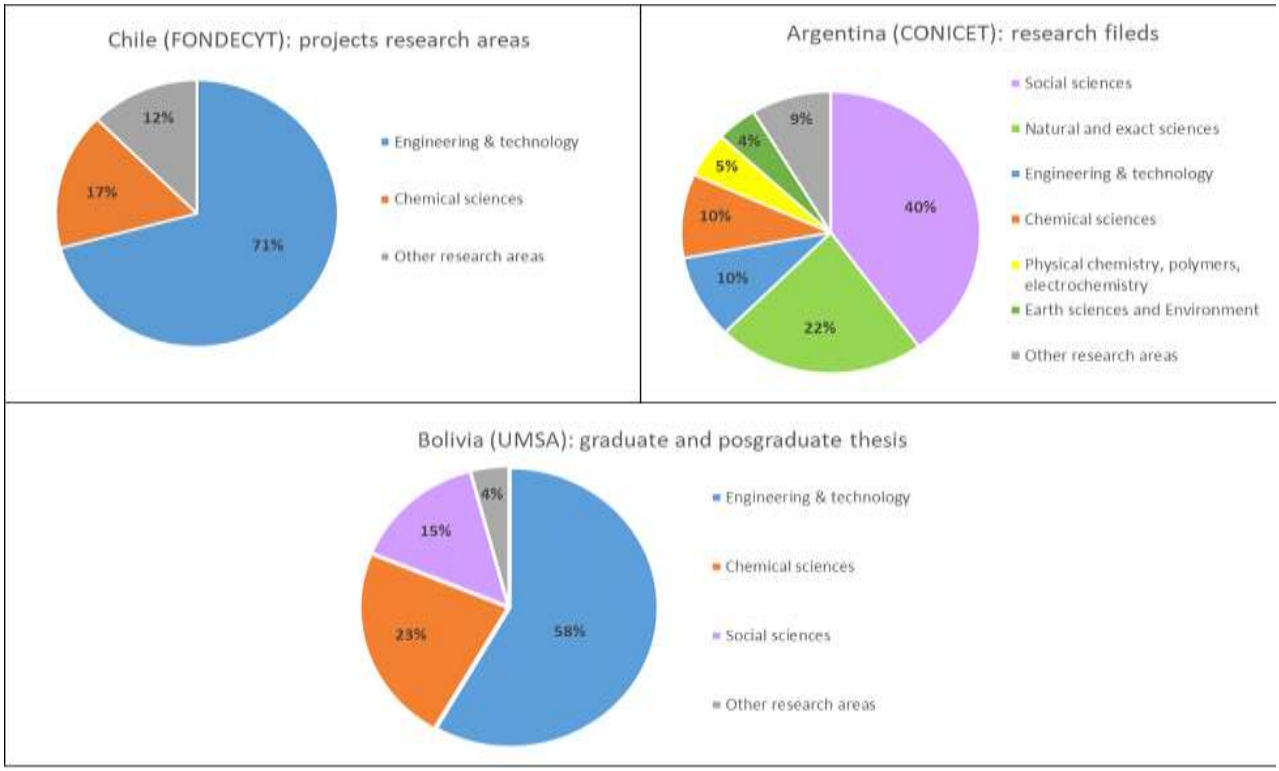
Although there are many voices analyzing the environmental challenges in the face of the extraction of natural resources in pursuit of the energy transition –with topics such as the erosion of citizen participation standards and the democratic debate of extractive projects–, the dominant regional scientific discourse on lithium tends to accommodate to the interests of lithium extraction and industrialization.

Fig. 1A and 1B: Mentions and citations of lithium in the high Andean salt flats and Chile in the academic literature, 1975-2024.



Source: Own elaboration based on data from Google Scholar, access December, 2024.

Fig. 2. Disciplinary fields of lithium research in academic institutions in Argentina, Bolivia and Chile, 2000-2024.



Source: Own elaboration based on data accessible from Fondecyt (*Scientific Outlook Reports*, 2005-2014), CONICET and UMSA online repositories, access December, 2024.

A Growing Concern: Lithium, Impacts and Conflicts in ABC

The "environmental impact" category finds its origins in the USA as part of the Environmental Impact Assessment (EIA) instruments and the National Environmental Policy Act (NEPA) of 1969. This type of study measures the possible consequences of certain human actions on the environment, in order to provide information to decisions-makers as to correct or mitigate the negative environmental effects of the initiatives evaluated. In this case, field data is captured according to watertight compartments that establish effects on the biotic (fauna, flora) and abiotic (air, soil, water) components of the study area[33]. In other words, cause-effect analysis seeks to

[33] Judith Petts, ed., Handbook of environmental impact assessment, Volume 2: Impact and limitations. Vol. 2. (John Wiley & Sons, 2009).

isolate the phenomenon in time and space, abstracting from the natural history of the environment and the complexity of the socio-cultural phenomena linked to it.

In turn, the notion "socio-environmental conflict" comes from the field of political ecology, with a Marxist and post-positivist approach to the nature/society relationship, with a growing presence of feminist and post-colonial trends[34]. The socio-environmental conflict emerges then as a category to understand power relations, ecological-distributive conflicts and as a form of valuation, significance and appropriation of nature that emerges from the actions of some social actors, and in the case of lithium, especially from the indigenous peoples who inhabit or claim the basins of the salt flats as their own territories[35].

The socio-environmental impacts and conflicts are linked in three areas of scientific production: a) production in indexed journals, specialized books and gray information; b) institutional reports generated by observatories, human rights agencies and NGOs; c) technical instruments of the national environmental evaluation systems, both in public regulatory agencies and in the departments of the operating companies. The following systematizes and analyzes the academic production and although we note some figures on the production of university theses, we exclude, in this section, the grey literature from the analysis. Table 3 below shows the topics and the increase in the scientific literature concerning lithium and salt flats in ABC since the beginning of this century until today.

Since 2010, it is possible to identify in the scientific literature related to the role of lithium in the energy transition, two opposing dominant narratives in the countries of interest. Obviously, there are nuances between and within those discourses according to the framework of thought and the interests of each researcher. On the one hand, there are academics who lean towards the international insertion of their respective countries in the process of energy transition. This discourse focuses on the evaluation of the techno-economic potential of lithium reserves, the possibilities of industrialization, the scientific-technological activities linked to the mineral, the

[34] Thomas Perreault, Gavin Bridge, and James P. McCarthy, eds., The Routledge handbook of political ecology (London: Routledge, 2015).
[35] Joan Martinez-Alier, "The Environmentalism of the poor: a study of ecological conflicts and valuation," In *The Environmentalism of the Poor*. Edward Elgar Publishing, 2002.

deepening of mining and the associated risks[36,3738]. On the other hand, there are researchers critical to the energy transition that focus their interest and concern for the extraction territories and that give prominence to the impacts –real, potential or perceived– and the participation of communities in the debate and actions concerning their territories, the role they play in the energy transition, the sustainability of water reserves and traditional ways of life[39,40,41,42,43].

Table 3: Thematic characterization of scientific production on lithium, with examples of key literature, 2000 – 2024

Before 2000	They correspond to studies on lithium oriented to the field of geological prospecting, atomic energy and health that do not address the potential impacts of lithium mining[44,45].
2000 - 2005	In Chile, some pioneering studies have surfaced on and include concerns on the socio-environmental issue[46,47].
2006 - 2010	First approximations on the environmental impacts of the lithium industry. More than 100 papers on the potential and some environmental risks in the value chain are detected[48,49].
2011 - 2015	The potential territorial impacts of lithium extraction are analyzed from the perceptions of local communities regarding the progressive water scarcity caused by mining and tourism[50,51].

[36] Bruno Fornillo, Litio en Sudamérica: geopolítica, energía y territorios (Buenos Aires: El Colectivo, CLACSO, IEALC, 2019).
[37] Enrique J. Baran, ed. Litio: un recurso natural estratégico: desde los depósitos minerales a las aplicaciones tecnológicas (Buenos Aires: Academia Nacional de Ciencias Exactas, Físicas y Naturales, 2017).
[38] Martín Obaya, et al., "From local priorities to global responses: Assessing sustainability initiatives in South American lithium mining." The Extractive Industries and Society 19 (2024): 101509
[39] Marina Weinberg, "The off-sites of lithium production in the Atacama Desert." *The Extractive Industries and Society* 15 (2023): 101309.
[40] Diego Fuentealba et al., "Technological tendencies for lithium production from salt lake brines: Progress and research gaps to move towards more sustainable processes." *Resources Policy* 83 (2023): 103572.
[41] Walter F. Díaz, et al., "Lithium mining, water resources, and socio-economic issues in northern Argentina: We are not all in the same boat." *Resources Policy* 81 (2023): 103288.
[42] Barbara Jerez et al., "Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility." *Political geography* 87 (2021): 102382
[43] Axel Anlauf, "Greening the imperial mode of living? Socio-ecological (in) justice, electromobility, and lithium mining in Argentina." In *Fairness and justice in natural resource politics*, pp. 176-192. Routledge, 2016.
[44] George E. Ericksen, and Raul Salas, "Geology and resources of Salars in the central Andes," Report (N° 88–210), US Geological Survey, 1987.
[45] François Risacher, and Bertrand Fritz, "Quaternary geochemical evolution of the salars of Uyuni and Coipasa, Central Altiplano, Bolivia," Chem. Geol. 90(3-4) (1991): 211-231.
[46] Arlene Ebensperger et al., "The lithium industry: Its recent evolution and future prospects," Resour. Policy. 30, 3 (2005): 218-231.
[47] Martin Grosjean, and Heinz Veit, "Water Resources in the Arid Mountains of the Atacama Desert (Northern Chile): Past Climate Changes and Modern Conflicts", in: Global Change and Mountain Regions: An Overview of Current Knowledge, ed. U. Huber et al., (Springer, 2005), 93-104.
[48] Dominic A. Notter et al., "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles," Environ. Sci. Technol. 44, 17 (2010): 6550–6556.
[49] Meridional International Research, MIR, "The Trouble with Lithium". Project EV Research, 29th May, 2008.
[50] Paola Bolados, "Procesos transnacionales en el salar de Atacama – norte de Chile. Los impactos de la minería y el turismo en las comunidades indígenas atacameñas," Intersecc. Antropol. 15 (2014b): 431-443.
[51] Barbara Göbel, "La minería del litio en la Puna de Atacama: interdependencias transregionales y disputas locales", Iberoamericana. 13(49) (2013): 135-149.

2016 - 2020	Impacts are beginning to be analyzed in depth by combining ethnographic data, statistics and indicators using spatial tools and ecological indicators[52,53].
2021 - 2024	Most studies consider integral analysis of lithium value chain impacts, in the framework of sustainability standards and regulations designing, including: Environmental, Social, and Governance (ESG) standards; life-cycle assessments; carbon and water footprint analysis; technologies for value recovery from spent lithium-ion batteries; among others[54,55,56].

Source: Own elaboration.

Likewise, the debate and scientific production in each of the countries of interest has its own characteristics.

In Argentina, there are three groups of studies, with different scientific contributions: one linked to the development of the mining sector and its challenges[57,58]; a second group whose work addresses issues of national development and the primarization of the economy[,59,60]; and a third group that, linked to social organizations, questions the environmental sustainability of mega-mining[61,62]. For the first two, international insertion takes center stage in terms of the opportunities and advantages that the energy transition has for international trade and the country's industrialization options, giving a marginal character to environmental issues. The third group highlights the contradictions of the energy transition and questions the sustainability of lithium extraction in salt flats warning about its socio-environmental

[52] Gonzalo Gajardo, and Stella Redón, "Andean hypersaline lakes in the Atacama Desert, northern Chile: between lithium exploitation and unique biodiversity conservation," Conserv. Sci. Pract. 1, e94.

[53] Wenjuan Liu et al., "Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile". Int. J. Appl. Earth Obs. Geoinf. 80 (2019) 145-156.

[54] Mudit Chordia et al., "Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene," Resour. Conserv. Recycl. 187, 106634.

[55] Evi Petavratzi et al., "The impacts of environmental, social and governance (ESG) issues in achieving sustainable lithium supply in the Lithium Triangle," Miner Econ. 35 (2022) 673-699.

[56] Maria L. Vera et al., "Environmental impact of direct lithium extraction from brines," Nat. Rev. Earth Environ. 4 (2023) 149-165.

[57] Julieta Godfrid, and Gerardo Damonte. "La Provincia de San Juan entre la promoción minera y la defensa del agua: "narrativas territoriales" en disputa." QUID 16. Revista del Área de Estudios Urbanos 13 (2020): 85-112

[58] Alejandro Casalis,~~,~~ and Arturo Trinelli. "Minería y modelo de desarrollo: Sustentabilidad y capacidades estatales." El Neoliberalismo tardío (2017): 133

[59] Victor Quinteros, "Paradiplomacy in the Lithium Triangle" in: REPIT (ed.), Encuentro de Estudios sobre Paradiplomacia e Internacionalización Territorial, Editorial CEIC, Córdoba, (2020).

[60] Diego I. Murguia et al., "Continuidades y rupturas en el marco regulatorio y las políticas públicas para el sector minero metalífero argentino (1990-2019)." (2019).

[61] Victoria Arias Mahiques et al., Gobernanza socioambiental de la minería de litio," (Buenos Aires: Fundar, 2022).

[62] Maristella Svampa and Pablo Bertinat, La transición energética en la Argentina: una hoja de ruta para entender los proyectos en pugna y las falsas soluciones, comp. (Buenos Aires: Siglo XXI editores, 2022).

impacts[63,64,65,66] or showing the gaps existing in the legislation and the inexistence of adequate management tools for their sustainable use[67,68]

Furthermore, in Argentina, impacts have been addressed from different methodological frameworks that combine documentary analysis, ethnographic research and expert interviews. There are studies on the impacts on water resources of lithium mining and others that describe the social impacts and consequences related to territorial management and the participation of the communities affected by the projects. These studies are based on two sources of information: the perceptions and fears of the indigenous communities and social organizations in the extraction territories, and the estimates, recommendations and warnings of expert academics on the risks implied by lithium mining operations in salt flats. This highlights the existing environmental information gaps, the need to conduct case studies on the impacts of lithium mining, the discretionary management of existing information by companies, the permissiveness of environmental assessment instruments and the bias of Environmental Impact Assessments (EIAs) that do not comprehensively consider the risks of lithium mining on aquifers[69,70,71].

The impacts mentioned by the Argentinean publications focus on the high-water consumption and the impacts on subway aquifers caused by the brine pumping and the use of fresh water in the processing plants. Also, they mention other impacts such as the generation of polluting sludge, the emission of dust resulting from the accumulation of magnesium hydroxide during the refining process, the modification of the landscape associated with the removal of land and the expansion of evaporation ponds and the

[63] Melisa Escosteguy et al., "The political ecology of justice outcomes of lithium mining: The case of Salar del Hombre Muerto, Argentina," The Extractive Industries and Society 18 (2024): 101477

[64] Vera Mignaqui, "Impactos ambientales por extracción del litio en salmuera en la Puna argentina: un llamado a la investigación." *Ambiens* 2, no. 4 (2020)

[65] Miguel Lacabana et al., "Globalización y territorios vulnerados-Sustentabilidad de la explotación del litio en Argentina," Revista Política y Planeamiento Regional 6, no. 3 (2019): 343-367.

[66] Deborah Pragier et al., "Comunidades indígenas y extracción de litio en Argentina: juridificación y estrategias de acción," Íconos. Revista de Ciencias Sociales 72 (2022): 79-96

[67] Araceli Clavijo et al., "Environmental information access and management in the Lithium Triangle: is it transparent information?," Journal of Energy & Natural Resources Law 40, no. 3 (2022): 293-314

[68] Romina L. Steinmetz, and Shao Bing Fong, "Water legislation in the context of lithium mining in Argentina," Resources Policy 64 (2019): 101510.

[69] Vera Mignaqui, "Impactos ambientales por extracción del litio en salmuera en la Puna argentina: un llamado a la investigación."

[70] Patricia Marconi, et al., "The arid Andean plateau waterscapes and the lithium triangle: flamingos as flagships for conservation of high-altitude wetlands under pressure from mining development," Wetlands Ecology and Management 30, no. 4 (2022): 827-852.

[71]Axel Anlauf, "¿Secar la tierra para sacar litio? Conflictos socio-ambientales en la minería del litio." In *ABC del litio sudamericano. Soberanía, ambiente, tecnología e industria* (2015): 171-191.

impact suffered by traditional economies indigenous[72,73,74]. Finally, in Argentina it is also noteworthy that third sector institutions, networks and NGOs are promoting research and debate on the sustainability and equity of the lithium extraction processes, including Fundar, Fundación Ambiente y Recursos Naturales (FARN), Cenital, Centro de Estudios Legales y Sociales (CELS), Fundación Yuchan, among others[75,76,77,78].

At the same time, the debate on lithium in Bolivia has focused on the management of the state lithium industrialization project, mainly on economic and socio-technic aspects, from the fields of economics, history and politics[79,80,81,82]. Some experts have been concerned on the technological challenges of lithium extraction in Bolivia and perspectives of lithium battery manufacturing, from the fields of material science and engineering[83,84,85,86]. Environmental costs, local participation, indigenous territorialities, conflict and local imaginaries associated with lithium in the Salar de Uyuni have been incorporated into that discussion by some researchers[87,88,89]. On the one hand, regional commissions, and international NGOs and inter-governmental organizations are concerned on installing an intellectual debate through the generation of technical results on the sustainability of extractive process, its impacts and, in general, the costs and benefits associated with the energy transition and

[72] Martin I. Thames Cantolla et al., "La industria del litio en la Puna Salteña: impacto en la calidad de vida." (2020)
[73] Andrés Castello, and Marcelo Kloster. "Industrialización del litio y agregado de valor local." Buenos Aires: Centro Interdisciplinario de Estudios en Ciencia Tecnologia e Innovación. (2015)
[74] Susana Gallardo, "Extracción de litio en el Norte argentino. La fiebre comienza," Exactamente 48, (2011): 26-29.
[75] María Victoria Arias, "Gobernanza socioambiental de la minería de litio."
[76] María Victoria Arias et al., Convergence, ¿divergence or mixed-results? A comparison between private and public rules governing lithium mining in Argentina (Buenos Aires: Fundar, 2024).
[77] Martín Obaya et al., Una cadena de valor de baterías de litio justa y sostenible: Encuesta Delphi-Informe de resultados. Executive Report, (Buenos Aires: Green Dealings Project, 2023).
[78] Pía Marchegiani, "Litio, ¿el oro blanco del siglo XXI qué fin justifica qué medios?" (2013).
[79] Manuel Olivera Andrade, La industrialización del litio en Bolivia: un proyecto estatal y los retos de la gobernanza, el extractivismo histórico y el capital internacional.
[80] Juan Carlos Zuleta, El litio en Bolivia. Una evaluación preliminar (Cochabamba: CEDIB, 2022).
[81]Juan Carlos Montenegro, "El modelo de industrialización del litio en Bolivia," Revista de Ciencias Sociales 34 (2018): 69-82.
[82] Anna C. Revette, "This time it's different: lithium extraction, cultural politics and development in Bolivia," Third World Quarterly 38, 1 (2017): 149-168.
[83] Gerardo Zamora, Jorge Gutierrez, and Omar Conde. "Bases técnicas para el diseño conceptual sustentable para la producción de carbonato de litio de las salmueras del salar de Coipasa," Revista de Medio Ambiente y Mineria 9, 1 (2024): 61-77.
[84] Guillermo Manrique Morales, Litio Metal Versátil. Un camino tortuoso en Bolivia (La Paz: Editorial Greco, 2022).
[85] Rosendo Sanjinés Zeballos, El oro blanco de los Andes. Paradigmas de la minería e industrialización del litio en Bolivia (La Paz, 2022).
[86] Saúl Cabrera et al. "Perspectivas en el procesamiento de materiales-electrodos para baterías de ion litio en Bolivia," Revista Boliviana de Química 29, 1 (2012): 15-38.
[87] Janine Romero Valenzuela, Natural resource governance, grievances and conflict (Wiesbaden: Springer Fachmedien, 2020).
[88] Daniela Sanchez-Lopez. "From a white desert to the largest world deposit of lithium: Symbolic meanings and materialities of the Uyuni Salt Flat in Bolivia," Antipode 51, 4 (2019): 1318-1339.
[89] Juliana Ströbele-Gregor, Litio en Bolivia: El plan gubernamental de producción e industrialización del litio, escenarios de conflictos sociales y ecológicos, y dimensiones de desigualdad social. (Berlin: Research Network on Interdependent Inequalities in Latin America, 2012).

governance[90,91]. On the other hand, some experts from NGOs and regional networks, some associated with human rights defense, are worried on the magnitude of environmental risks in a context of mining operations expansion and weak access to environmental information[92,93] .

There are few studies dedicated to foresee impacts on the Salar de Uyuni and the existing ones are developed from a prospective approach based on a combination of documentary analysis, ethnographic research and interviews with experts and managers of the national project for the industrialization of this resource. Among the effects detected are: the production of large quantities of toxic sludge associated with the use of the liming technique (addition of calcium oxide), which run the risk of alkalinizing the soil; the production of large quantities of residual salts that are intended to be returned to the aquifer without safety studies; the emission of suspended dust; and the risk of deepening the climate crisis due to water overexploitation[94,95,96].

The findings of these investigations suggest specific studies on the potential impacts of lithium mining in the Salar de Uyuni and the implementation of specific tasks such as searching for the water balance of the sat flat, monitoring the impacts of mining activities and improving the current weak and inefficient environmental regulation system. Therefore, unlike Argentina and Chile, during the pilot phase, the debate on environmental impacts in Bolivia was not focused on brine pumping but on the possible contamination of soil, air and water. However, nowadays the situation is different, due to the perceived risks associated to industrial production, initiated in 2024, and the eminent entrance of transnational companies, projected for 2025. Additionally, the most serious impacts of the water crisis arising from lithium and potassium salt mining operations are just beginning to become evident.

[90] ECLAC, Economic Commission for Latin America and the Caribbean, Lithium extraction and industrialization: Opportunities and challenges for Latin America and the Caribbean (Santiago de Chile: CEPAL, 2023).
[91] Martín Obaya, Estudio de caso sobre la gobernanza del litio en el Estado Plurinacional de Bolivia (Santiago de Chile: CEPAL, 2019).
[92] Amanda Romero et al., Globalización de las empresas de energía renovable: extracción de litio y derechos de los pueblos indígenas en Argentina, Bolivia y Chile. (Santiago de Chile: Observatorio Ciudadano, 2019).
[93] OPSAL, Salares andinos. Ecología de sabores por la protección de nuestros salares y humedales (Fundación Tantí, 2021).
[94] Ricardo Calla et al., Un presente sin futuro. El proyecto de industrialización del litio en Bolivia (La Paz: CEDLA, 2014).
[95] Ströbele-Gregor, Litio en Bolivia: El plan gubernamental de producción e industrialización del litio, escenarios de conflictos sociales y ecológicos, y dimensiones de desigualdad social.
[96] Rebecca Hollender, and Jim Shultz. Bolivia and its Lithium: Can the Gold of the 21st Century Help Lift a Nation out of poverty (A Democracy Center Special Report, 2010).

Meanwhile, in Chile, the studies on mining, especially copper mining, have a long tradition, but have only recently begun to integrate socio-environmental issues into the economic analysis[97,98,99]. In the last ten years, the scientific literature on lithium mining has diversified, paying special attention to the territorial dimension. There is an important range of works related to biophysical characterization and environmental transformations produced by mining that contemplates: hydrogeological descriptions and modelling[100,101,102]; biodiversity adapted to hyperaridity conditions, particularly poly-extremophiles microorganisms[103,104], and environmental topics that analyze the effect of water pumping on aquifers and ecosystems[105,106,107]. Relevant production from the social sciences addressing lithium-related issues at the local and national level is also identified, from: a) political science, which is generally critical of the energy transition[108,109,110]; b) economics, which unlike the previous group, analyzes the dynamics of the mining sector from a more encouraging perspective[111,112]; c) anthropology, which has focused on highlighting the relationship between mining company, state and indigenous communities[113,114,115,116]; d) political ecology, which has been responsible for highlighting the effects of extractivism on the configuration of

97 Patricio Meller, "Cobre chileno: productividad, innovación y licencia social." *Programa CIEPLAN/UTALCA* (2019).
98 Patricio Meller, La viga maestra y el sueldo de Chile: mirando el futuro con los ojos del cobre (Santiago: Uqbar Editores, 2013).
99 Patricio Meller, Dilemas y debates en torno al cobre (Santiago: Dolmen Ediciones, 2002).
100 Miguel Angel Marazuela et al., "Hydrodynamics of salt flat basins: The Salar de Atacama example," Science of the Total Environment 651 (2019): 668-683.
101 Christian Herrera et al., "Groundwater origin and recharge in the hyperarid Cordillera de la Costa, Atacama Desert, northern Chile," Science of the Total Environment 624 (2018): 114-132.
102 Joseline Tapia et al., "Geology and geochemistry of the Atacama Desert," Antonie Van Leeuwenhoek 111, no. 8 (2018): 1273-1291.
103 Carolina Cubillos et al., "Microbial communities from the world's largest lithium reserve, Salar de Atacama, Chile: Life at high LiCl concentrations," Journal of Geophysical Research: Biogeosciences 123, 12 (2018): 3668-3681.
104 Alan Bull, and Juan A. Asenjo, "Microbiology of hyper-arid environments: recent insights from the Atacama Desert, Chile," Antonie Van Leeuwenhoek 103, 6 (2013): 1173-1179.
105 Gajardo and Redón, "Andean hypersaline lakes in the Atacama Desert…".
106 Liu, et al., "Spatiotemporal patterns of lithium mining…".
107 Miguel Angel Marazuela, Enric Vázquez-Suñé, Carlos Ayora, and Alejandro García-Gil, "Towards more sustainable brine extraction in salt flats: Learning from the Salar de Atacama," Science of the Total Environment 703 (2020): 135605.
108 Weinberg, "The off-sites of lithium production…".
109 Cristian Flores-Fernández, "The Chilean energy "transition": between successful policy and the assimilation of a post-political energy condition," Innovation: The European Journal of Social Science Research 33, 2 (2020): 173-193.
110 Andrea Furnaro, "Neoliberal energy transitions: The renewable energy boom in the Chilean mining economy," Environment and Planning E: Nature and Space 3, 4 (2020): 951-975.
111 Philip Maxwell, and Mauricio Mora, "Lithium and Chile: looking back and looking forward," Mineral Economics 33, 1 (2020): 57-71.
112 Lagos, Gustavo, and Edgar Blanco, "Mining and development in the region of Antofagasta," Resources Policy 35, 4 (2010): 265-275.
113 Gundermann, "Comunidades indígenas, empresas del litio y sus relaciones...".
114 Morales, "Crónica analítica de un triunfo etnoambiental...".
115 Sally Babidge, ""Socios": The contested morality of "partnerships" in indigenous community–mining company relations, Northern Chile," The Journal of Latin American and Caribbean Anthropology 18, 2 (2013): 274-293.
116 Mauricio Lorca, Manuel Olivera Andrade, and Ingrid Garcés, ""Se instaló el diablo en el Salar". Organizaciones atacameñas, agua y minería del litio en el Salar de Atacama," Estudios atacameños 69 (2023).

mining territories and the increase in social conflict[117,118,119]. Likewise, studies conducted by governmental entities such as the Comisión Chilena del Cobre (COCHILCO) and international organizations such as the Comisión Económica para América Latina y el Caribe (CEPAL) that promote natural resource-based development should also be cited[120,121].

THE COMPLEX COEXISTENCE BETWEEN MINING AND INDIGENOUS COMMUNITIES IN THE ATACAMA SALT FLAT

The Salar de Atacama is by far the case that offers the most lessons in the socio-environmental field: located in the Atacama Desert and considered a mining territory, lithium has been exploited there for 40 years[122,123,124,125]. As it has been shown before, Atacama is the best studied salt flatin ABC.

Apart from the language and scientific data, the conflict seems to have been the most effective strategy to make visible the environmental issue in the Atacama region. In this scenario, scientific knowledge seems to be only tangentially linked to the socio-territorial movements that fight for the defense of wetlands and respect for the human and economic rights of local populations.[126,127,128,129].

Compared to Argentina and Bolivia, scarcity and sustainability of the water resource in the Salar de Atacama attract mostly the attention of the scientific literature analyzed, possibly, due to the existence of certain information on the hydrogeological

117 Jerez, "Lithium extractivism and water injustices ..."
118 Hugo Romero-Toledo, "Extractivismo en Chile: la producción del territorio minero y las luchas del pueblo aimara en el Norte Grande," Colombia Internacional 98 (2019): 3-30.
119 Hugo Romero et al., "Mining development and environmental injustice in the Atacama Desert of Northern Chile," Environmental Justice 5, 2 (2012): 70-76.
120 Rafael Poveda Bonilla, Estudio de caso sobre la gobernanza del Litio en Chile (Santiago: CEPAL, 2020).
121 COCHILCO, Comisión Chilena del Cobre, *Mercado internacional del litio y su potencial en Chile* (Santiago, 2018)
122 Lorca, "“Se instaló el diablo en el Salar”. Organizaciones atacameñas, agua y minería del litio en el Salar de Atacama."
123 David A. Torres, and Norman Toro, La fuerza del litio (SQM and Universidad Arturo Prat, 2023).
124 Rodrigo Azócar, "La instalación de la minería de litio en el Salar de Atacama y su relación inicial con las comunidades atacameñas: obreros, campamentos y asistencialismo (Chile, 1962-1998)," Estudios atacameños 68 (2022).
125 Garcés, Ingrid, and Gabriel Álvarez, "Water mining and extractivism of the Salar de Atacama, Chile," WIT Transactions on Ecology and the Environment 245 (2020): 189-199.
126 Olivera Andrade, “La industrialización del litio en Bolivia…”.
127 Javiera Barandiarán, "Lithium and development imaginaries in Chile, Argentina and Bolivia," World development 113 (2019): 381-391.
128 Sally Babidge et al., "'That's the problem with that lake; it changes sides': mapping extraction and ecological exhaustion in the Atacama," Journal of Political Ecology 26, 1 (2019): 738-760.
129 Paola Berdichevsky, and Sepúlveda, Claudia, "Desafíos de una Política Pública en base a Dos Décadas de Aprendizaje," Espacio Público 27 (2016): 2-51.

and ecosystemic behavior, after decades of brine pumping and water evaporation. These studies use environmental indicators and indices based on satellite images, hydrological and biodiversity data that include demographic and economic indicators and official environmental information from companies (SQM and Albemarle) and regulatory agencies (Servicio de Evaluación Ambiental and CORFO). These studies agree that lithium mining is a high environmental impact activity for the watersheds where it is located (Table 4).

Although the Salar de Atacama is a desert ecosystem with a natural negative water balance, scientific literature establishes that the water stress to which the territory is subjected has intensified due to the action of lithium mining. The process of aquifer and soil desiccation coincides with the expansion of lithium mining exploitations that have quadrupled in the last two decades, going from 20.54 km^2 in 1997 to 80.53 km^2 in 2017[130]. Effectively, according to a technical report, satellite images of the expansion of evaporation pools began in 1985 whose evaporation ponds had an area of 1,6 km^2, which after 10 years increased to 8,0 km^2; by the year 2000 they were 32,8 km2 and in 2017 they become 90,9 km^2.[131]

Indeed, it has been estimated that the production of 1 ton of lithium carbonate in the Salar de Atacama, involves the evaporation of between 400,000 to 2 million liters of brackish water to which are added about 5,000 to 50,000 liters of fresh water for treatment plant operations[132,133,134,135,136,137,138]. In this sense, lithium mining expansion in the Salar de Atacama affects water reserves and the integrity of the territory, impacting the quality of wetlands which, in turn, generates a domino effect on biodiversity causing, for example, the decline of populations of Andean flamingos and other

[130] Liu, et al., "Spatiotemporal patterns of lithium mining…".
[131] Manuel Prieto, and Gino Sandoval, "Informe expansión de la extracción de salmuera en el Salar de Atacama," 2018.
[132] Garcés and Álvarez, "Water mining and extractivism...".
[133] Barandiarán, "Lithium and development imaginaries...".
[134] Babidge, ""Socios": The contested morality ...".
[135] Berdichevsky and Sepúlveda, "Desafíos de una Política Pública...".
[136] Delgado et al., "A global assessment of SAOCOM-1 L-band...".
[137] Liu and Agusdinata. "Interdependencies of lithium mining…".
[138] Flexer, et al., "Lithium recovery from brines…".

threatened and migratory species[139,140,141]. In other words, saline ecosystems, as fragile as they are unique in the world, are suffering pressures that include climate change, conventional mining, and currently the extraction of evaporite resources.

Table 4: Socio-environmental impacts of lithium mining in the Salar de Atacama, Chile, according to results of published studies between 2018 and 2024.

BIOPHYSIC COMPONENT		
Components	**Estimated parameter**	**Findings**
Terrain	Soil Moisture Index (SMI).	Strong negative correlation with the expansion of operations, which means that humidity decreases with extractive activities[142].
	Daytime land surface temperature (Day-LST).	Strong positive correlation with the expansion of operations[143].
	Night-time land surface temperature (Night-LST).	Strong positive correlation with the expansion of operations[144].
	Observations of ground deformation with SAOCOM-1 stripmap data.	Pumping of brine occurs at a faster rate than the recharge of aquifers, leading to subsidence due to irreversible changes in permeability, sinking the terrain at an annual rate of up to 2 centimeters[145].
Water	Water availability (2010-2017).	Tendency to depletion of water reserves[146].
	Water consumption in mining (2002-2017).	50 times greater than domestic water consumption[147].
	Water depletion as a result of brine pumping and evaporation	95% of the original brine water needs to be evaporated and it is required on average the evaporation of half a million liters of brine per ton of lithium carbonate[148].

139 Gajardo and Redón, "Andean hypersaline lakes in the Atacama Desert...".
140 Marconi, et al., "The arid Andean plateau waterscapes…".
141 Jorge Gutiérrez et al., "Climate change and lithium mining influence flamingo abundance in the Lithium Triangle," Proceedings of the Royal Society B 289, no. 1970 (2022): 20212388.
142 Liu, et al., Spatiotemporal patterns …".
143 Idem.
144 Idem.
145 Francisco Delgado et al., "A global assessment of SAOCOM-1 L-band stripmap data for InSAR characterization of volcanic, tectonic, cryospheric, and anthropogenic deformation," IEEE Transactions on Geoscience and Remote Sensing 62 (2024): 1-21
146 Wenjuan Liu, and Datu Agusdinata, Interdependencies of lithium mining and communities' sustainability in Salar de Atacama, Chile. J. Clean. Prod. 260 (2020): 120838.
147 Idem
148 Victoria Flexer et al., "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 (2018) 1188–1204.

	Water table variation (1986-2018).	The pumping of water caused a lowering of the water table, reducing the "natural" evaporation rate[149].
		The salt flat nucleus evolved from water table depths shallower than 0.5 m in 1986 to depths below 2 m in 2018, caused by the brine pumping[150].
	Age of water traced by stable isotope $^{18}O/^{2}H$ ratio and radiogenic (^{3}H) isotopic tracer	All inflow to the Atacama basin is composed of water recharged >65 years ago (relic groundwater), whereby brine extraction added to climate change might not be sustainable[151].
Vegetation	Normalized Difference Vegetation Index (NDVI).[152]	Strong negative correlation with the expansion of operations.[153]
Wildlife	Conservation status of flamingo breeding and feeding habitats.	The reduction in wetland area affects negatively the quality of sediments used for nest building and food availability.[154] [155]
	Conservation status of amphibian populations.	Slow-flowing streams (critical habitats of endemic species) exposed to climate change and intense anthropogenic activities, mainly mining[156].
SOCIOECONOMIC COMPONENT		
Job	Labor inflow[b] (2002-2017).[157]	The total labor force in the mining sector increased 2.3 times.[158]
	Employment (1997-2017).	Local labor participation in mining fell from 52% (1997-2002) to 18% (2002-2017).[159]
Collective action	Social mobilizations and pronouncements against mining and lithium mining.	Significant increase of social claims since 1998, judicializing since 2010 and mobilizations since 2019.[160] [161]

[149] Miguel Angel Marazuela et al., The effect of brine pumping on the natural hydrodynamics of the Salar de Atacama: The damping capacity of salt flats. Sci. Total Environ. 654 (2019b) 1118-1131.
[150] Marazuela, et al., "Towards more sustainable brine extraction…".
[151] Brendan J. Moran et al., "Relic groundwater and prolonged drought confound interpretations of water sustainability and lithium extraction in arid lands," Earth's Future 10,7 (2022): e2021EF002555.
[152] NDVI is an indicator of vegetation quantity, quality, and development.
[153] Liu, et al., "Spatiotemporal patterns…".
[154] Gajardo and Redon, "Andean hypersaline lakes in the Atacama Desert…".
[155] Marconi, et al., "The arid Andean plateau waterscapes…".
[156] María J. Salica et al., "Threatened aquatic Andean frogs and mining activity in the Lithium Triangle of South America: Can both coexist?" Aquat. Conserv. Mar. Freshw. Ecosyst. 34,1 (2024): e4044.
[157] Labor influx, or influx of workers, refers to the rapid migration and settlement of workers in the project area, in circumstances where the labor/skills and goods and services required by a project are not available locally. Jay Wagner, et al., "Managing Social Impacts of Labour Influx: Lessons Learned from a World Bank Global Portfolio Review." SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability. SPE, 2018.
[158] Liu and Agusdinata, "Interdependencies of lithium mining…".
[159] Idem.
[160] Lorca, et al., "Mining Indigenous Territories…".
[161] Morales and Azócar, "Crónica analítica de un triunfo etnoambiental…".

Extension of benefits	Corporate Social Responsibility (CSR) at SQM.	Increase in education and social development projects.[162]

Source: Own elaboration.

There is yet a lack of adequately defined quantifiable impact categories (e.g. water toxicity, eutrophication) for lithium mining in salt flats[163]. For a better understanding of these factors, researchers recommend careful monitoring of hydrogeological components, avifaunal breeding and feeding habitats, as well as macroinvertebrate and algal diversity in water bodies[164], and identify the need to address a holistic understanding of the impacts, including baseline studies that are capable of projecting risk scenarios.[165]

In the social sphere, indicators such as labor influx and employment indicate the formation of a lithium mining enclave in the Salar de Atacama where local labor is progressively being displaced by migrant workers[166]. This is despite the historical importance of Atacameños as a labor force in nitrate, copper and early lithium mining[167,168]. For this reason, the Atacameño communities have led several administrative and judicial appeals based on the deficiency of the models and studies carried out by the companies themselves that do not consider valid the daily experience and the perceptions that the local population has about the hydrological resources, vegetation, wetlands and their traditional economic activities.

In the Salar de Atacama there are plenty of works that, from an ethnographic perspective, incorporate the concerns of communities affected by mining in general

[162] Liu et al., Interdependencies of lithium mining…".
[163] Rennie Kaunda, "Potential environmental impacts of lithium mining," Journal of energy & natural resources law 38.3 (2020): 237-244.
[164] Mattia Saccò et al., "Salt to conserve: a review on the ecology and preservation of hypersaline ecosystems." *Biological Reviews* 96, no. 6 (2021): 2828-2850.
[165] Datu Agusdinata et al., "Socio-environmental impacts of lithium mineral extraction: towards a research agenda," Environ. Res. Lett. 13, (2018): 1-14.
[166] Liu, "Interdependencies of lithium mining...".
[167] Lorca, "Mining indigenous territories...".
[168] Azócar, "La instalación de la minería de litio en el Salar de Atacama...".

and lithium mining in particular, describing and analyzing the expansion of collective action as a response to the deterioration of the territory[169,170,171].

LITERATURE AND THE NARRATIVE OF A LITHIUM SUSTAINABLE MINING

Recent scientific literature has been supporting the hypothesis of the non-sustainability of lithium extraction in highly fragile and vulnerable territories such as the salt flats and salt lakes of ABC. Consequently, the analysis of socio-environmental sustainability has become a controversial issue on a global scale. For instance, although there is research that supports the existence of undeniable environmental impacts of lithium mining on the socio-ecological systems associated with salt flats (see Table 4), these dimensions still do not occupy a large part of the world's population meanings and concerns, and do not have a significant place in the public agenda. Indeed, there have also been studies investigating lithium that, from an economic and market perspective, report on management experiences in the region. In them it is possible to notice a narrative that omits or tends to justify the socioecological impacts of extraction, tending to legitimate the extraction of strategic materials for the energy transition[172,173,174,175].

However, environmental impacts are a topic of growing concern in academic debate around sustainable development, responsible mining and monitoring schemes[176,177]. At a more global scale, a first group of studies analyzes the potential impacts of lithium industry worldwide, according to technology type, mineral type and stage of the value chain, through a review of statistics and the use of life cycle and water

169 Morales, "Crónica analítica de un triunfo etnoambiental...".
170 Bolados, "Procesos transnacionales en el salar de Atacama-norte de Chile…".
171 Garcés and Álvarez, "Water mining and extractivism...".
172 Agustín Barberón, "El litio en Argentina: Impacto productivo y políticas científico-tecnológicas." *Ciencia, tecnología y política* 5, no. 9 (2022): 081-081.
173 Michel Jorratt, Renta económica, régimen tributario y transparencia fiscal de la minería del litio en la Argentina, Bolivia (Estado Plurinacional de) y Chile (Santiago: CEPAL, 2022).
174 Deborah Pragier, "Relaciones Estado, empresas y comunidades indígenas en el caso de la explotación de litio en la Puna Argentina," POSTData: Revista de Reflexión y Análisis Político 29, 2 (2024): 293-323.
175 Magalí Vedoy, "Gobernanza ambiental: el caso de Argentina y el litio (2020-2022)," (Tesis de Grado, Universidad Nacional de Mar del Plata, 2024).
176 Fuentealba, "Technological tendencies...".
177 Eline Rentier et al., "Lithium brine mining affects geodiversity and Sustainable Development Goals," Renewable and Sustainable Energy Reviews 202 (2024): 114642.

footprint analysis techniques[178,179,180,181,182]. In the case of the impacts of the salt extraction phase, researchers agree that the selective extraction of lithium from brine involves the use and loss of huge amounts of water and that this would not be resolved with the reinjection of balances to the aquifer that would barely compensate for 5% of the initial volume. In addition, these processes would generate enormous amounts of waste derived from liming and carbonation processes[183,184,185]. Likewise, evapotranspiration losses account for 89% of the water footprint of lithium-ion battery production[186,187,188]. Finally, more than 95% of the habitat destruction involved in cathode manufacturing comes from the extraction of lithium from brines, mainly from the expansion of large evaporation ponds[189,190,191,192].

A second group analyzes the environmental impacts of lithium mining, considering other dimensions in the territories, including the problematic absence of key data for explaining current impacts. While there is a general consensus that this type of mining accelerates socio-environmental degradation, it is also recognized that, even at the most extensively studied sites, there is insufficient information to guarantee sustainability. For instance, the scarcity of environmental baseline studies, or comprehensive hydrogeological studies at basin level. On the other hand, some studies call for a better framing of the impact of lithium. Thus, represent only 8% of the total

178 Aser A. Ahmed et al., "Global warming potential, water footprint, and energy demand of shared autonomous electric vehicles incorporating circular economy practices," Sustainable Production and Consumption 36 (2023): 449-462.
179 Anna Schomberg et al., "Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage," Communications Earth & Environment 2, no. 1 (2021): 11.
180 Seyedkamal Mousavinezhad et al., "Environmental impact assessment of direct lithium extraction from brine resources: Global warming potential, land use, water consumption, and charting sustainable scenarios," Resources, Conservation and Recycling 205 (2024): 107583.
181 James Blair et al., "Lithium and water: Hydrosocial impacts across the life cycle of energy storage," Wiley Interdisciplinary Reviews: Water 11, 6 (2024): e1748.
182 Vanessa Schenker et al., "Regionalized life cycle assessment of present and future lithium production for Li-ion batteries." Resources, Conservation and Recycling 187 (2022): 106611.
183 Flexer et al., "Lithium recovery from brines…".
184 Walter Torres et al., "Lithium carbonate recovery from brines using membrane electrolysis," Journal of Membrane Science 615 (2020): 118416.
185 César Díaz Nieto et al., "Transmembrane fluxes during electrolysis in high salinity brines: Effects on lithium and other raw materials recovery." Electrochimica Acta 454 (2023): 142401.
186 Chordia et al., "Life cycle environmental impacts…".
187 Schomberg, "Extended life cycle assessment...".
188 Xin Lai et al., "Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective," Etransportation 12 (2022): 100169.
189 Sophie Parker et al., "Potential impacts of proposed lithium extraction on biodiversity and conservation in the contiguous United States." *Science of the Total Environment* 911 (2024): 168639.
190 Shyam Sharma et al., "Evaluating the impact of mining for critical electric vehicle and stationary storage battery minerals on land use and biodiversity," (2023).
191 Sharma, Shyam, and Arumugam Manthiram. "Towards more environmentally and socially responsible batteries." Energy & Environmental Science 13, no. 11 (2020): 4087-4097.
192 Laura Sonter et al., "Renewable energy production will exacerbate mining threats to biodiversity." Nature communications 11, 1 (2020): 4174.

freshwater consumption in Atacama that basin, would correspond to lithium mining, being other factors more relevant, including conventional mining and extreme weather events[193]. Even a few studies that argue the regional lagoon systems have not undergone significant changes during the stage of increased salt production.[194,195]

However, the most cited publications, register relevant environmental transformations derived from mining activities in salt flats, even considering this high complexity and the information gaps. In this sense, the expansion of lithium operations remains a growing concern in academia[196,197]. The technological transition in lithium sector (as Direct Lithium Extraction), which promises to be ecologically friendly, is still to be a debate topic, in terms of its real impacts in freshwater, waste generation, energy requirements and the uncertainties behind the reinjection of residual brine[198,199,200].

SCIENTIFIC PRODUCTION: A BALANCE OF FINDINGS

Scientific production in ABC related to lithium extraction in salt flats highlights the contradictions of the energy transition as a green horizon in territories vulnerable due to their naturally arid condition. Scientific literature on the socio-environmental impacts of lithium extraction is still scarce, but socio-environmental concerns and intellectual debate have increased in recent decade, as a result of the expansion of existing operations, the accelerated inauguration of new projects and demand for information from local populations.

Differences in the scientific understanding of the impacts of lithium extraction in the three countries exist. However, there is a strong consensus on the negative impacts of the extraction technology currently used given the interconnection between

193 Moran et al., "Relic groundwater and prolonged drought…".
194 Juan I. Guzmán et al., "Evolution of the Surface Area of Critical Lagoon Systems in the Salar de Atacama," Nat Resour Res. 31 (2022): 2571–2588.
195 Diana Roa et al., "Accounting for unintended ecological effects of our electric future: Optimizing lithium mining and biodiversity preservation in the Chilean High-Andean wetlands," Resource and Energy Economics 75 (2023): 101389.
196 Liu et al., "Spatiotemporal patterns…".
197 Vera et al. "Environmental impact of direct lithium extraction from brines".
198 Fuentealba, "Technological tendencies...".
199 Mousavinezhad, "Environmental impact assessment of direct lithium extraction...".
200 Javad Farahbakhsh et al., "Direct lithium extraction: A new paradigm for lithium production and resource utilization," Desalination 575 (2024): 117249.

the hydrodynamic freshwater and brine systems present in the salt flats. This means that, if pumping and evaporation of large amounts of water and exploitation areas and production quotas continue to expand, paradoxically, desertification of the Atacama's Desert and Puna will intensify. That is to say, it is urgent to discard the use of evaporation ponds and favor the development of alternative non-evaporation technologies. At the same time, considering the high levels of uncertainty in a context of scarce scientific information for decision making, particularly in salt flats with little or no information, it would also be prudent to open the possibility of applying the precautionary principle, even more so since the high vulnerability of these ecosystems.

The scientific information on the socio-environmental impacts caused by lithium mining in ABC, gives an account of the inconsistencies and paradoxes faced by the green energy transition. In spite of this, this narrative is still subaltern to a mainstream of opinion that advocates for the subsidies implied by the international economic insertion of the countries of interest either as producers of a raw material strategic for the global green economy or as participants in a higher link in the lithium value chain.

From the analysis of the scientific literature collected, it is possible to identify six characteristics in the scientific production related to the subject and places of study:

1. Scientific narratives move between two poles of information that generate opinion, debate and public mobilization. On the one hand, a discourse in favor of international insertion via energy transition, which promotes the evaluation of the techno-economic potential of lithium reserves, the possibilities of industrialization, the scientific-technological activities linked to the mineral and the deepening of extractivism to favor social and national income. On the other hand, a critical discourse of the energy transition, of territorial perspective, which gives prominence to the denouncement of injustices, the impacts of these industries on territories, the lack of participation of the communities in the decision making and the disruption of their livelihoods, as well as concerns about the irreversible impact on water reserves.

2. The information on socio-environmental impacts is dispersed, has different levels of depth and rigor and responds to different technical, theoretical and referential frameworks. The consequence of this dispersion is the existence of information gaps regarding the quantification and qualification of the impacts that lithium mining implies in salt flats. This happens precisely because there is little research and there are no baselines or socio-environmental monitoring systems and basic information that would allow understanding the risks and impacts of this type of mining in the hydrogeology of the salt flats; the ecological functions of water reserves, wetlands and lagoons; the role of biodiversity in the provision of ecosystem services, among others. These information gaps explain the first prospective approaches of scientists, human rights organizations and social organizations.

3. The treatment of the impacts perceived by local populations in the scientific literature analyzed is limited. These perspectives and concerns emerge mainly through the category of socio-environmental conflicts as social response for the defense of their territories, particularly water. In addition, this mainly ethnographic information base relies on the category of perceived impacts, which can be defined as the perception of the local inhabitant on territorial transformations resulting from an economic activity. This aspect should be further explored in works addressing local perceptions of environmental impacts and their relationship with conflicts.

4. The scientific information is not transferred to the territories, which translates into an asymmetric management of information between the citizens and the mining business world. In this sense, there is a clear hegemony on the part of the latter in the control of "valid knowledge" for territorial management. This entails dangers such as: leaving the production of knowledge about the impacts of mining in the hands of the companies, deepens scientific uncertainty about the effects of lithium mining and raises suspicions about the lack of crucial information such as the hydrogeological functioning of the intervened basins.

5. The analysis of the collected scientific literature shows that technical sustainability criteria promote the uninterrupted supply of lithium salts for energy transition industries. The dominant scientific production and narrative pushes the

supply of strategic materials, such as lithium, through strategies of insertion, compensation and negotiation between actors. This issue affects the definition of sustainability standards, which run the risk of not considering that the reality of the territories at the frontiers of the extraction of these resources must be understood in a complex and integral way.

6. The lithium salt extraction technology in ABC, consisting of pumping and depositing in evaporation ponds, causes the loss of significant amounts of water that do not return to the system, which has been called “water mining”. The scientific literature shows that, under current conditions, lithium mining entails significant impacts and risks to the sustainability of ecological functions and the lives of human populations. This calls into question the green and sustainable character of the energy transition which, paradoxically has been increasing the vulnerability of territories strongly affected by the climate crisis.

CONCLUSIONS

The findings demonstrate that lithium extraction in salt flats embodies a structural contradiction at the heart of the energy transition: the pursuit of a “green” global economy relies heavily on extractive practices that exacerbate socio-environmental vulnerability in already fragile territories. The subordinate position of critical perspectives within dominant techno-economic narratives further limits the visibility of these contradictions in political and investment decisions.

In this context, the persistence of scientific uncertainty—due to a lack of data, deficiencies in monitoring systems, and asymmetries in knowledge control—strengthens the case for reorienting both technological and governance approaches. This implies questioning the continued reliance on evaporation-based extraction methods and considering alternative technologies, as well as incorporating precautionary principles into decision-making processes, especially in ecosystems characterized by high vulnerability and low resilience.

Ultimately, the sustainability of the energy transition cannot be assessed merely in terms of carbon emissions reduction or security of supply. It requires integrating the socio-ecological limits of extraction territories into the definition of sustainability itself, thereby challenging dominant development paradigms and opening the door to more equitable and ecologically grounded alternatives.

ACKNOWLEDGMENTS

First author appreciates the support of the research project “Lithium: The global political ecology of lithium commodity chain", Swiss National Science Foundation grant 100017_172698, which allowed elaborate the first document layout of this paper. Also, authors thank PhD Marc Hufty, PhD Luis Pacheco and MSc. Pablo Poveda Avila for their valuable comments and suggestions to the first versions of this work. The second author is grateful for the funding of the Fondecyt Regular project no. 1240279 “Lithium mining and indigenous appreciation of nature in the Salar de Maricunga”, from the National Agency for Research and Development (ANID) of the Chilean government.

REFERENCES

Agusdinata, Datu, Wenjuan Liu, Hallie Eakin, Hugo Romero. "Socio-environmental impacts of lithium mineral extraction: towards a research agenda". Environmental Research Letters 13.12 (2018): 123001. https://doi.org/10.1088/1748-9326/aae9b1

Aser A. Ahmed, Mohammad A. Nazzal, Basil M. Darras, and Ibrahim M. Deiab. “Global warming potential, water footprint, and energy demand of shared autonomous electric vehicles incorporating circular economy practices”. Sustain. Prod. Consum. 36 (2023): 449-462. http://dx.doi.org/10.1016/j.spc.2023.02.001

Anlauf, Axel. "¿Secar la tierra para sacar litio? Conflictos socio-ambientales en la minería del litio". in: F. Nacif, M. Lacabana (Coord.)- ABC del litio sudamericano. Soberanía, ambiente, tecnología e industria (2015): 171-191.

Anlauf, Axel. "Greening the imperial mode of living? Socio-ecological (in) justice, electromobility, and lithium mining in Argentina." In Fairness and justice in natural resource politics, pp. 176-192. Routledge, 2016 https://doi.org/10.4324/9781315638058

Arias M. Victoria, Malena Galuccio, and Carlos Freytes. Gobernanza socioambiental de la minería de litio. Instituciones, acceso a la información y participación pública en Argentina". (Buenos Aires: Fundar, 2022).

Arias M. Victoria, Tomás Allan, Melisa Escosteguy, Teresa Kramarz, and Donald Kingsbury, Convergence, divergence or mixed results? A comparison between private and public rules governing lithium mining in Argentina. (Buenos Aires: Fundar, 2024).

Azócar, Rodrigo. "La instalación de la minería de litio en el Salar de Atacama y su relación inicial con las comunidades atacameñas: obreros, campamentos y asistencialismo (Chile, 1962-1998)". Estudios atacameños 68, e4887 (2022). https://dx.doi.org/10.22199/issn.0718-1043-2022-0033

Babidge, Sally. "Socios: The Contested Morality of 'Partnerships' in Indigenous Community–Mining Company Relations, Northern Chile". (2013) J. Lat. Am. Caribb. Anthropol. 18(2) 274–293. https://doi.org/10.1111/jlca.12020

Babidge, Sally, Fernanda Kalazich, Manuel Prieto, Karina Yager. "That's the problem with that lake; it changes sides': mapping extraction and ecological exhaustion in the Atacama". Journal of Political Ecology 26.1 (2019): 738-760. https://doi.org/10.2458/V26I1.23169

Balaram, Vysetti. "Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact." Geoscience Frontiers 10.4 (2019): 1285-1303. https://doi.org/10.1016/j.gsf.2018.12.005

Barán, Enrique J., ed. Litio: un recurso natural estratégico: desde los depósitos minerales a las aplicaciones tecnológicas. Academia Nacional de Ciencias Exactas, Físicas y Naturales [ANCEFN], 2017.

Barandiarán, Javiera. "Lithium and development imaginaries in Chile, Argentina and Bolivia." *World development* 113 (2019): 381-391. https://doi.org/10.1016/j.worlddev.2018.09.019

Barberón, Agustín. "El litio en Argentina: Impacto productivo y políticas científico-tecnológicas." Ciencia, tecnología y política 5.9 (2022): 081-081. https://doi.org/10.24215/26183188e081

Berdichevsky, Paola and Claudia Sepúlveda. "Desafíos de una Política Pública en base a Dos Décadas de Aprendizaje". Espacio Público 27 (2016): 2-51.

Blair, James J.A., Noel Vineyard, Dustin Mulvaney, Alida Cantor, Ali Sharbat, Kate Berry, Elizabeth Bartholomew, Ariana Firebaugh Ornelas. "Lithium and water: Hydrosocial impacts across the life cycle of energy storage".Wiley Interdisciplinary Reviews: Water 11.6 (2024): e1748. https://doi.org/10.1002/wat2.1748

Bolados G. Paola. "Los conflictos etnoambientales de" Pampa Colorada" y" el Tatio" en el salar de Atacama, norte de Chile: Procesos étnicos en un contexto minero y turístico

transnacional." Estudios Atacameños 48 (2014a): 228-248. http://dx.doi.org/10.4067/S0718-10432014000200015

Bolados G. Paola. Procesos transnacionales en el salar de Atacama – norte de Chile. Los impactos de la minería y el turismo en las comunidades indígenas atacameñas, Intersecc. Antropol. 15 (2014b) 431-443. http://suquia.ffyh.unc.edu.ar/handle/suquia/16849

Bridge, Gavin, and Ludger Gailing. "New energy spaces: Towards a geographical political economy of energy transition." Environment and Planning A: Economy and Space 52.6 (2020): 1037-1050. https://doi.org/10.1177/0308518X20939570

Bull, Alan T., and Juan A. Asenjo. "Microbiology of hyper-arid environments: recent insights from the Atacama Desert, Chile." Antonie Van Leeuwenhoek 103.6 (2013): 1173-1179. https://doi.org/10.1007/s'10482-013-9911-7

Cabrera, Saúl, Fabián Benavente, Max,Vargas, José Luis Flores, Manuel Ortega, Jaime Villca, Rafael Mamani, Naviana Leiva, Martin Luna, Waldo Yapu, Mario Blanco, Eduardo R. Palenque, Rodny Balanza. "Perspectivas en el procesamiento de materiales-electrodos para baterías de ion litio en Bolivia". Revista Boliviana de Química 29.1 (2012): 15-38. http://www.scielo.org.bo/scielo.php?pid=S0250-54602012000100003&script=sci_arttext

Calla, Ricardo, Juan Carlos Montenegro, Yara Montenegro, and Pablo Poveda. Un presente sin futuro. El proyecto de industrialización del litio en Bolivia. La Paz: Centro de Estudios para el Desarrollo Laboral y Agrario, 2014.

Calvo, Ernesto. Procesos de extracción de litio de sus depósitos en salares argentinos, in: E. Baran (ed.) Litio: un Recurso natural estratégico desde los depósitos minerales a las aplicaciones tecnológicas. (2017) 69-83.

Casalis, Alejandro, and Arturo Trinelli. "Minería y modelo de desarrollo: Sustentabilidad y capacidades estatales." El Neoliberalismo tardío (2017): 133-147.

Castello, Andrés, and Marcelo Kloster. "Industrialización del litio y agregado de valor local." Bue-nos Aires: Centro Interdisciplinario de Estudios en Ciencia Tecnología e Innovación. (2015).

Clavijo, Araceli, Walter Díaz Paz, Mauricio Lorca, Manuel Olivera Andrade, Martin Alejandro Iribarnegaray and Ingrid Garcés. "Environmental information access and management in the Lithium Triangle: is it transparent information?" Journal of Energy & Natural Resources Law 40.3 (2022): 293-314. https://doi.org/10.1080/02646811.2022.2058770

Cubillos, Carolina F., Pablo Aguilar, Mario Grágeda and Cristina Dorador. "Microbial communities from the world's largest lithium reserve, Salar de Atacama, Chile: Life at high LiCl concentrations". Journal of Geophysical Research: Biogeosciences 123.12 (2018): 3668-3681. https://doi.org/10.1029/2018JG004621

Chohan, Usman W. "A green new deal: Discursive review and appraisal." Notes on the 21st Century (CBRI) (March 2019). http://dx.doi.org/10.2139/ssrn.3347494

Chordia, Mudit, Sanna Wickerts, Anders Nordelöf, Rickard Arvidsson, "Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene," Resour. Conserv. Recycl. 187, 106634. https://doi.org/10.1016/j.resconrec.2022.106634

Dehghani-Sanij, Alireza, Eric Tharumalingam, Maurice B. Dusseault, and Roydon Fraser. "Study of energy storage systems and environmental challenges of batteries." Renewable and Sustainable Energy Reviews 104 (2019): 192-208. https://doi.org/10.1016/j.rser.2019.01.023

Delgado, Francisco, Tara Shreve, Sven Borgstrom, Pablo León-Ibáñez, Joaquín Castillo, Michael Poland. "A global assessment of SAOCOM-1 L-band stripmap data for InSAR characterization of volcanic, tectonic, cryospheric, and anthropogenic deformation". IEEE Transactions on Geoscience and Remote Sensing 62 (2024): 1-21. DOI: 10.1109/TGRS.2024.3423792

Díaz N. César, Matías A. Mata, Camilo J.O. Palacios, Noelia A. Palacios, Walter R. Torres, María L. Vera, Victoria Flexer. "Transmembrane fluxes during electrolysis in high salinity brines: Effects on lithium and other raw materials recovery". Electrochim. Acta. 454, (2023) 42401. https://doi.org/10.1016/j.electacta.2023.142401

Díaz P. Walter, Melisa Escosteguy, Lucas Seghezzo, Marc Hufty, Eduardo Kruse, Martín A. Iribarnegaray. "Lithium mining, water resources, and socio-economic issues in northern Argentina: We are not all in the same boat." Resources Policy 81 (2023): 103288. https://doi.org/10.1016/j.resourpol.2022.103288

Ebensperger, Arlene, Philip Maxwell, and Christian Moscoso, The lithium industry: Its recent evolution and future prospects, Resour. Policy. 30 (3) (2005) 218-231. https://doi.org/10.1016/j.resourpol.2005.09.001

ECLAC, Economic Commission for Latin America and the Caribbean, Lithium extraction and industrialization: Opportunities and challenges for Latin America and the Caribbean (Santiago de Chile: CEPAL, 2023).

Ericksen G. Edward, and Raul Salas, "Geology and resources of Salars in the central Andes," Report (N° 88–210), US Geological Survey, 1987. https://doi.org/10.3133/ofr88210

Ericksen G. Edward, James D. Vine, and Raul Ballón. Lithium-rich brines at Salar de Uyuni and nearby salars in southwestern Bolivia. No. 77-615. US Geological Survey, 1977. https://doi.org/10.3133/ofr77615

Escosteguy, Melisa, Carlos Ortega, Walter F. Díaz, Christian Brannstrom, Martín A. Iribarnegaray, Marc Hufty, Lucas Seghezzo. "The political ecology of justice outcomes

of lithium mining: The case of Salar del Hombre Muerto, Argentina." The Extractive Industries and Society 18 (2024): 101477. https://doi.org/10.1016/j.exis.2024.101477

European Commission, The European Green Deal. COM (2019) 640 final. 11 December 2019. Brussels. (2019) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

Farahbakhsh, Javad, Faezeh Arshadi, Zahra Mofidi, Masoud Mohseni-Dargah, Cansu Kök, Mohammad Assefi, Asieh Soozanipour, Masoumeh ZargarMohsen Asadnia, Yasaman Boroumand, Volker Presser, Amir Razmjou. "Direct lithium extraction: A new paradigm for lithium production and resource utilization". Desalination 575 (2024): 117249. https://doi.org/10.1016/j.desal.2023.117249

Flexer, Victoria, Celso F. Baspineiro, and Claudia Galli. "Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing." Science of the Total Environment 639 (2018): 1188-1204. https://doi.org/10.1016/j.scitotenv.2018.05.223

Flores-Fernández, Cristián. "The Chilean energy "transition": between successful policy and the assimilation of a post-political energy condition". Innovation: The European Journal of Social Science Research 33,2 (2020): 173-193. https://doi.org/10.1080/13511610.2020.1749836

Fornillo, Bruno, coord. Litio en Sudamérica: geopolítica, energía y territorios (Buenos Aires: El Colectivo, CLACSO, IEALC, 2019), 1-323. http://www.jstor.org/stable/j.ctvtxw25t

Fuentealba, Diego, Cherie Flores-Fernández, Elizabeth Troncoso, Humberto Estay. "Technological tendencies for lithium production from salt lake brines: Progress and research gaps to move towards more sustainable processes." *Resources Policy* 83 (2023): 103572. https://doi.org/10.1016/j.resourpol.2023.103572

Furnaro, Andrea. "Neoliberal energy transitions: The renewable energy boom in the Chilean mining economy." Environment and Planning E: Nature and Space 3.4 (2020): 951-975. https://doi.org/10.1177/2514848619874685

Gajardo, Gonzalo, and Stella Redón. "Andean hypersaline lakes in the Atacama Desert, northern Chile: Between lithium exploitation and unique biodiversity conservation." *Conservation Science and Practice* 1.9 (2019): e94. https://doi.org/10.1111/csp2.94

Gallardo, Susana. "La fiebre comienza." Revista Exactamente 48 (2011): 26-29. http://www.fcen.uba.ar/fotovideo/EXm/PDF/EXM48.pdf

Garcés, Ingrid and Gabriel Álvarez. "Water mining and extractivism of the Salar de Atacama, Chile". WIT Trans. Ecol. Environ. 245 (2020) 189-199. https://doi.org/10.2495/EID200181

Göbel Barbara. La minería del litio en la Puna de Atacama: interdependencias transregionales y disputas locales, Iberoamericana. 13(49) (2013) 135-149. https://doi.org/10.18441/ibam.13.2013.49.135-149

Godfrid, Julieta, and Gerardo Damonte. "La Provincia de San Juan entre la promoción minera y la defensa del agua:“narrativas territoriales” en disputa." QUID 16. Revista del Área de Estudios Urbanos 13 (2020): 85-112.

Grosjean, Martin, and Heinz Veit, Water Resources in the Arid Mountains of the Atacama Desert (Northern Chile): Past Climate Changes and Modern Conflicts, in: U. Huber, H. Bugmann, M. Reasoner (Eds.), Global Change and Mountain Regions: An Overview of Current Knowledge, Springer, 2005, pp. 93-104. https://doi.org/10.1007/1-4020-3508-X_10

Guirao Goris, Silamani. "Utilidad y tipos de revisión de literatura." Ene 9.2 (2015): 0-0. https://dx.doi.org/10.4321/S1988-348X2015000200002

Gundermann, Hans, and Barbara Göbel. "Comunidades indígenas, empresas del litio y sus relaciones en el Salar de Atacama." Chungará (arica) 50.3 (2018): 471-486. http://dx.doi.org/10.4067/S0717-73562018005001602

Gutiérrez, Jorge, Johnnie Moore, John Patrick Donnelly, Cristina Dorador, Juan G. Navedo, Nathan R Senner. "Climate change and lithium mining influence flamingo abundance in the Lithium Triangle". Proceedings of the Royal Society B 289.1970 (2022): 20212388. https://doi.org/10.1098/rspb.2021.2388

Guzmán, Juan Ignacio, Candelaria Retamal, Patricio Faúndez, and José Joaquín Jara. “Evolution of the Surface Area of Critical Lagoon Systems in the Salar de Atacama”. Nat Resour Res. 31 (2022): 2571–2588 https://doi.org/10.1007/s11053-022-10070-7

Herrera, Christian, Carolina Gamboa, Emilio Custodio, Teresa Jordan, Linda Godfrey, Jorge Jódar, José A Luque, Jimmy Vargas, Alberto Sáez. “Groundwater origin and recharge in the hyperarid Cordillera de la Costa, Atacama Desert, northern Chile”. Sci. Total Environ. 624 (2018): 114-132 https://doi.org/10.1016/j.scitotenv.2017.12.134

Hollender, Rebecca, and Jim Shultz. "Bolivia and its Lithium: Can the Gold of the 21st Century Help Lift a Nation out of poverty." A Democracy Center Special Report , 2010.

Hund, Kirsten, Daniele La Porta, Thao P. Fabregas, Tim Laing, and John Drexhage, Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition, World Bank Group, Washington DC, 2020.

Jerez, Bárbara, Ingrid Garcés, and Robinson Torres. "Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility." Political geography 87 (2021): 102382. https://doi.org/10.1016/j.polgeo.2021.102382

Jorrat, Michel. Renta económica, régimen tributario y transparencia fiscal de la minería del litio en la Argentina, Bolivia (Estado Plurinacional de) y Chile. CEPAL, Santiago de Chile, 2022.

Kaunda, Rennie B. "Potential environmental impacts of lithium mining." Journal of energy & natural resources law 38.3 (2020): 237-244. https://doi.org/10.1080/02646811.2020.1754596

Lacabana, Miguel, Federico Nacif, Vera Mignaqui, Alejandro Casalis, and Diego Rogers. "Globalización y territorios vulnerados-Sustentabilidad de la explotación del litio en Argentina." Revista Política y Planeamiento Regional 6.3 (2019): 343-367

Lagos, Gustavo, and Edgar Blanco. "Mining and development in the region of Antofagasta". Resources Policy 35.4 (2010): 265-275. https://doi.org/10.1016/j.resourpol.2010.07.006

Lagos, Gustavo. El Desarrollo del Litio en Chile: 1984-2012, Programa de Investigación en Economía de Minerales, Pontificia Universidad Católica de Chile, Santiago, Chile. Publicación Electrónica (2012).

Lai, Xin, Quanwei Chen, Xiaopeng Tang, Yuanqiang Zhou, Furong Gao, Yue Guo, Rohit Bhagat, Yuejiu Zheng. “Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective”. eTransportation, Vol. 12, (2022) 100169. https://doi.org/10.1016/j.etran.2022.100169

Liu, Wenjuan, Datu B. Agusdinata, and Soe W. Myint. "Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile". International Journal of Applied Earth Observation and Geoinformation 80 (2019): 145-156. https://doi.org/10.1016/j.jag.2019.04.016

Liu, Wenjuan, and Datu B. Agusdinata. "Interdependencies of lithium mining and communities sustainability in Salar de Atacama, Chile". Journal of Cleaner Production 260 (2020): 120838. https://doi.org/10.1016/j.jclepro.2020.120838

Lorca, Mauricio, Manuel Olivera Andrade, Melisa Escosteguy, Jonas Köppel, Morgan Scoville-Simonds, and Marc Hufty. "Mining indigenous territories: Consensus, tensions and ambivalences in the Salar de Atacama." The Extractive Industries and Society 9 (2022): 101047. https://doi.org/10.1016/j.exis.2022.101047

Lorca, Mauricio, Manuel Olivera Andrade, and Ingrid Garcés. "“Se instaló el diablo en el Salar”. Organizaciones atacameñas, agua y minería del litio en el Salar de Atacama." Estudios atacameños 69 (2023). http://doi.org/10.22199/issn.0718-1043-2023-0004

Manrique Morales, Guillermo. Litio Metal Versátil. Un camino tortuoso en Bolivia. La Paz: Editorial Greco, 2022.

Marazuela, Miguel Ángel, Enric Vázquez-Suñé, Carlos Ayora, Alejandro García-Gil. “Towards more sustainable brine extraction in salt flats: Learning from the Salar de

Atacama". Sci. Total Environ. 703, (2020): 135605. https://doi.org/10.1016/j.scitotenv.2019.135605

Marazuela, Miguel Ángel, Enric Vázquez-Suñé, Carlos Ayora, Alejandro García-Gil, Teresa Palma. "Hydrodynamics of salt flat basins: The Salar de Atacama example". (2019a) Sci. Total Environ. 651(1) 668-683. https://doi.org/10.1016/j.scitotenv.2018.09.190

Marazuela, Miguel Ángel, Enric Vázquez-Suñé, Carlos Ayora, Alejandro García-Gil, Teresa Palma. "The effect of brine pumping on the natural hydrodynamics of the Salar de Atacama: The damping capacity of salt flats". (2019b) Sci. Total Environ. 654, 1118-1131. https://doi.org/10.1016/j.scitotenv.2018.11.196

Marconi, Patricia, Felicity Arengo, and Amelia Clark. "The arid Andean plateau waterscapes and the lithium triangle: flamingos as flagships for conservation of high-altitude wetlands under pressure from mining development." Wetlands Ecology and Management 30.4 (2022): 827-852. https://doi.org/10.1007/s11273-022-09872-6

Marchegiani, Pía. "Litio, el oro blanco del siglo XXI: ¿qué fin justifica qué medios?" In *Informe medioambiental anual*, ed. Fundación Ambiente y Recursos Naturales (Buenos Aires: FARN, 2013), 457 – 470.

Martinez-Alier, Joan. "The Environmentalism of the poor: a study of ecological conflicts and valuation." The Environmentalism of the Poor. Edward Elgar Publishing, 2002.

Maxwell, Philip, and Mauricio Mora. "Lithium and Chile: looking back and looking forward." Mineral Economics 33.1 (2020): 57-71. https://doi.org/10.1007/s13563-019-00181-8

Meller, Patricio. "Cobre chileno: productividad, innovación y licencia social." Programa CIEPLAN/UTALCA (2019).

Meller, Patricio. La viga maestra y el sueldo de Chile: mirando el futuro con los ojos del cobre. Uqbar Editores, 2013.

Meller, Patricio. Dilemas y debates en torno al cobre. Dolmen Ediciones, Santiago, 2002.

Meridional International Research, MIR, The Trouble with Lithium. Project EV Research, 29th May, 2008. http://www.meridian-int-res.com/Projects/EVRsrch.htm

Mignaqui, Vera. "Impactos ambientales por extracción del litio en salmuera en la Puna argentina: un llamado a la investigación." Ambiens 2.4 (2020), 68-84. https://doi.org/10.22395/ambiens.v2n4a4

Montenegro, Juan Carlos. "El modelo de industrialización del litio en Bolivia," Revista de Ciencias Sociales 34 (2018): 69-82 https://ridaa.unq.edu.ar/handle/20.500.11807/1736

Moore, Jason W. "El auge de la ecología-mundo capitalista (I)." Laberinto 38 (2013): 9-26.

Morales, Héctor, and Rodrigo Azócar. "Crónica analítica de un triunfo etnoambiental en el Salar Atacama: Pampa Colorada." *Revista Chilena de Antropología* 39 (2019). https://revistadeantropologia.uchile.cl/index.php/RCA/article/view/53720

Moraga, Aldo, Chong, Guillermo, Fortt, María Angélica and Henríquez, Hugo. "Estudio geológico del Salar de Atacama, Provincia de Antofagasta". (1974). Instituto de Investigaciones Geológicas, IIG, Santiago de Chile. Boletín nº029.

Moran, Brendan, David F. Boutt, Sarah McKnight, Jordan Jenckes, Lee Ann Munk, Daniel Corkran, Alexander Kirshen. "Relic groundwater and prolonged drought confound interpretations of water sustainability and lithium extraction in arid lands". Earth's Future 10.7 (2022): e2021EF002555. https://doi.org/10.1029/2021EF002555

Mousavinezhad, Seyedkamal, Sheida Nili, Ario Fahimi, Ehsan Vahidi. "Environmental impact assessment of direct lithium extraction from brine resources: global warming potential, land use, water consumption, and charting sustainable scenarios". Resour. Conserv. Recycl. 205, (2024) 107583. https://doi.org/10.1016/j.resconrec.2024.107583

Murguía Diego, and Julieta Godfrid. "Continuidades y rupturas en el marco regulatorio y las políticas públicas para el sector minero metalífero argentino (1990-2019)." (2019). Revista de Economía Política de Buenos Aires 14(19) 137-170.

Notter Dominic, Marcel Gauch, Rolf Widmer, Patrick Wäger, Anna Stamp, Rainer Zah, and Hans-Jörg Althaus, Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles, Environ. Sci. Technol. 44(17) (2010) 6550–6556. https://doi.org/10.1021/es903729a

Obaya, Martín. Estudio de caso sobre la gobernanza del litio en el Estado Plurinacional de Bolivia. No. 44776. Naciones Unidas Comisión Económica para América Latina y el Caribe (CEPAL), 2019.

Obaya, Martin, Diego Murguía, Carlos Freytes and Tomás Allan. Una cadena de valor de baterías de litio justa y sostenible. Executive Report, (Buenos Aires: Green Dealings Project, 2023).

Obaya, Martín, Diego I. Murguía, and Daniela Sánchez-López. "From local priorities to global responses: Assessing sustainability initiatives in South American lithium mining." The Extractive Industries and Society 19 (2024): 101509. https://doi.org/10.1016/j.exis.2024.101509

Olivera A. Manuel. La industrialización del litio en Bolivia: un proyecto estatal y los retos de la gobernanza, el extractivismo histórico y el capital internacional. La Paz: CIDES-UMSA, 2017.

OPSAL, Observatorio Plurinacional de Salares Altoandinos. Salares andinos. Ecología de sabores por la protección de nuestros salares y humedales. Santiago de Chile: Fundación Tantí, 2021.

Parker, Sophie S., Michael J. Clifford, and Brian S. Cohen. "Potential impacts of proposed lithium extraction on biodiversity and conservation in the contiguous United States." Science of the Total Environment 911 (2024): 168639. https://doi.org/10.1016/j.scitotenv.2023.168639

Paul, Harpreet Kaur. "The Green New Deal and global justice." Renewal, vol. 28, no. 1, 2020, p. 61+.

Perez, Carlota. Technological revolutions and financial capital: The dynamics of bubbles and golden ages. Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing, 2002.

Petavratzi, Evi, Daniela Sanchez-Lopez, A. Hughes, J. Stacey, Jonathan R. Ford, and A. Butcher, The impacts of environmental, social and governance (ESG) issues in achieving sustainable lithium supply in the Lithium Triangle, Miner Econ. 35 (2022) 673-699. https://doi.org/10.1007/s13563-022-00332-4

Petts, Judith, ed. Handbook of environmental impact assessment, Volume 2: Impact and limitations. Vol. 2. John Wiley & Sons, 2009.

Perreault, Thomas Albert, Gavin Bridge, and James P. McCarthy, eds. The Routledge handbook of political ecology. London: Routledge, 2015. https://doi.org/10.4324/9781315759289

Poveda Bonilla, Rafael. Estudio de caso sobre la gobernanza del litio en Chile. CEPAL, 2020.

Pragier, Deborah, Mariano A. Novas, and Lucas G. Christel. "Comunidades indígenas y extracción de litio en Argentina: juridificación y estrategias de acción." Íconos. Revista de Ciencias Sociales 72 (2022): 79-96. https://doi.org/10.17141/iconos.72.2022.5030

Pragier, Deborah. “Las relaciones entre el Estado, las empresas y las comunidades indígenas en el caso de la explotación del litio en la Puna argentina” POSTDATA. 29(2), (2024): 293-323. https://revistapostdata.com.ar/index.php/postdata/article/view/362/340

Prieto, Manuel, and Gino Sandoval. Informe expansión de la extracción de salmuera en el Salar de Atacama. 2018. https://doi.org/10.13140/RG.2.2.32059.77607

Quinteros, Victor. “Paradiplomacia en el triángulo del litio.” (paper presented at Encuentro de Estudios sobre Paradiplomacia e Internacionalización Territorial, Córdoba, 2020).

Rentier, Eline S., Carina Hoorn, Arie Christoffel Seijmonsbergen. “Lithium brine mining affects geodiversity and Sustainable Development Goals”. " Renewable and Sustainable Energy Reviews 202 (2024): 114642 https://doi.org/10.1016/j.rser.2024.114642

Revette, Anna C. "This time it’s different: lithium extraction, cultural politics and development in Bolivia." Third World Quarterly 38.1 (2017): 149-168. https://doi.org/10.1080/01436597.2015.1131118

Risacher, François, and Bertrand Fritz, Quaternary geochemical evolution of the salars of Uyuni and Coipasa, Central Altiplano, Bolivia, Chem. Geol. 90(3-4) (1991) 211-231. https://doi.org/10.1016/0009-2541(91)90101-V

Roa, Diana, Ståle Navrud, and Knut Einar Rosendahl. "Accounting for unintended ecological effects of our electric future: Optimizing lithium mining and biodiversity preservation in the Chilean High-Andean wetlands." Resource and Energy Economics 75 (2023): 101389. https://doi.org/10.1016/j.reseneeco.2023.101389

Romero, Amanda, José Aylwin, and Marcel Didier. Globalización de las empresas de energía renovable: extracción de litio y derechos de los pueblos indígenas en Argentina, Bolivia y Chile (“Triángulo del litio”). Santiago: Centro de Información sobre Empresas y Derechos Ciudadanos-Observatorio Ciudadano, 2019.

Romero Valenzuela Janine. Natural Resource Governance, Grievances and Conflict. The Case of the Bolivian Lithium. Springer Fachmedien Wiesbaden, 2020. DOI:10.1007/978-3-658-27236-4

Romero-Toledo, Hugo. "Extractivismo en Chile: la producción del territorio minero y las luchas del pueblo aimara en el Norte Grande." Colombia Internacional 98 (2019): 3-30. https://doi.org/10.7440/colombiaint98.2019.01

Romero, Hugo, Manuel Méndez, and Pamela Smith. "Mining development and environmental injustice in the Atacama Desert of Northern Chile." Environmental Justice 5.2 (2012): 70-76. https://doi.org/10.1089/env.2011.0017

Saccò, Mattia, Nicole E. White, Chris Harrod, Gonzalo Salazar, Pablo Aguilar, Carolina F. Cubillos, Karina Meredith, Bonnie K. Baxter, Aharon Oren, Elena Anufriieva, Nickolai Shadrin, Yeri Marambio-Alfaro, Víctor Bravo-Naranjo, Morten E. Allentoft. "Salt to conserve: a review on the ecology and preservation of hypersaline ecosystems". Biological Reviews 96.6 (2021): 2828-2850. https://doi.org/10.1111/brv.12780

Salica María José, María S. Gastón, Mauricio Akmentins, and Marcos Vaira, “Threatened aquatic Andean frogs and mining activity in the Lithium Triangle of South America: Can both coexist?” Aquat. Conserv. Mar. Freshw. Ecosyst. 34,1 (2024): e4044. https://doi.org/10.1002/aqc.4044

Sanchez-Lopez, Maria Daniela. "From a white desert to the largest world deposit of lithium: Symbolic meanings and materialities of the Uyuni Salt Flat in Bolivia." Antipode 51.4 (2019): 1318-1339. https://doi.org/10.1111/anti.12539

Sanjinés Zeballos, Rosendo. El oro blanco de los Andes. Paradigmas de la minería e industrialización del litio en Bolivia. La Paz, 2022. https://es.scribd.com/document/723630760/Oro-Blanco-de-Los-Andes-RSZ

Schenker, Vanessa, Christopher Oberschelp, and Stephan Pfister. "Regionalized life cycle assessment of present and future lithium production for Li-ion batteries." Resources, Conservation and Recycling 187 (2022): 106611. https://doi.org/10.1016/j.resconrec.2022.106611

Schomberg, Anna C., Stefan Bringezu, and Martina Flörke. "Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage." Communications Earth & Environment 2.1 (2021): 11. https://doi.org/10.1038/s43247-020-00080-9

Sérandour, Audrey. "Le «triangle du lithium» existe-t-il? Géographie politique d'une régionalisation andine (Argentine, Bolivie, Chili)." Belgeo. Revue belge de géographie 4 (2020). http://journals.openedition.org/belgeo/43717 ; DOI : https://doi.org/10.4000/belgeo.43717

Sharma, Shyam, and Arumugam Manthiram. "Towards more environmentally and socially responsible batteries." Energy & Environmental Science 13.11 (2020): 4087-4097. https://doi.org/10.1039/d0ee02511a

Sharma, Shyam, Jacqueline Edge, and John Mumford. "Evaluating the impact of mining for critical electric vehicle and stationary storage battery minerals on land use and biodiversity." (2023). https://doi.org/10.21203/rs.3.rs-3307549/v1

Sonter, Laura J., Marie C. Dade, James E. M. Watson, and Rick K. Valenta. "Renewable energy production will exacerbate mining threats to biodiversity". Nat. Commun. 11, (2020) 4174. https://doi.org/10.1038/s41467-020-17928-5

Steinmetz, Romina, Lucrecia López, and Shao Bing Fong. "Water legislation in the context of lithium mining in Argentina". Resources Policy 64 (2019): 101510. https://doi.org/10.1016/j.resourpol.2019.101510

Ströbele-Gregor, Juliana. Litio en Bolivia: El plan gubernamental de producción e industrialización del litio, escenarios de conflictos sociales y ecológicos, y dimensiones de desigualdad social. Working Paper n. º 14, Berlin: Research Network on Interdependent Inequalities in Latin America, 2012.

Svampa, Maristella. Las fronteras del neoextractivismo en América Latina: conflictos socioambientales, giro ecoterritorial y nuevas dependencias. Bielefeld University Press, 2019.

Svampa, Maristella and Pablo Bertinat, comp. La transición energética en la Argentina: una hoja de ruta para entender los proyectos en pugna y las falsas soluciones. Siglo XXI editores, 2022.

Tapia, Joseline, Rodrigo González, Brian Townley, Verónica Oliveros, Fernanda Alvarez-Amado, Germán Aguilar, Andrew Menzies, Mauricio Calderón. “Geology and geochemistry of the Atacama Desert”. Antonie van Leeuwenhoek 111, 1273–1291 (2018). https://doi.org/10.1007/s10482-018-1024-x

Thames Cantolla, Martin, Silvana K. Valdez, and María de los A. Tinte Montalbetti. "La industria del litio en la Puna Salteña: impacto en la calidad de vida." (2020). https://doi.org/10.36995/j.recyt.2020.34.004

Torres, David and Norman Toro. La fuerza del litio. SQM/Universidad Arturo Prat, 2023 . https://doi.org/10.61303/978-956-416-471-7

Torres, Walter R., César H. Díaz Nieto, Antonin Prévoteau, Korneel Rabaey, Victoria Flexer. "Lithium carbonate recovery from brines using membrane electrolysis." Journal of Membrane Science 615 (2020): 118416. https://doi.org/10.1016/j.memsci.2020.118416

United Nations, "Paris Agreement on Climate Change", United Nations Framework Convention on Climate Change, 2015a, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations, "Transforming our world: the 2030. Agenda for Sustainable Development A/RES/70/1", Department of Economic and Social Affairs Sustainable Development, 2015b, https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

UMSA, Universidad Mayor de San Andrés, Potencial científico tecnológico Universidad Mayor de San Andrés (2015-2020), DIPGIS – UMSA, La Paz, 2020.

Vedoy Granja, Magalí. "Gobernanza ambiental: el caso de Argentina y el litio (2020-2022)”. Tesis de Grado, Universidad Nacional de Mar de Plata, Mar del Plata, 2024. http://humadoc.mdp.edu.ar:8080/xmlui/handle/123456789/1276

Vera, Mignaqui, and Lacabana Miguel. "Economía y Ambiente: la extracción del litio en salmuera en la Puna Argentina." SaberEs 14.2 (2022): 148-168.

Vera, María L., Walter R. Torres, Claudia I. Galli, Alexandre Chagnes, Victoria Flexer. "Environmental impact of direct lithium extraction from brines". Nature Reviews Earth & Environment 4.3 (2023): 149-165. https://doi.org/10.1038/s43017-022-00387-5

Wagner, Jay, Susan Dowse, Murray Jones, and Marla Orenstein. "Managing Social Impacts of Labour Influx: Lessons Learned from a World Bank Global Portfolio Review." SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability. SPE, 2018.

Weinberg, Marina. "The off-sites of lithium production in the Atacama Desert." The Extractive Industries and Society 15 (2023): 101309. https://doi.org/10.1016/j.exis.2023.101309

Zamora, Gerardo, Jorge Gutiérrez, and Omar Conde. "Bases técnicas para el diseño conceptual sustentable para la producción de carbonato de litio de las salmueras del salar de Coipasa." Revista de Medio Ambiente y Mineria 9.1 (2024): 61-77. http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S2519-53522024000100005&lng=es&tlng=es

Zuleta, Juan Carlos. El litio en Bolivia. Una evaluación preliminar. Cochabamba: CEDIB, 2022.

Litio, Impactos Ambientales y Salares Altoandinos en Argentina, Bolivia y Chile. Una Revisión Integral de la Literatura Científica

RESUMEN

Este artículo revisa la literatura científica sobre los impactos ambientales de la minería de litio en Argentina, Bolivia y los salares de Chile, analizando el periodo 1975-2024. La literatura se divide en dos puntos de vista: uno optimista que promueve el litio como vital para la transición energética y los mercados globales, y otro crítico que advierte sobre el daño irreversible a los frágiles ecosistemas y los estilos de vida locales. A pesar del creciente interés socioambiental durante más de 50 años, persisten las lagunas de conocimiento, la información sobre impactos socioambientales es dispersa, con distintos niveles de profundidad y rigor, y con una distribución desigual de los datos y las capacidades entre estos países. El Salar de Atacama, en Chile, muy investigado debido a la influencia de la minería, muestra importantes impactos en el agua, la biodiversidad y las comunidades, pero la extracción de litio continúa a pesar de la insuficiencia de datos para una gestión responsable. Además, gran parte de esta información no llega a los territorios locales, y la atención prestada a los impactos percibidos por las comunidades locales sigue siendo limitada, lo que acentúa las desigualdades. A menos que se introduzcan innovaciones significativas, la extracción de sales de litio en los salares altoandinos está acelerando, paradójicamente, la degradación socioambiental de estos frágiles ecosistemas.

Keywords: triángulo del litio; impactos ambientales; conflictos socio-ambientales; minería del litio; salares.

Recibido: 09/09/2025
Aprobado: 09/04/2026