Lithium brines in South America: A research roadmap to facilitate rapidly and responsibly sourced lithium

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View across Laguna Verde, Bolivia. Photo by Rowan Halkes. © UKRI 2025.

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Need for lithium and relevance to the region

Climate change necessitates a move away from fossil fuels, and an energy transition towards decarbonisation. This transition is driving increased demand for lithium required for electric mobility and energy storage batteries. Over the coming decades, the demand for lithium is expected to surge, potentially outpacing supply, creating a pressing need to scale up production. The British Geological Survey (BGS), one of the world's oldest geological surveys, as an organisation that is avowedly impartial, is using its expertise to address this challenge in an open and transparent manner.

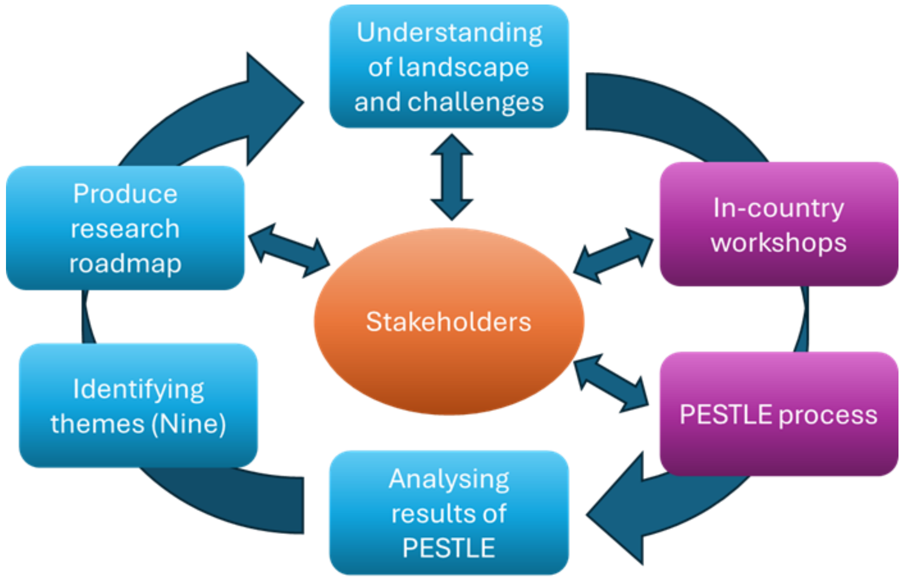
Of current global lithium supply (148.9k tonnes; Iodine *et al*., 2024), a significant portion (34%), comes from salars—large basins of internal drainage—in South America's 'Lithium Triangle' countries: Argentina, Chile, and the Plurinational State of Bolivia (Bolivia). While these salars are a crucial source of lithium, they exist in arid environments and support highly complex and valuable ecosystems. Extracting lithium from them presents significant challenges, requiring extensive resources to fully understand their intricacies. Additionally, the extraction process raises significant social, environmental, and governance concerns, making sustainable management and responsible production a key issue for the future of lithium production. These complex issues can only be fully addressed by a global community involving both local and international partners.

Approach taken

There is, therefore, a need to understand how to rapidly increase production whilst ensuring the responsible sourcing of lithium from salar brines. To enhance the current state of knowledge and collaboratively create a research roadmap to be used by the global community, BGS convened six workshops with local experts to capture current understanding and uncertainties, as well as to further develop the international community. Funded under the UK Government's Science and Innovation Network (SIN)[1], the workshops were held in Argentina (Buenos Aires and Salta) and Chile (Santiago and Copiapó) and brought together specialists from different types of organisations: national and local government, academics, Indigenous Peoples (IPs), mine operators, and consultants (see flowchart below). All these specialists exchanged knowledge on an equitable basis in a spirit of cooperation.

A PESTLE (political, economic, social, technological, legal and environmental) analysis was used as the underpinning framework to identify the issues that could prevent rapid and responsible lithium production (blockers), but also those that could enhance it (enablers). Given that the workshops were undertaken in Argentina and Chile, the initial analysis was undertaken for each country separately. Nine themes common to both countries were identified from the PESTLE analysis and then prioritised to identify the future research activities required. The results from the workshops have been further analysed and the resulting research roadmap summarised below.

[1] The SIN funding doesn't cover Bolivia which was visited after these workshops to ensure that the conclusion were relevant to all Lithium Triangle countries; this visit was funded from a different source.



Results of the PESTLE analysis

Whilst individual results were developed for each country visited (see Section 1.4 below), the common themes from each workshop were distilled in order to identify ‘blockers’ and ‘enablers’ common to all the countries for each PESTLE category (see table below):

PESTLE category	Blocker	Enabler
Political	Desire for longer-term stability and improved collaboration along with tensions between central and local government.	Political support for the process of increasing lithium production, and improving responsible practices, along with regional/national instruments to support this.
Economic	Volatility of the market (lithium price) and economic governance.	Investment in the sector and development of expertise; developing local supply chains to enhance value added to each country.
Social	Variable nature of communication and associated lack of trust, regional inequality and issues over development.	Appetite for engagement, requirement for social engagement and improvement of local communities by inward investment. Improving relations with indigenous peoples (IPs).
Technological	Lack of detailed knowledge of salar processes alongside uncertainty over future extractive / processing technologies (e.g. Direct Lithium Extraction or DLE).	Opportunities presented by new technologies. Strength of local expertise and research organisations, e.g CONICET.
Legal	Complexity of governance / legal system along with lack of “fit for purpose” system for regulating lithium brine extraction.	Increasing implementation of lithium-brine specific environmental standards and frameworks.

Environmental	Lack of holistic understanding based on long-term monitoring data; environmental impact of waste / mine closure; impact of climate change.	Growing environmental consciousness and standards alongside recognition of the need to protect salars and surrounding environments.

The PESTLE analysis highlighted numerous challenges, including factors beyond the control of most organisations, such as lithium price volatility. However, it also identified many areas where research organisations and projects can exert significant influence. Further, there were many beacons of good practice identified in both Argentina and Chile. One example being the agreement between the provincial governments in Argentina to share data and understanding. These good practices are, however, fragmented, and need to be more consistently applied across the region.

The process also reinforced the complex stakeholder landscape which exists, where multiple organisations are working side by side in lithium brine mining. An example of this is the scientific understanding of salar processes which is required by local stakeholder such as Indigenous Peoples or IPs to complement their traditional understanding; operators for their running of the wellfield; regional authorities to manage the resource and reduce cumulative impacts; central government to provide appropriate environmental legislation and regulators to determine environmental impacts. The relationship is typically symbiotic with, for example, government departments often relying on data / models from operators. An example of good practice of data availability is the Salar de Atacama, Chile where the operator, SQM, make their environmental monitoring data available via a website[2]. The challenge, therefore, is to produce a research roadmap that is tractable and that will allow knowledge to increase and be bought to bear on this complex problem.

Interconnectedness / themes identified

The PESTLE analysis and workshops revealed that this is a highly complex multi-faceted problem requiring a multi-agency approach. It is essential to account for the differing spatial scales and disciplines operating in different jrisdictions. Environmental regulation requires strong governance at a range of scales (project, salar, region, country) and across all interested parties and associated jurisdictions, as well as across disciplines.

Further, there was a recognition of the interdependence and connectedness between categories. For example, the reduction of disputes requires the sharing of knowledge on an equitable basis, which in turn is based on a suitable conceptual model of salar processes; developed by all stakeholders and communicated in a manner that all who have contributed to the understanding can appreciate.

To help develop the research roadmap and to characterise the interconnectedness, nine themes were identified from the outcomes of the PESTLE. The themes were developed by using the blockers and enablers identified by the workshop participants in Argentina and Chile for each PESTLE category. The blockers and enablers identified were analysed for common themes. These, in order of spatial scale, starting from the salar to the global are:

1. Salar processes
2. Environmental challenges
3. New technologies for Li production
4. Infrastructure, supply chains and development
5. Data & Transparency
6. Governance
7. Social issues
8. Standards & Certification
9. Global Li market

Using the results of the discussions which took place during the workshops, the activities required to address the ‘blockers’ identified during the PESTLE analysis were identified. The activities were associated with one of the nine themes. However, some of the activities have been identified as

[2] www.sqmsenlinea.com

being determined by external influences, i.e. geo-political and are outside of the research remit. To tease out a research framework, therefore, the main activities for each theme were categorised into research led, co-creation and those with limited influence by research. They have been prioritised for each theme based on differing timescales: short-, medium- and longer-term activities as well as those that are classed as "on-going", i.e. started as soon as possible and iterated as time goes on.

Recommendations

Given the urgency for increased lithium supply and the short time scales needed to meet demand, we have summarised the short-term (<3 year) priority activities (see Figure below). The rapidly changing landscape means that these activities are the foundation on which the rest of the research roadmap can be developed. We have aimed to portray the issues starting from the scale of the salar itself and up through country scale to the global markets. The issues are presented in the diagram below and are outlined in the following text. Whilst not all the suggested activities are research-based, many of them require joint working / co-creation between the stakeholders involved and researchers.

Further, no one organisation can take on all these tasks and provide the outcomes required. Given the number of stakeholders involved and the complexity of the proposed activities a combination of regional (South American) and international organisations are required to work together. An example would be the assessment of Direct Lithium Extraction (DLE) alongside reinjection (DLE/R) which would require a range of organisations from different disciplines such as engineers, environmental specialists, geologists, hydrologists and hydrogeologists working alongside social scientists. Likewise for participatory processes which require a combination of different stakeholders including IPs working alongside social and biophysical scientists in conjunction with government organisations and industry partners.

A fundamental scientific understanding of salar processes is required and the data on which to build this is still lacking. Developing this understanding along with a salars observatory for the region alongside the international research community is, therefore, required. The environmental challenge related to wellfield operation and the impact on key environmental receptors needs to be established. The use of new technology such Direct Lithium Extraction (DLE), particularly when used in combination with reinjection, requires investigation to develop an understanding of its impact. A technology roadmap would enable the novel lithium processing techniques to be characterised and understood. A pilot facility for DLE located at a university or a research park in the region (preferably one in each country) and funded by government research organisations / subscription and available to researchers from various organisations to assess different technologies would be beneficial. An example would be the UK's Battery Industrialisation Centre or BIC[3].

Infrastructure that is fit for purpose for development of multiple operations is key, along with developing shared infrastructure in collaboration with local communities to facilitate production whilst ensuring the least environmental harm and maximum benefit. An understanding of local supply chains with mapping of appropriate member stakeholders would enable current facilities to be determined and gaps to be identified. A holistic view of data and information availability is required. Bringing together different sources of information and making them available to stakeholders in a form that's appropriate to their background and scientific training has the potential to reduce conflict as well as facilitating access in an efficient manner. This would be combined with enabling all stakeholders to view the available information in a form that's appropriate to their background and training.

Such stakeholder mapping would also help to ensure the interactions between stakeholders are understood for each country and their power balance characterised. Consultation and participatory processes could then be developed that are fit for purpose. To reduce social conflict, participatory processes need to be put in place, and measures implemented to reduce disputes and increase transparency in the decision-making process. To address the potential skills gaps

[3] www.ukbic.co.uk

within the mining sector, then “on the job” training across a range of organisations needs to be enhanced.

Ensuring that good practice for standards and certifications are disseminated, including development of resources and reserves estimations for lithium brines, is important. Assessment of existing sustainability frameworks is required to identify the ones that are fit-for-purpose as well as a need to keep a watching brief on standards and certification schemes to avoid unnecessary proliferation and duplication. Further, it is necessary that interoperability of standards and their joint use is possible.

It is important that an overview of the lithium market, enabling tracking of lithium prices and mass balance to provide feedback on supply/demand balance, is maintained and made easily available. This will ensure that an understanding of market volatility is available to all the relevant decision-makers, enhancing investment stability. Developing an understanding of the global value chain for lithium and identifying where opportunities exist for mid-stream activities (between the lithium mining operations and battery producers) exists thus facilitating technology development and manufacturing growth in the region is required.

The final point to consider is the inter-connectedness and integrated nature of these challenges where progress in one area can lead to positive impacts in others. However, the reverse is also true and only by moving forward on meeting of a number of these challenges and opportunities will rapid uptake of lithium production from brines in a responsible manner be achieved.

Short-term research priorities to support responsible lithium supply.

1 Introduction

This report summarises the findings from a series of workshops (see Appendix 1 and 2 for further details) undertaken in Argentina and Chile in March 2024. The workshops were funded as part of the UK Government's Science and Innovation (SIN) network TACTICAL fund. The project to deliver the workshops entitled "Responsible sourcing framework to enable up-scaling of lithium production and supply" was carried out by staff from the British Geological Survey (BGS) from January 2023 to June 2024.

1.1 BACKGROUND AND THE NEED FOR LITHIUM

Lithium is a critical mineral essential for the manufacture of Lithium-Ion Batteries (LIB) for electric vehicles and energy storage. According to the International Energy Agency (IEA), global demand for lithium is predicted to reach 500kt of lithium by 2030 requiring close to a four-fold increase relative to the 2022 production and several new lithium mines.

The 'Lithium Triangle' (Argentina, Chile, Bolivia, Figure 1) hosts over 50% of the global lithium resources. These resources exist as liquid 'brines' in the arid Andean region. Significant controversy exists around the potential negative impacts of brine-mining on the region's sensitive habitats, groundwater, and local communities including Indigenous Peoples (IPs). Therefore, there is a need to balance the requirements for rapid up-scaling of production with responsible sourcing of lithium from brines.

1.2 SCOPE OF THIS REPORT

The workshops for this project were held in Argentina and Chile as these countries are eligible for UK's SIN (Science and Innovation Network) funding. Whilst a complete picture can only be gathered by working in the three Lithium Triangle countries, a series of workshops were not held in Bolivia as part of this work. However, during the period of this project BGS staff visited Bolivia and interaction occurred with the state-owned lithium concern, *Yacimientos de Litio Bolivianos* or YLB, enabling insights from these meetings to be fed into this report.

1.3 STRUCTURE OF THE REPORT

The report is split up into five main sections: Section 1 describes the results of the PESTLE analysis and the subsequent identification of nine themes; Section 2 describes the results from the workshops in terms of the nine main themes; Section 3 outlines a research roadmap as identified by the process; Section 4 provides the outline of the approach and methodology; Section 5 summarises the main recommendations. Appendices present supporting materials describing the agenda of the workshops and the outputs produced.

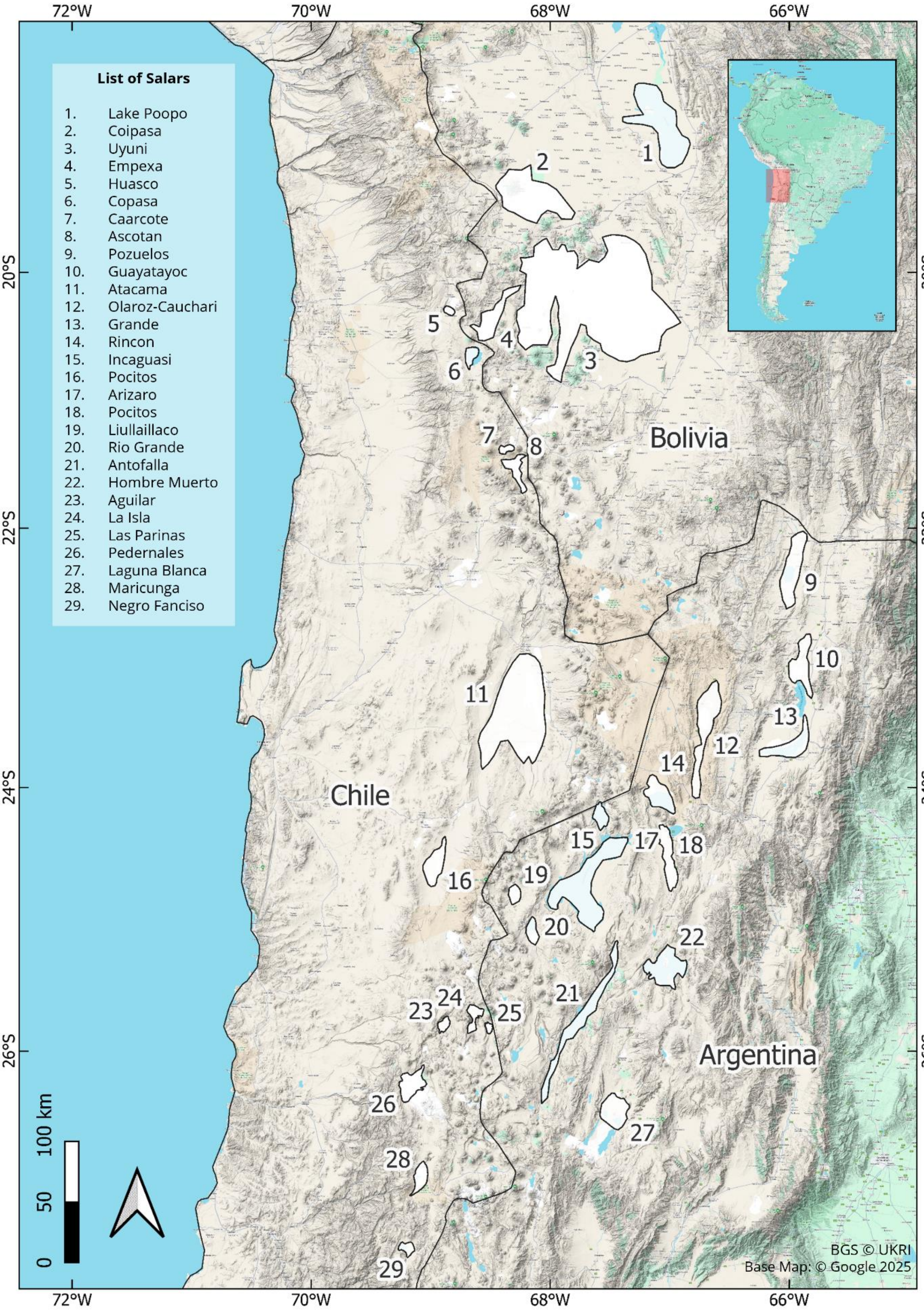


Figure 1. Location of the main salars in the Lithium Triangle countries of Argentina, Bolivia and Chile

1.4 PESTLE ANALYSIS AND IDENTIFICATION OF OVERARCHING THEMES

1.4.1 Outline of process

Figure 2 summarises the process undertaken within this project. Using a series of workshops the initial understanding of the lithium brine landscape was tested against stakeholder knowledge and experience. A PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis was undertaken as part of a series of workshops in Argentina and Chile, the results of which were used to determine nine overarching themes. These themes were used for more detailed analysis to feed into a research roadmap, which was refined with stakeholders. The overall process resulted in an improved understanding of the nature of the lithium brine landscape in Argentina and Chile.

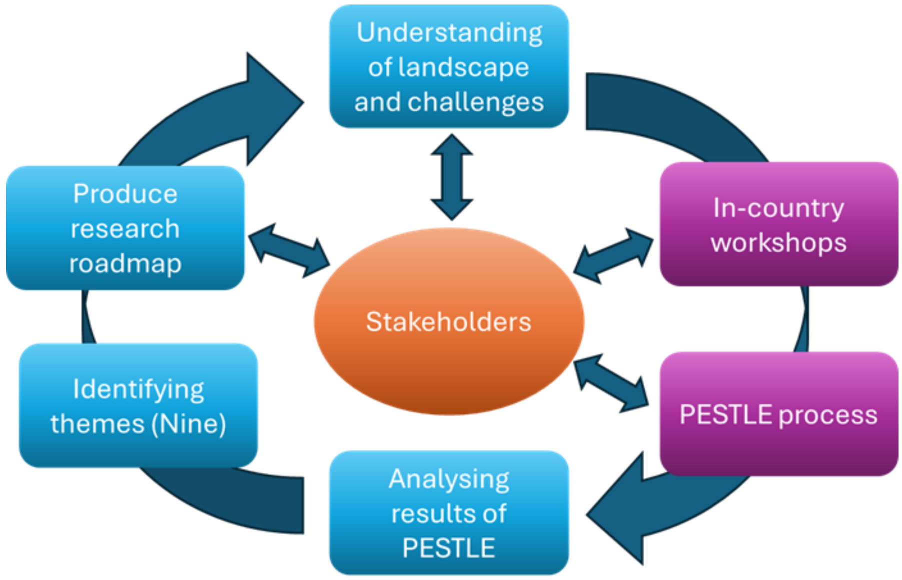


Figure 2. Summary of the overall project process to produce a research roadmap

1.4.2 Summary of the PESTLE analysis

The results of the PESTLE analysis from two workshops undertaken in each country are summarised in Table 1. that whilst there are differences, similar themes have been identified for each country:

- Political – Desire for longer-term stability and improved collaboration between central and local government. Political support for the process of increasing lithium production, and improving responsible practices, along with regional/national instruments to support this.
- Economic – Volatility of the market (lithium price) and economic governance. Investment in the sector and development of expertise.
- Social – Variable degrees of communication (accessibility, transparency and nature) and associated lack of trust, regional inequality and issues over local development. Appetite for engagement, requirement for social engagement and improvement of local communities by inward investment. Improving relations and dialogue with indigenous peoples (IPs).
- Technological – Lack of detailed knowledge of salar processes alongside uncertainty over future extractive / processing technologies (DLE). Strength of local expertise and research organisations, e.g CONICET.
- Legal – Complexity of governance / legal system along with lack of "fit for purpose" system for regulating lithium brine extraction. Increasing implementation of lithium-brine specific environmental standards and frameworks.
- Environmental – Lack of holistic understanding based on long-term monitoring data ; environmental impact of waste / mine closure; impact of climate change. Growing

environmental consciousness and standards alongside recognition of the need to protect salars.

Category	Chile	Argentina
Political	Horizontal and vertical integration and collaboration in government Lack of defined social contract Changes in government and policy and potential lack of continuity Limited government capacity Central-focused government National Lithium Strategy & Government involvement Involvement of research Public-private partnership - state involvement	Political stability Transparency Federal/complex governance - provinces & federal Lack of central body and/or capability & resources in government Granting/concessions of mines Lithium is high on agenda Favourable conditions for inwards investment Lithium board - promoting provincial government communication
Economic	Revenue generation and distribution and lack of resources Economic risks Uncertainty in market conditions and demand Resources invested in sector Knowledge, expertise and experience Lithium market/demand	Lithium market - volatility and low prices Economic conditions Lack of infrastructure investment Governance - tax & revenues (generation and distribution), imports and exports Good job generation Revenue generation Favourable conditions for inwards investment Development role of companies - Corporate Social Responsibility (Education, Healthcare, Infrastructure)
Social	Global need for lithium to decarbonise - Chile's role as a "provider" = pressure	Governance complexities Communication challenges/access to information and lack of mechanisms to implement change in response

	Territorial inequality (northern regions compared to central/capital) Difficulties of conflict management Lack of communication/dialogue and distrust Openness to dialogue and communication Requirement for community consultation Indigenous communities empowered Access to data and information	Labour force issues - provision of skilled labour Lack of local development Increasing focus on social issues & related issues Generation of jobs, development and education/training provision Inclusion of communities in decision making process
Technical	Extraction Technology - uncertainties Knowledge/expertise - lack of related to salar processes & technologies, concentrated in private sector Knowledge/expertise and experience (strong mining and education sector) Investment in research and innovation Extraction technology - potential benefits	Extraction Technology - uncertainties Infrastructure and supply chains Permissions and access to materials for research (e.g. samples) Extraction technology - potential benefits Knowledge/expertise and experience Strength of research community (CONICET)
Legal	Lack of legislation/regulation specific to lithium production from salars Complexity in governance frameworks and processes Legislative complexity of community consultation and indigenous rights Lack of fit-for-purpose environmental standards (non-governmental) for lithium production from salars	Bureaucracy and delays Lack of regulation/implementation of FPIC Complexities of legal system and enforcement EIA framework - Cumulative impacts not assessed

	Environmental regulation/protection - SEA and protected salars CEOL framework - allows private sector to develop and increasing public involvement in processes Economic cooperation agreements	Increasing implementation of responsible mining standards/certifications e.g. EITI Labour regulation frameworks Growing focus on FPIC implementation
Environmental	Lack of holistic knowledge and understanding (socio-environmental) Lack of ongoing monitoring and baselines Presences of valuable and delicate ecosystems and lack of protected areas Operators not fulfilling agreements Growing environmental consciousness and positive change Environmental studies - biodiversity and microorganisms Protection of sites/salars High environmental standards and increasing implementation	Waste Mine closure Water related impacts Climate change impacts Lack of holistic knowledge, capacity and understanding (and technical expertise for environmental) Growing environmental consciousness and positive change Technology Growing focus on sampling and data generation High work standards

Note: 'Blockers' – black text; 'Helpers' – green text.

Table 1. Summary of the results from PESTLE analysis

1.4.3 Identification of themes

Resulting from the collation of the PESTLE analysis the outcomes were further analysed to establish overarching themes. Nine themes were identified by this process, as follows:

1. Salar Processes (Technical and Environmental)
2. Environmental Challenges (Legal and Environmental)
3. New Technology for Lithium Production (Technical)
4. Infrastructure and Supply Chains (Economic, Social and Environmental)
5. Data and Transparency/Effective Communication (Political, Economic, Legal and Environmental)
6. Governance (Political, Economic, Legal and Environmental)
7. Social (Social)
8. Standards and Certifications (Political, Legal and Environmental)
9. Global Lithium Markets and Economics (Political and Economic)

Each one is described in more detail below (Section 2).

2 Themes

The following sections provide more detailed descriptions of the status of each of the themes identified. Each section consists of three sub-sections: background, opportunities and challenges and then recommendations for work to address the challenges. Given the different level of knowledge for each of the themes, the descriptions provided are of variable lengths.

2.1 SALAR PROCESSES

2.1.1 Background

2.1.1.1 Hydrogeology of salars

Salars are complex systems typically located in arid / semi-arid basins, see Figure 3. High Andean salars are typically found in basinal settings surrounded by volcanic deposits that are the source of mineralised lithium (e.g. andesite, tuff). Lithium is leached into the salars by the movement of surface waters and groundwater (Rossi *et al*., 2022). The process of forming lithium-rich brines can take of the order of 100,000s years (e.g. Atacama; Corenthal *et al*. (2016)) and have been the result of differing climatic conditions in the past: cycles of wetter and dryer conditions. The salars themselves comprise sedimentary deposits ranging from clays, silts, sands and various evaporite minerals through to halite, NaCl. They are formed within a highly active system geologically, which has changed significantly over the last few million years, e.g. Salisbury *et al*. (2010). The salars are characterised by a central area or nucleus in which the brines are created by evaporative processes (Figure 3). The nucleus is typically where the greatest concentration of lithium occurs.

Rainfall is typically very low on the salars, of the order of 10s mm/annum, but rising to 100s mm/annum as the elevation increases away from the salar itself e.g. Atacama (Marazuela *et al*., 2018). Rainfall recharge is, therefore, very limited, if it occurs at all in the nucleus. Surface water and groundwater inflows to the salars, whilst small, are important to maintaining the fresh / brackish surface water systems. Periodic flooding by surface waters helps maintain the water balance, sporadically in Atacama (Boutt *et al*., 2016) and more regularly in wetter salars such as Salar de Uyuni, Bolivia (Petavratzi *et al*., 2022). Outflows are primarily from evaporation, which is orders of magnitude higher than the rainfall (Godfrey *et al*., 2013).

The main input to the salars in terms of fresh water is both surface water and groundwater which have elevated solute concentrations for sodium chloride as well as lithium and other solutes. The fresh water is cycled through the system via evaporation which provides the main outflow and this concentrates the solutes in the inflow waters to produce the lithium-rich brines. However, in the short-term the input of fresh water provides a source of water for abstraction as well as ecological support. Abstraction can take place for potable water supply, industrial supply or brine extraction itself. Climate change, likely to result in an increase in temperature but forecast to produce variable impacts on rainfall, will change the balance of inflows and outflows over time (Oyarzún & Oyarzún, 2011). Whilst they exist in an arid environment, the salars themselves contain significant amounts of water associated with the brine system.

2.1.1.2 Regional variation

There are similarities between salars in the Lithium Triangle but also significant differences as well, which result in variation of the economic value of their deposits as well as their vulnerability to environmental harm. The geological setting mainly consists of volcanic deposits, but can vary in their age, nature as well as lithium content. Whilst the elevation is broadly similar (around 3500-4000 m ASL), some salars are found at lower altitudes, e.g. Atacama at 2304 m ASL. The lithium-rich brines are found close to the surface but as deeper drilling hasn't been undertaken then the true depth of occurrence of lithium at depth isn't known. Climatically defined as arid or semi-arid, there are spatial variations in rainfall totals as well as evaporation depending on salar location, not only due to orographic effects but also variation in the predominant wind direction and associated air mass movements (Houston, 2006). Their size also differs considerably, Table 2 shows values for the three most studied salars which shows a variation of pan area from 700 km^2 for Hombre Muerto to over 12000 km^2 for Uyuni.

To date, there has been limited work to identify possible correlations (e.g., similarities and outliers) in salars' groundwater system considering the deposit model parameters mentioned by Bradley *et al*. (2013) and Munk *et al*. (2016). Al-Jawad *et al*. (2023) used regional correlations of 29 salars to examine similarities based on a deposit model to identify anomalies in the salars within the Lithium Triangle. They used a normalised parameter by dividing by mean lithium concentration set to further understand why salars have different lithium concentrations. The driving parameter/parameters for this variation in lithium concentration have been identified as elevation, rainfall and evaporation along with a set representing percentage geological outcrop, land use area, basin area and salar size.

Name	Pan area[1] (km2)	Elevation[2] (m.a.s.l)	Pr[3] (mm/y)	ET[4] (mm/y)	Basin area[5] (km^2)	TDS[6] (g/l)	Land cover[7] (km^2)	Volc. Area[8] (km^2)	Li[6] (mg/l)
Argentina									
Salar de Hombre Muerto	732.72	3967.00	219.76	805.75	3888.20	167.00	3974.44	2040.44	628.00
Bolivia									
Salar de Uyuni	12617.90	3660.00	337.02	831.61	47350.80	123.00	34257.21	22949.54	715.00
Chile									
Salar de Atacama	3522.41	2304.00	96.74	1031.75	15658.90	181.00	14418.37	8040.31	1000.00

[1](GoogleEarthPro, 2022), [2](Farr *et al*., 2007), [3](Muñoz-Sabater *et al*., 2021), [4](Haran, 2015), [5](Lehner *et al*., 2008), [6](López Steinmetz & Salvi, 2021), [7](GlobCover, 2009), [8](Gómez, 2019), [a](mean values of adjacent salars), [b](Doran *et al*., 2010), [c](Murray *et al*., 2019), [d](GHD, 2019)

Table 2. Comparison between Atacama, Uyuni and Hombre Muerto.

2.1.1.3 Mass Balance and sustainability issues

Brines are made up of water, NaCl and other trace elements – lithium being one of them. Relative masses of each component means that water is the most important followed by NaCL and then the trace elements. Lithium, whilst economically viable is only small fraction of the brine mass. Whilst the brines are being continually created within a salar, the process is slow and takes "geological time" – 100,000 to 1 million years.

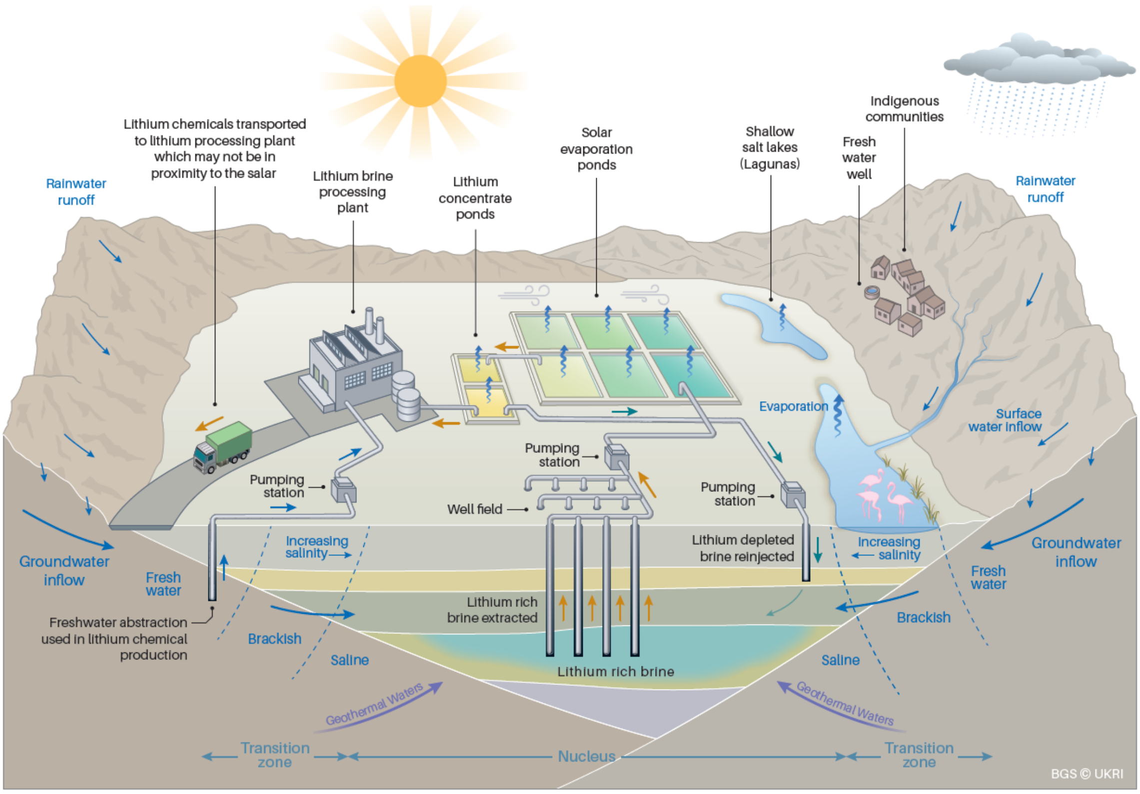
Once abstracted, the brine is processed either via evaporation ponds (open pools that evaporate into the atmosphere) or via Direct Lithium Extraction (DLE) (see Figure 3). DLE covers a range of processing technologies but aims to recover the lithium faster than evaporation ponds although it requires energy, chemical and fresh water input (Vera *et al*., 2023). Both approaches are discussed in more detail below.

Water inflow to the system is derived from both surface waters and groundwater. Whilst the region is arid and semi-arid nonetheless the salars do receive significant inflows from either surface waters or groundwater. The Salar de Atacama is in the driest part of the region and receives limited surface flow (Rio San Pedro) and fossil groundwater (Moran *et al*., 2022), whilst other salars such as Salar de Uyuni are flooded every year (Rossi *et al*., 2022). This means that the sustainability for freshwater abstraction (i.e. non-brine) is potentially possible depending on the amount of rainfall, contemporary recharge and abstraction but will have to be assessed on a case-by-case basis. In addition, significant water molecules are locked up in the brines within the salars and given the likely depth of the aquifers this could be significant amounts of water. However, this is difficult to access and as a result of limited input so any abstraction could be seen as being mined.

Sodium Chloride, NaCl, is lost as a waste product, mainly via precipitation in the evaporation ponds (Flexer *et al*., 2018). However, reinjection of brine is undertaken which has the benefit of returning NaCl and potentially lithium to the salar. As well as this, the negative impacts of pumping are mitigated by injecting the spent brine between the wellfield and any environmentally sensitive locations like lagunas.

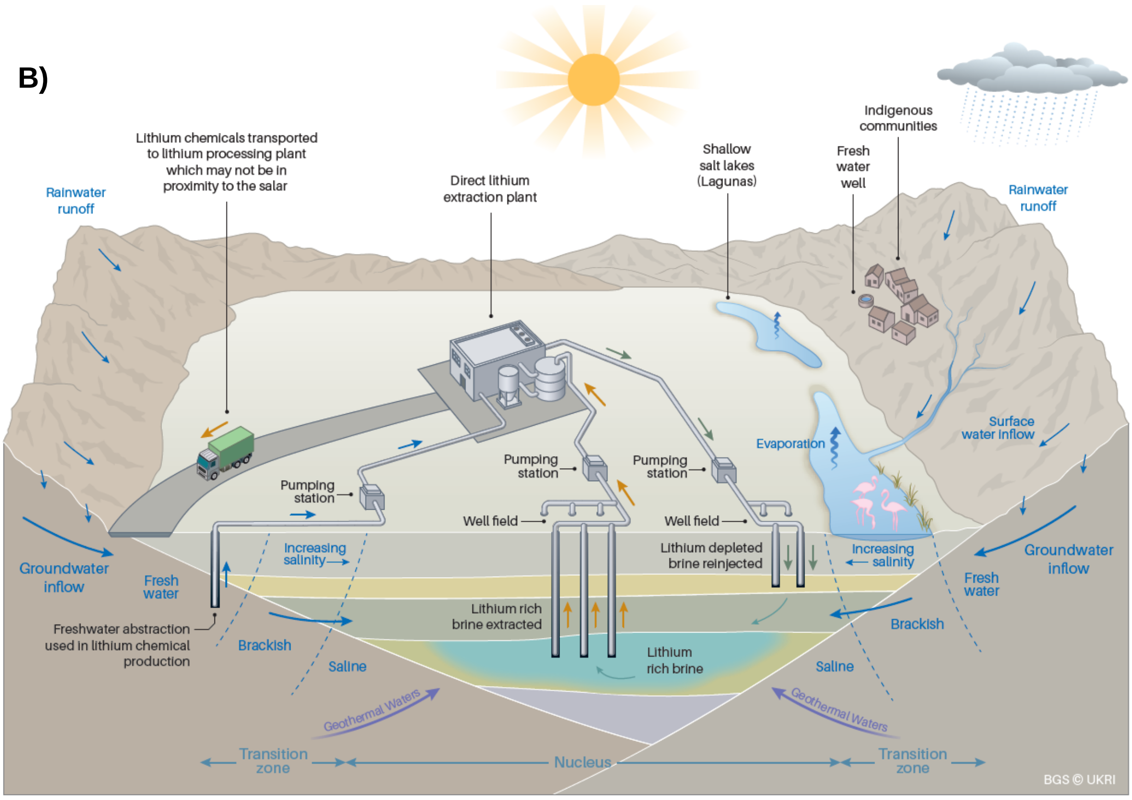
The term sustainability in lithium production needs to be clearly defined due to its differing use. However, in terms of abstraction of lithium-rich brines and the processing and concentrating of the lithium into 6%wt/wt lithium chloride then there is a net reduction in lithium within the salar. Whilst this reduction year-on-year may represent a small percentage of the overall mass, nonetheless a reduction occurs which means that the lithium extracted is not being replaced like-for-like and, therefore, is not being sustainably produced.

A)



Not to scale. Diagram is schematic and may not accurately represent all scenarios.

B)



Not to scale. Diagram is schematic and may not accurately represent all scenarios.

Figure 3. Schematic block diagram of a salar illustrating brine extraction and concentration with a) evaporation ponds and b) direct lithium extraction (DLE). Hydrogeological and other salar features are also displayed. Diagram is schematic and not to scale, position and nature of extraction and reinjection is indicative and may not reflect actual practices.

2.1.2 Summary of Challenges & Opportunities

Opportunities: A strong and vibrant research community exists, in particular, related to microbiological, biodiversity, socio-environmental as well as downstream technologies. Whilst there are significant in-country research activities, access to materials such as brines for research purposes can be problematic. There was a call to create an international research community and for this to be associated with an environmental observatory located on a salar. For example in Chile this could be in one of the protected areas as 30% ecosystems are to be protected by 2030 (Gutiérrez & Ruiz-León, 2024).

Three dimensional understanding (basin to salar): Salars are recognised as complex systems with limited understanding and baseline data. There is a need for a fully 3D understanding of the sub-surface (geological and hydrogeological) and how this changes with time (4D). Given that in Argentina, for example, all the salars are permitted then lithium resources will be sourced from deeper parts of the system. This compounds the need for a 3D characterisation.

Mass balance and sustainability: In terms of the provenance of the brine and lithium then there is a need for the quantification of the mass balance, particularly related to the input of water, major solutes (e.g. NaCl) and lithium as well as other trace minerals such as magnesium and potassium. Determining freshwater resources in any basin remains a priority and an understanding of how all abstractors affect these resources and environmentally vulnerable features is important. Further, the impact of climate change needs to be understood to determine how the freshwater system will change in the future.

Abstraction, reinjection and its impact: There have been concerns raised in terms of environmental impact, however it is difficult to ascertain how abstraction has affected the environment given that the system response can take years or even decades to become apparent. The impact of abstraction is not straight-forward to determine given the aridity of the area, complexity of the system and the variation of conditions related to inter-annual and decadal changes in climate. The impacts of climate change could exacerbate any abstraction effects and whilst temperatures are likely to increase affecting evaporation, it remains relatively uncertain what changes to rainfall may occur. The latter could reduce surface water and groundwater inflows where they are resulting from contemporaneous rainfall.

Whilst strictly related to the anthropogenic influences on the salars, the environmental impact of wellfield operation needs to be better understood. Of particular importance is how brine abstraction affects the main environmental indicators such as lagunas and their flora and fauna, e.g. Flamingos. It is likely that Direct Lithium Extraction (DLE) will increasingly become the most common method to process the brines for lithium production and the spent brine reinjected. Therefore, reinjection and its environmental impact in terms of both quantity (how much) and quality (geochemical) impacts is required to understand how reinjection will work effectively in conjunction with DLE.

2.1.3 Recommendations & Research Priorities

- Development of an agreed conceptual model of the watershed including salar processes
- Development of salar observatories in all three countries funded by country specific research funds and international research projects.
- Geological and hydrogeological understanding (incl. deep)
- Microbiological and geochemical processes
- Vertical heterogeneity and lithium dilution over time due to inputs / outputs
- Development of integrated understanding and simulation of laguna processes and interaction of wellfield processes with lagunas
- Quantification of recharge processes incl. cryosphere
- Understanding of lithium 3D distribution and how it changes with time (4D)
- Undertaking mass balances with associated uncertainty quantified
- Understanding impact of other riparian users on watershed

2.2 ENVIRONMENTAL CHALLENGES

2.2.1 Background

While lithium is needed to decarbonise, the environmental impacts of its production must be minimised so that the green transition does not have excessive and unforeseen negative impacts. In some aspects, salar brines represent the lowest potential impact source of lithium, e.g. carbon footprint compared to spodumene sources (Jiang *et al*., 2020; Grant *et al*., 2020; Kelly *et al*., 2021; Manjong *et al*., 2021; Chordia *et al*., 2022; Lagos *et al*., 2024).

However, salars systems are extremely sensitive and unique, host indigenous communities and globally significant and precious ecosystems, of high biodiversity, cultural and symbolic value (Babidge and Bolados, 2018; Gajardo and Redón, 2019; Marazuela *et al*., 2019; Bonelli and Dorador, 2021; Gutiérrez *et al*., 2022; Liu and Agusdinata, 2021; Lorca *et al*., 2022; Marazuela *et al*., 2019) and other environmental factors of production (i.e. water-related impacts) are more of a concern than carbon footprints. Furthermore, salars are often within, or in proximity to, RAMSAR sites, national parks, Key Biodiversity Areas (Stacey, 2019) or other protected and valuable areas.

While increasing environmental awareness, understanding of salar systems and implementation of standards and regulations is improving the environmental performance of salar-based operations (IRMA, 2023a; IRMA 2023b), there are still significant concerns and unknowns.

2.2.2 Summary of Challenges & Opportunities

There is a lack of holistic knowledge and capacity when it comes to understanding the environmental impacts of lithium production from salars, due to a lack of experience and baseline data coupled with the complexity of salar systems.

Fresh water consumption is one of the most important factors in resource sustainability assessments (Zipper *et al*., 2020), and is the most significant sustainability concern of lithium production from salars, which potentially reduces water availability to local indigenous communities and sensitive ecosystems (Babidge and Bolados, 2018; Marazuela *et al*., 2019; Liu and Agusdinata, 2021; Gutiérrez *et al*., 2022; Lorca *et al*., 2022; Díaz Paz *et al*., 2024). Impacts will be unique to each salar and project, with the hydrogeology, hydrology, geomorphology, geology, elevation and technology used all influencing how impacts materialise (Flexer *et al*., 2018; Munk *et al*., 2021).

Brine abstraction affects the inflow of fresh water from salar margins and/or depth, and therefore potentially freshwater availability in the wider system; but there is no linear relationship between brine abstraction and decreases in water storage (Marazuela *et al*., 2019). Fluctuations in the water table and brine concentration, influenced by reinjection as well as abstraction, can affect the evaporation rate (Houston, 2006; Marazuela *et al*., 2019, 2020). In turn, this could impact the salars hydrogeology, especially brine circulation, freshwater inflow, the position of the brine-fresh water interface (Rosen, 1994; Marazuela *et al*., 2020) and subsequently lagunas, ecosystems and freshwater availability to communities.

Mining operations also often have separate freshwater supplies, with the potential to directly reduce groundwater levels, impacting water availability to ecosystems and communities as well as introducing salinity into fresh parts of the system (Herrera *et al*., 2016; Petavratzi *et al*., 2022). Freshwater abstraction is thought to have a direct and larger impact than brine abstraction on wetlands, lagunas and freshwater resources (Moran *et al*., 2022). However, it should be noted that in some areas the freshwater may not be suitable for human consumption without further treatment (Concha *et al*., 2010; Flexer *et al*., 2018).

Furthermore, there is debate around how brine is assessed and classified (Ejeian *et al*., 2021; Kelly *et al*., 2021; Schomberg *et al*., 2021; Schenker *et al*., 2022; Chordia *et al*., 2022; Fernández and Alba, 2023; Blair *et al*., 2024) as well as flaws in some method of assessing environmental impacts (Halkes *et al*., 2024).

Reinjection of lithium-depleted brines is a new technology that is emerging, however, akin to DLE, its potential benefits and impacts are not yet well understood for salars. Whilst reinjection of groundwater and brines is not a new phenomena, i.e. Managed Aquifer Recharge and reinjection of saline waters in oil fields, the current knowledge related to salars is largely concentrated in commercial organisations / private bodies (Fuentealba *et al*., 2023). There are also significant unknowns regarding how operations can affect ecosystems. Waste has also been highlighted as an understudied aspect of environmental impacts. Additionally, the clustering of salars and competition with other economic sectors also necessitates consideration of cumulative impacts (Petavratzi *et al*., 2022).

Approaches that could help minimise environmental harm include the mitigation hierarchy and International Finance Corporation's Performance Standards:

The use of the mitigation hierarchy as an approach to avoid and minimise impacts. The mitigation hierarchy is a tool designed to help users limit, as far as possible, the negative impacts of development projects on biodiversity and ecosystem services. Its approach involves a sequence of four key actions—'avoid', 'minimize', 'restore', 'rehabilitate' and 'offset'—and provides a best practice approach to aid in the sustainable management of living, natural resources by establishing a mechanism to balance conservation needs with development priorities. It is hierarchical in that it places a primary emphasis on "impact avoidance" as much as is possible, so reducing the scale of ongoing obligations to minimization, restoration and offsetting.

The use of the International Finance Corporation's (IFC) Performance Standards, and in particular Performance Standard 6: Biodiversity Conservation and Sustainable Management of Living Natural Resources, which provide a recognition of the risks that extractive industry developments can have on biodiversity and ecosystems services. Overall, there is a need for standards that require the identification of critical natural habitats for species that may be negatively impacted by lithium development. The identification of Key Biodiversity Areas (KBAs) and globally and nationally threatened species which may feature within such KBAs (or outside of them) will be key features of interest, guiding and informing how the mitigation hierarchy is to be applied to a lithium project. Such biodiversity values need to be identified in the development and profile of baseline studies used in EIAs.

2.2.3 Recommendations & Research Priorities

- Baseline data and monitoring: improvements in collecting baseline data and monitoring are essential to enable comprehensive environmental assessments. This includes developing schemes for pristine areas, and integrating existing techniques with novel approaches like Earth Observation (EO)
- Mine closure: While not an immediate priority, the closure and rehabilitation of salar-based mining projects needs to be studied. No known salar-based project has gone through closure, and sustainable closure practices that leave a positive legacy must be explored
- Understanding environmental receptors and assessing the impact of wellfields on key environmental receptors is crucial. Building on existing data, for example Integrated Biodiversity Tool[4] and GCFA-sponsored Flamingo surveys, to provide a holistic understanding of changes to key environmental receptors.
- Improved understanding of salar processes to be able to understand and quantify impacts (see Salar Processes Section)
- Clarity and coherence on the assessment and classification of brine and freshwater
- Reinjection: understanding how to effectively use reinjection to minimise environmental impacts, as well as increasing understanding of its potential impacts, both positive and negative
- Quantifying waste streams and exploring opportunities for waste valorisation is an important aspect to improving environmental, as well as economic performance
- Assessing and managing the cumulative impacts of multiple projects and economic sectors in salar regions is essential, especially with the clustering of salar operations and the salars themselves
- Progress towards comprehensive assessment of environmental impacts with social and governance aspects – development of holistic approaches

[4] IBAT - www.ibat-alliance.org

2.3 TECHNOLOGIES FOR LITHIUM PRODUCTION

2.3.1 Background

Growing demand and the desire to minimise environmental impacts is driving innovation and development of lithium production from salars. Most notable among these is the emergence of Direct Lithium Extraction (DLE) (Fuentealba *et al*., 2023; Nicolaci *et al*., 2023; Vera *et al*., 2023; Farahbakhsh *et al*., 2024), alongside developments in processing and other stages of the value chain. These developments can potentially reduce environmental footprints, improve social acceptance and relations, and enhance project economics.

Each salar brine has a unique composition, requiring a tailored processing method (Wietelmann and Steinbild, 2014), but most follow a common framework of concentration, purification, then chemical processing. Two types of technologies are used in the concentration and purification - evaporation processes (EP) and direct lithium extraction (DLE).

During EP, solar and wind-driven evaporation progressively concentrates the brine in a succession of evaporative ponds. Different intermediate salts may be harvested as they precipitate and impurities removed (Swain, 2017; Flexer *et al*., 2018; Garcés and Alvarez, 2020). Fresh water is also consumed in the process (Kelly *et al*., 2021). EP have a lithium recovery rate of 40–60% (Nicolaci *et al*., 2023). Meanwhile, 85–95% of water contained within the brines is lost through evaporation (Flexer *et al*., 2018).

DLE is a blanket term used to refer to several different technologies that actively concentrate lithium (Tabelin *et al*., 2021; Nicolaci *et al*., 2023; Vera *et al*., 2023; Farahbakhsh *et al*., 2024). DLE processes have higher lithium extraction efficiency, 70 – 90%, and a significantly reduced surface footprint compared to EP (Fuentealba *et al*., 2023; Nicolaci *et al*., 2023; Farahbakhsh *et al*., 2024). DLE requires energy, fresh water and chemicals that must be considered during environmental impact assessments (Vera *et al*., 2023). Pre-treatment of the brines and post-treatment of the concentrated lithium solution may also be necessary (Vera *et al*., 2023).

DLE could have a transformative impact on lithium production and several countries promote it, including Chile and Bolivia (Nicolaci *et al*., 2023). However, the introduction of these technologies and techniques is not without potential risks (Fuentealba *et al*., 2023; Vera *et al*., 2023; Farahbakhsh *et al*., 2024). At the time of writing, with the exception of the long-standing plant at Hombre Muerto, operational since 1998, DLE has not been implemented at scale.

2.3.2 Summary of Challenges & Opportunities

DLE has the potential to reduce brine consumption, and by extension, related impacts. It can also improve production timelines, reduce land footprint, and improve economics compared to EP (Nicolaci *et al*., 2023; Vera *et al*., 2023; Fuentealba *et al*., 2023; Farahbakhsh *et al*., 2024). It also provides an opportunity to exploit lithium deposits that are uneconomically justifiable with conventional EP (Farahbakhsh *et al*., 2024).

However, challenges include higher freshwater, energy and reagent requirements (Vera *et al*., 2023; Fuentealba *et al*., 2023; Blair *et al*., 2024) and a greater embodied footprint compared to EP, as well as the reinjection of spent brine (which is of greater volumes compared to EP) (Fuentealba *et al*., 2023; Vera *et al*., 2023). There is uncertainty surrounding the impacts of DLE, and a lack of data and understanding outside of private entities, which is hindering independent assessment (Vera *et al*., 2023; Fuentealba *et al*., 2023) and it is yet to be widely deployed commercially in South America. Though improvements to DLE technologies, such as material and process developments, may reduce water dependence and result in more efficient, sustainable and cost-effective DLE processes (Farahbakhsh *et al*., 2024).

While EP have inherent drawbacks, timeliness, climate dependency, high brine usage, and large footprint (Flexer *et al*., 2018; Nicolaci *et al*., 2023; Vera *et al*., 2023). It still offers a low-energy, low-cost, and relatively straightforward process, that can be used in conjunction with DLE, and it may be necessary to combine EP and DLE processes (Vera *et al*., 2023).

Furthermore, advancements in extraction and processing technologies may enable increased production of by- and co- products, as well as waste re-processing and valorisation. These have the potential to improve economics and potentially lower the environmental footprint of products, while waste valorisation could aid the reduction of significant waste volumes and associated problems (Vera *et al*., 2023).

The Puna Plateau receives some of the highest solar irradiation in the world (Global Solar Atlas, 2024), with strong potential to power lithium operations through photovoltaics (PVs). This could reduce environmental impacts through clean energy provision. However, challenges include infrastructure requirements, the robustness of PVs in these extreme environments, embodied environmental footprint and social impacts of PV production (Frischknecht *et al*., 2015; Crawford and Murphy, 2023), as well as the land area needed for installation.

The LIB market is constantly evolving, including battery chemistries. For example, the recent growth of LFP batteries compared to NMC, has resulted in increased demand for lithium carbonate. It is possible that demand for different lithium battery chemicals, including new lithium compounds, will change in response to evolving battery chemistries in the future.

2.3.3 Recommendations & Research Priorities

- Understanding of DLE and potential impacts, both positive and negative of its implementation, including independent assessment and verification
- Investigation and assessment of reinjection techniques and technologies, especially their use alongside DLE
- Investigation and assessment of the potential benefits and drawbacks of hybrid EP and DLE systems and development of a framework to assess the trade-offs and aid decision making between different processing types i.e. DLE vs EP systems
- Investigation of the potential for co- and by- products, and how this could be best achieved from varying salars and processing systems
- Potential of waste re-processing and valorisation, development of techniques and technologies to enable this
- Hurdles of PV instillation for clean energy generation, such as the possibility of shared energy infrastructure and robust systems
- Identification of future potential lithium compounds and associated demand, and potential production pathways from salar brines

2.4 INFRASTRUCTURE, SUPPLY CHAINS AND DEVELOPMENT

2.4.1 Background

Operations in the Lithium Triangle are often situated in remote areas, which may lack in a well-developed infrastructure (Wilson Center, 2024). This poses significant challenges for project development and operations, which can have knock-on effects on ESG factors. In resource-rich countries, such as those of the Lithium Triangle, mining can play a key role in increasing access to infrastructure (Toledano and Maennling, 2018) and providing local benefits, a crucial element of Social Licence to Operate (SLO) (Prno, 2013). Development of local supply chains can be especially important, with procurement often having the single largest potential economic impact in a host country (Geipel, 2017).

To ensure continued SLO, it is essential to have “an equitable sharing of benefits” among local stakeholders, inequitable distribution of risks, impacts and benefits are core drivers of community disputes related to mining operations (Kemp *et al*., 2011; Prno, 2013). Access to infrastructure and services, benefit sharing, and revenue distribution have been identified as significant concerns of local communities within the Lithium Triangle, with infrastructure perceived as a method to obtain benefits into the future, post-mining (Lorca *et al*., 2022; Escosteguy *et al*., 2024).

2.4.2 Summary of Challenges & Opportunities

One of the most significant challenges in upscaling lithium production is regional infrastructure, including transportation links, water and energy supply, and upstream supply chains. This complicates the already challenging prospect of identifying resources, and then developing, and upscaling operations.

However, the development of infrastructure and supply chains represents a significant opportunity for operations to 'benefit share' with local communities and on a wider regional scale. The development of infrastructure (e.g., roads, improved water and power supply) can provide substantial benefits if it is done in a considered and appropriate manner (Prno, 2013; Geipel, 2017; Collier and Ireland, 2018; Toledano and Maennling, 2018).

For example, company-community agreements, or Community Development Agreements (CDA) can create inter- and intra- community stress (Lorca *et al*., 2022; Cornejo Puchner, 2024) and issues can also arise surrounding the nature of development and infrastructure, and supply chain building (Escosteguy *et al*., 2024).

Mining-related infrastructure can be developed to serve the exclusive need of mining companies but shared 'open access' infrastructure and investments can improve access to services and unlock economic potential across other industries (Collier and Ireland, 2018; Toledano and Maennling, 2018). Water-related infrastructure is of particular importance in the Lithium Triangle and investment in water infrastructure by mining companies can generate substantial benefit to local communities, often with only incremental increase in spending (Admiraal *et al*., 2017; Toledano and Maennling, 2018).

With development, and infrastructure and supply chain building it is necessary to account for local and regional contextual differences which may require bespoke approaches (Collier and Ireland, 2018), it also necessary to respect the desires of local communities. There is potential for a collaborative approach at local and regional level, which can enable targeted and effective projects (Esteves, 2008), though this is not without challenge itself.

Consideration also needs to be given to the sustainability of any developments, and provisions made for the potential unexpected or unplanned closure of projects, and obligations on companies not excessive (Esteves, 2008; Syahrir *et al*., 2021), as well as to future regional scenarios post the 'lithium mining boom.', to avoid 'fall-offs' similar to those seen in Chile with the decline in nitrate production in the 20th century and closure of other mining projects in the region (Gregory, 2023).

2.4.3 Recommendations & Research Priorities

- Environmentally sensitive infrastructure development in partnership with local communities
- Investigations into the direct and indirect benefits of infrastructure and supply chain development to aid decision-making, how to build local and regional supply chains strategically
- Strategies for providing sustainable development and longevity beyond mining cycles should be explored, ensuring any developments can continue to provide benefits post-mining and continue in case of downturns
- Assessment of regional collaboration for the development and sharing of 'open' infrastructure
- Development of Social Investment Decision Analysis Tool(s) specific to the Lithium Triangle by a trusted, independent organisation in conjunction with stakeholders

2.5 DATA TRANSPARENCY AND EFFECTIVE COMMUNICATION

2.5.1 Background

The process of mine development from the exploration stage, through production and then subsequent closure has significant data and information requirements. To make these data and information available are a challenge due to the differing ownership, hosting and nature of these data. Examples include PDF reports of EIAs, current updates on operations, e.g. Argentine government's "state of development" (see below) through to detailed scientific data collected as part of a monitoring campaign, e.g. Sernageomin's data portal (see below). Data and information requirements are significant and varied with differing data types including environmental data (e.g. baseline monitoring) and social data (e.g. socio-economic assessment). Further, for the mine development process data and information are collected for the permitting process, scheme development, resources and reserves quantification and at a regional and country level revenue from taxation and other economic data. Effective communication of these data are required as not all stakeholders will be familiar with scientific data or able to digest reporting from mine production activities.

Standards and best practice do exist for data and its metadata (descriptions of the data itself) with international and local standards for all parts of the mining cycle, e.g. ISO and BSi. The Q-FAIR principal is well established for Findable, Accessible, Interoperable and Reusable as well as quality (Q) checked data. Further, metadata standards do exist such as ISO 15836 or Dublin Core.

2.5.2 Summary of Challenges & Opportunities

There is a considerable amount of data and information related to the development of lithium brine sources from salars. In particular, there are publicly available, typically internet-based documents and data related to lithium brines. For example, Chile environmental monitoring is available as a webgis (see SNIFA website - https://snifa.sma.gob.cl/) and operators such as SQM provides information and data via its website (see www.sqmsenlinea.com). The Chilean geological survey (Sernageomin) also makes the geochemical data it collects related to salar surveys available online (see https://insights.arcgis.com/#/view/9105c17bc0b046dc864c2f10641fc545).

The Argentine government captures the current status of schemes in PDF documents relating to the stage of the scheme's development along with the reported reserves and resources (see https://www.argentina.gob.ar/sites/default/files/portfolio_lithium_2024.pptx.pdf). Clearly, there are a number of data available related to different parts of the salar mining process / supply chain and in different forms and by different organisations. There are limited or no attempts to use metadata approaches, e.g. Dublin core and to follow data standards.

Transparency of the process of assessing and regulating operations is important in reducing conflict. To facilitate conflict reduction, good data availability and accessibility is required. However, the fragmented nature of the data and information and its availability means that it takes time and effort to build up an overall picture of what is going on in the Lithium Triangle. Means by which reporting and reflecting back the steps taken by individual operators, salar and regional development is not yet available.

There may well be current and immediate future developments in digital technology that could assist in this process including examples of best practice that can help. Initiatives such as blockchain for lithium passports, Artificial Intelligence (AI) for data assimilation and use of earth observation data are potential examples. Alongside this, the use of arts-based approaches to assist communication of scientific ideas to non-scientific stakeholders could be considered. Improved ways of communicating the data to a range of audiences, e.g. non-specialists, need to be found. Interpretation of the results of any study need to be undertaken with the audience in mind. Addressing power imbalances requires transparency of the processes undertaken which can be achieved by making data available and accessible.

2.5.3 Recommendations & Research Priorities

- Development of data infrastructure and portals to improve data accessibility and transparency
- Making data accessible to a range of stakeholders in the right language and form
- Improving reporting processes to reduce bureaucracy and minimise the time spent in collection and interpretation
- Collating and transferring good practice from elsewhere E.g. INSPIRE directive
- Using digital technologies to streamline data collation.

2.6 GOVERNANCE

2.6.1 Background

Governance, namely the ways that a country is managed, relates to activities taking place in several sectors. The Worldwide Governance Indicators (WGI) (Figure 4) comprise a compilation of data ranking the quality of governance in over 200 countries and territories globally, including

Chile and Argentina. WGI comprises of six indicators, namely (i) *voice and accountability*, (ii) *political stability and absence of violence/terrorism*, (iii) *government effectiveness*, (iv) *regulatory quality*, (v) *rule of law*, and (vi) *control of corruption* (Kaufmann & Kraay 2023). The WGI data suggest that Chile is in a more favourable position than Argentina for all the indicators included in the analysis (Figure 4). However, in 2022 a drop in Chile's ranking in all the indicators is shown compared to previous decades. This signifies that the quality of governance has reduced. In 2022, the largest year on year change is observed for the *government effectiveness* indicator in Chile. In Argentina, lower rankings are present for the indicators: *political stability and absence of violence/terrorism*, *government effectiveness* and *control of corruption*, whilst for the remainder indicators an improvement is seen compared to previous decades. The largest improvement in Argentina is seen for the *regulatory quality* indicator, but this also represents the indicator with the lowest overall ranking for Argentina. However, the situation is fluid and at the time of writing (autumn 2024), the overall picture in Argentina is mixed, but the need for better governance and management systems is apparent.

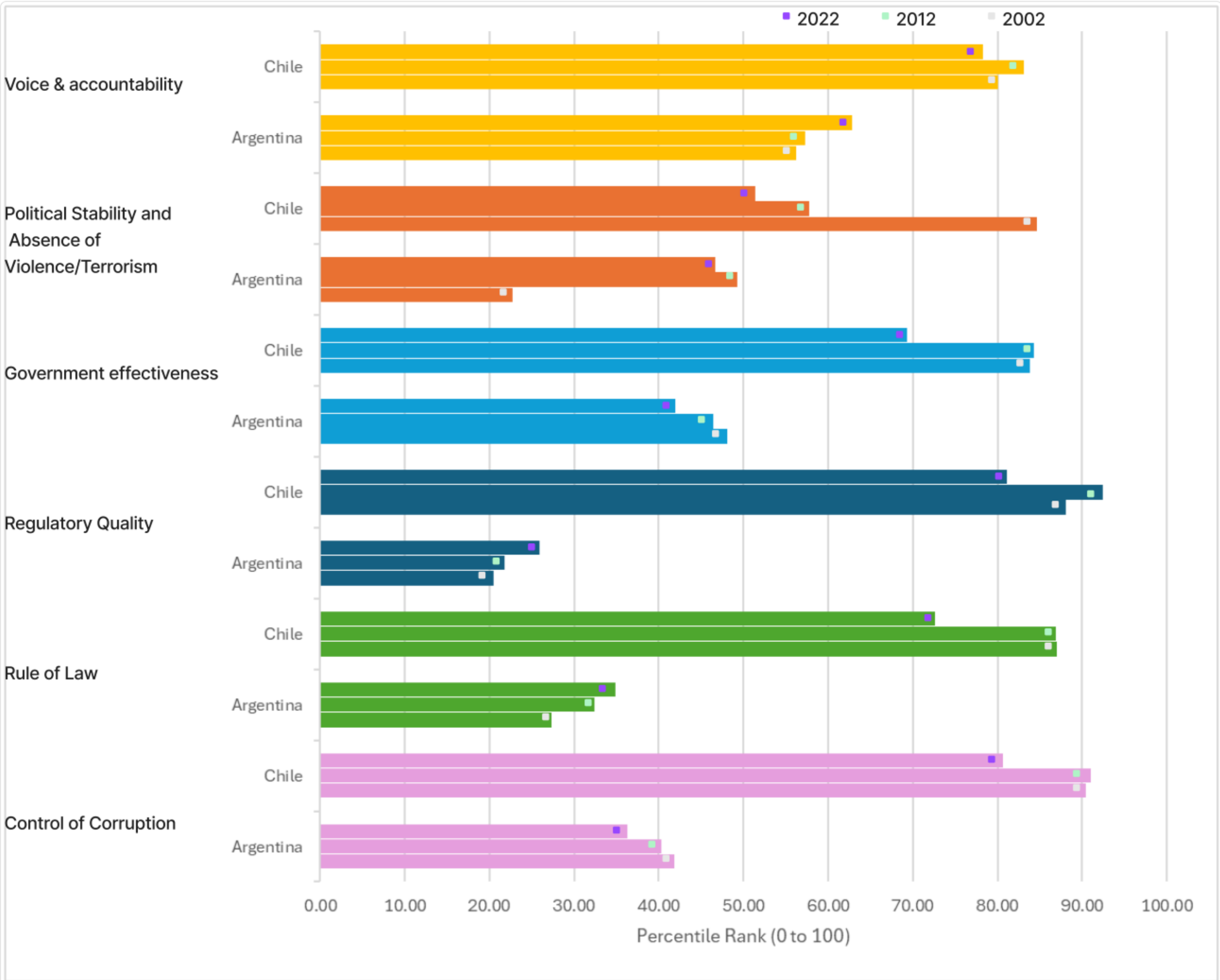


Figure 4. World governance indicators for Chile and Argentina. Rankings are presented for the past two decades (individual years: 2002, 2012, 2022). Data from (Kaufmann & Kraay 2023).

Even though the WGI data are not specific to mining, they provide useful insights about the general governance practices followed by a country, which most of the time, closely relate to mining. The term governance in mining has many different aspects that relate to the management of mineral resources (e.g. mining regulation), environmental governance aspects (e.g. environmental regulations, sustainability), economic governance (e.g. revenues, taxes, royalties, incentives) and the engagement with the wider stakeholder network linked to a particular mining activity.

Chile and Argentina are both rich in lithium resources found in over 70 salars with key production projects being the Salar de Atacama in Chile and the Salar del Hombre Muerto and Salar de Olaroz in Argentina. Despite the geological similarities in the two countries, their governance approaches are quite divergent.

In Chile, lithium is a strategic resource, see Gutiérrez and Ruiz-León (2024) for an excellent summary of the historical and current situation, and has been given the status of 'reserved for the state' since 1979. Post-1979, lithium mining activities are non-concessional except for mining concessions that have been provided prior to 1979. However, the exploration and extraction of non-concessional minerals is possible through mechanisms outlined in Chile's Constitution (article 19, No. 24, section10). These include exploitation by the State or state-owned companies, administrative concessions, special contracts of operations (Contratos Especiales de Operacion - CEOL).

Lithium mining in Argentina has been carried out for more than 20 years with lithium production taking place currently from two salt flats (Hombre Muerto, Olaroz) whilst about 36 projects are currently at different stages in exploration (Secretariat of Mining 2024). Mining activities are subject to the rules set by the National Mining Code (Law N° 24.585). Overall, in Argentina, lithium does not have strategic status and the governance of lithium resources has a decentralised structure in which provinces set their own procedural mining law. However, the Provincial Act of Jujuy (No. 5674, 2011) defines lithium a strategic resource and an important contributor to the province's socioeconomic development (ECLAC 2023). Provinces are responsible for the provision of exploration and extraction rights to private and state companies, for charging royalties and other non-fiscal measures, for environmental compliance and protection in line with the environmental regulations and for setting their own procedural mining law.

2.6.2 Summary of Challenges & Opportunities

The **opportunity** to improve the governance of lithium salt flats in Chile and Argentina arises from the strong global demand trend, which puts both countries in the epicentre of supply. Changes in the governance of mining projects are essential to ensure sustainable and responsible lithium supply, including:

- streamlined procedures for developing new projects
- ongoing monitoring of environmental impacts and progress towards targets
- best practice for improving the communication between involved stakeholders
- ways to deal effectively with conflicts and law enforcement
- new systems of reporting and management of data
- improved frameworks for increasing revenues
- de-risking mining projects and providing fiscal stability.

In Argentina, the Mining and Investment Law, 1993 (No. 24. 196) is possibly the most important legislation regarding the future of lithium in Argentina. The Law offers multiple incentives for increasing fiscal stability, reducing tax and risk in exploration and mining activities. The Mining and Investment Law is complemented by the Foreign Investment Law, which provides equal treatment to all investors (foreign and domestic). In addition, in 2021, the Investment Promotion Regime for Exports (No. 234/2021) was introduced, which enables investors access to foreign currency on the local foreign exchange market (CSIS 2024; Secretariat of Mining 2024)). Argentina's role towards investment is distinct across the "Lithium Triangle", as there are no restrictions on foreign investment and therefore private ownership of mineral rights is allowed. Finally, since 2019, Argentina has joined the Extractive Industries Transparency Initiative (EITI) and in 2022 launched the SIACAM initiative, which comprises an information system open to the community on mining activity in Argentina. The latter provides regular updates on the economic, geological, geographic, social, health and environmental aspects of mining in Argentina (Ministry of Economy, 2024).

In 2023, the Chilean government released their National Lithium Strategy, which is designed to expand the lithium sector through public private partnerships with a new state-owned lithium company and private investors. Key objectives in the new strategy include sustainable development in existing lithium producing activities, social and environmental sustainability, technological advances and domestic supply chain development, maximising economic revenues, increase supply diversification and value addition to their lithium resources (Government of Chile, 2023). The strategy is accompanied by an implementation plan which includes the following seven actions: (i) establishment of a strategic committee for lithium, (ii) stakeholder engagement and participation processes, (iii) public-private partnerships in the Atacama salt flat, (iv) defining protected salt flats, (v) the establishment of an National lithium company, (vi) the development of a public technology and research institute for lithium and salt flats, and (vii) assessing the resource potential and prospects in other salt flats. Another important initiative is the development of a regional mining strategy in Antofagasta, the Mining Strategy of Well-being for the region of Antofagasta 2023-2050 (EMRA) (OECD 2023; Regional Government and Regional Council of Antofagasta 2023). Antofagasta is the most important mining region in Chile, the world-leading producing region for copper and the second highest global producer of lithium. The aim of the strategy is to prepare the mining sector in the region in-line with the exponential demand for energy transition minerals (lithium, copper) that Antofagasta can offer to ensure that opportunities are not missed, and that social and environmental inequality that may increase due to intense growth in mining activities is reduced to the minimum.

The above points highlight the different approaches taken by Argentina and Chile for improving the governance of lithium. In the case of Argentina, the changes in the decentralised governance structure seek to improve inwards investment opportunities and data and information transparency. In Chile, the introduction of lithium-specific strategies aims to improve the State procedures for sustainable and responsible resource management. The release of the regional Antofagasta mining strategy is an indicator of the transition in Chile towards a decentralised governance structure, which may bring significant improvement to the existing framework.

Despite the opportunities and positive changes in governance discussed earlier, challenges remain, many of whom may cease in the future if the various strategic actions identified are implemented successfully.

The key challenges that have been identified are:

Institutional governance frameworks are not fit-for-purpose for the fast-growing lithium sector: In Argentina the three provinces (Salta, Catamarca and Jujuy) with lithium mining potential have different views associated with the governance of resources. In combination with the federal governance structure, results in conflicting views around lithium mining. For example, the federal government has set a range of initiatives to attract investment, but the management of the practical aspects of exploration and mining is left to provinces that often lack the capacity, expertise, tools and resources required to manage this process. Considering the fast pace at which lithium projects need to be developed, the fragmented co-existence of the provincial-federal government may pose delays and conflicts to industry willing to invest, to civil society in mining regions and to sustainable and responsible approaches to lithium mining. Other key aspects, such as transboundary issues between provinces, where lithium resources are shared (e.g. Salar del Hombre Muerto) may pose challenges to developing the industry, as conflicts could emerge from the different provincial governance approaches.

Further, there are difficulties for the Federal and Provincial Governments in Argentina (and perhaps elsewhere) to recruit and retain technical staff and civil servants. Given the limited number of professionals and the disparity in pay between the private and public sectors, the governments struggle to maintain suitable levels of qualified and experienced staff. Pooling resources, for example as the Salta Provincial Government is doing by sending SegemAR the EIA for the Taca Taca project for assessment, or having some activities done by the joint observatory, could guarantee consistency (even across borders) as well as ensure results are made available in a timely manner.

In Chile, the central governance structure is seen somehow challenging, as the ‘local’ dimension and deep understanding of local challenges is often limited. The implementation and enforcement of mining and environmental law at the regional level under such structure can be problematic, if adequate resources and capacity from the central to the regional level do not become available. This may result in conflicts and delays in the lithium value chain development.

Lack of transparency in decision making processes may reduce investors’ confidence and create adverse perception towards lithium mining: Both in Chile and Argentina, the lack of a system where decisions related to the lithium sector are trackable is the key contributor towards insufficient transparency, negative perceptions and claims on corruption. For example, Chile is not a member of EITI and therefore the lack of a multistakeholder assessment process for decisions and actions taken related to mining is missing. However, plans to join the EITI have been highlighted in the National Lithium Strategy. In addition, an analysis has been conducted on how transparent the Chilean lithium sector is, which provides a range of recommendations for improving transparency (Yurish *et al*, 2024). These are likely to help increase the transparency in the Chilean lithium value chain. In contrast, Argentina is part of EITI and this process is coordinated by the federal government. The inclusion into EITI has increased the transparency of information associated with mining activities at international level. However, issues at the provincial level persist, where the implementation of law and procedural processes on lithium activities is taking place. Access to information and data at the provincial level has been identified as problematic and one of the key issues associated with negative perceptions towards decision-making on lithium projects. Nevertheless, the development of the "lithium board", which consists of the three provinces of Jujuy, Salta and Catamarca aims to develop a regulatory framework that is consistent across the lithium provinces, to develop best practices to monitor environmental impact and to improve the mineral licensing system. The above initiative is likely to improve further the transparency of information and decision making at the provincial level.

Uneven distribution of revenues may cause challenges to the future of responsible lithium supply: The tax and revenue system in Argentina and Chile have significant differences. Argentina's focus on an investment positive tax system has royalties set at 3 percent and the tax system allows companies to retain 72 percent of their profits (CSIS 2024). In addition, companies that are investing in Argentina can maintain their concessions if an annual tax is paid and their investment obligations are met. Provinces in Argentina, to maintain economic benefits, have set up enterprises (state-owned) that participate in the extraction of lithium (e.g. YPF Lithium) (ECLAC 2023). These enterprises, depending on their mandate, can purchase lithium produced and sell it to the market. In the Province of Jujuy, an additional mechanism based on collecting dividends has been established. In that, the state-owned enterprise has a stake of 8.5% in two mining projects and a 5% purchasing priority in produced lithium. Despite the above options for revenue generation at the Provincial level, evidence on how these rights have been taken up is missing (Taquiri and Maennling 2024). In Chile, lithium production quotas constrain the amount of lithium that can be extracted, tax concessions have an expiration date and the new mining royalty law (2023) introduced significant changes to increase state revenue from lithium exploitation. The new royalties include an (i) *ad valorem* royalty rate based on sales prices, and (ii) a progressive rate based on the gross operating margin of the lithium producer. The *ad valorem* royalty applies to the gross sales of lithium and it is a fixed rate of 1%. The progressive royalty rate (maximum effective rate between 8 to 26%) that applies to the operating margin of the lithium producer and increases as the operation becomes more profitable (Ernst & Young 2024). The overall tax burden cannot exceed 46.5% of the operational profitability. In addition, Chile is planning to invest into public-private partnerships to exploit lithium and therefore keep an active role in the development of this industry.

Revenues in Argentina are substantially lower than in Chile, suggesting that the funds available to contribute towards the development of a responsible lithium supply chain are likely to be constrained. On the other hand, the reformed tax system in Chile aims to capture additional funds that can be provided for improving social and environmental challenges related to lithium extraction. Overall, revenues from lithium mining in Chile and Argentina are distributed through a range of mechanisms to ensure national and regional benefits. However, these mechanisms are not always clear and the actual allocations of funds towards regional development, community development, environmental protection and infrastructure, as well as their success in promoting sustainable development are difficult to track. They may also vary substantially between different provinces/ regions and the two countries. Governance transparency, and community engagement are crucial in ensuring that mining royalties contribute positively to sustainable development goals.

Increased involvement in decision making by communities and civil society: Despite the improvements in governance frameworks towards social engagement and communication, the involvement of local communities and civil society in the decision-making process remains challenging and often inconsistent. The issues raised by communities are many and diverse, for example, specific to indigenous communities (cultural and land rights and the implementation of free, prior, informed consent – FPIC), environmental issues (water use, waste, biodiversity) and economic issues (revenue distribution, employment). The engagement by the private sector is often in the form of information dissemination and communication, as well as consultation and training primarily for easing their concerns (Díaz Paz *et al* 2023). The ratification of the ILO (International Labour Organisation) Convention No.169 (Indigenous and tribal peoples convention) has been an important step forward and in both countries, it is linked to national law. However, its implementation and enforcement has been inconsistent (Petavratzi *et al* 2023).

Several other initiatives that are positive include participatory environmental monitoring, community engagement programmes from companies operating in the region (e.g. SQM, Albermarle, Livent, Sales de Jujuy) and improved national framework (e.g. National Lithium Strategy in Chile). Despite the various examples that are available and provide evidence towards improved actions, challenges remain on (i) the consultation processes and the timing that communities' involvement is sought after, which is often not during negotiation and execution stages and (ii) the equitable distribution of the benefits achieved through various initiative. Additional efforts to strengthen governance frameworks regarding their implementation and enforcement, to maintain ongoing dialogue between communities, government and industry, and to improve the transparency of decision making are essential for building trust in the involved actors.

Monitor and implementation of strategies beyond political cycles: The influence of political cycles on governance has been highlighted by several stakeholders as another obstacle to maintaining a strategic vision towards the development of an equitable lithium supply. The lack of political stability, economic issues and conflicts between different actors tend to be responsible for the lack of a unified vision for the lithium sector in both countries. Initiatives set up in the past, were abandoned or not implemented at that time. In some cases, they were revisited, but afterwards the country has taken different directions and actions. For example, in Chile in 2014, President Michelle Bachelet created the National Lithium Commission (NLC), which had the objective to reform the national policy on lithium governance so that sustainable development becomes a core part of it. The NLC recommended the creation of a lithium company and state involvement, which was subsequently abandoned by the following government, and they focused on public-private partnerships (Perotti and Coviello 2015). In Argentina, under the Mauricio Macri presidency (2015-2019), the National Mining Plan was established, which had specific focus on lithium constituting the equivalent of a National Lithium Strategy (Gutiérrez & Ruiz-León, 2024). However, this was not fully delivered as the next administration had different political priorities. The Milei government, elected in December 2023, has adopted a free-market approach and has instigated Incentive Regime for Large Investments or RIGI to attract foreign investment to Argentina. Changes in governance frameworks tend to complicate project development, prolong their timeline, discourage investors and blur the direction of drive required towards sustainability.

2.6.3 Recommendations & Research Priorities

- Equitable and transparent distribution of revenues
- Ongoing consultation and participatory processes (e.g. experts, IP etc)
- Institutional strengthening - critical mass of capacity with the right skills
- Optimised processes and systems (e.g. digitisation) to reduce bureaucracy and time delays
- Stakeholder mapping - power balance to be considered
- Cross intra-government collaboration to improve governance
- Improved legal frameworks/ fit-for-purpose
- Improving transparency in decision making processes

2.7 SOCIAL ASPECTS

2.7.1 Background

Given the potential importance of social aspects related to lithium brine production, this is reflected in the number of studies have been undertaken to define the overall challenges related to this topic. In Chile, the main issues are seen as labour rights, employment, social tensions, Corporate Social Responsibility (CSR) activities and water (Liu & Agusdinata, 2020). Examining the literature for both international scientific sources and organisations local to Argentina shows that water and socio-economic concerns, new technologies and social economic aspects including sociotechnical development, employment and human rights are seen as important issues (Díaz Paz *et al*., 2023). More widely, research issues have been identified as: baseline water data, wildlife / ecosystem, knowledge asymmetry, impact assessments and the improving the conceptual framework on impact (Agusdinata *et al*., 2018).

Whilst there are similarities over the region between salars, where studies exist, there are some significant regional differences. Given the complexity of the system both in terms of the natural and human / societal aspects, then this isn't perhaps surprising. In Chile, water rights can be traded in a market environment (Jerez *et al*., 2021), which is very different from the situation in Argentina. Further, there is significant number of studies have been focussed on the Salar de Atacama, e.g. Jerez *et al*. (2021). Given the length of development / operations and the complexities of the social situation, this is understandable. It is always worth considering how studies undertaken in Atacama is relevant to other settings given its unique features, such as lower rainfall, lower elevation, and longevity of production solely based on EPs. For Argentina, then studies have been report for the Salar del Hombre Muerto, with an example of Rio Trapiche and the reaction to the diversion of water drying up related wetland or vega (Escosteguy *et al*., 2024).

In Argentina, at a national level there are 39 indigenous peoples and more than 1,500 communities. The provinces of Salta, Jujuy and Catamarca have 509 communities with a predominance of indigenous groups Kolla (Jujuy and Salta) and Atacamas (Salta) (Argento & Puente, 2019). There are ten different Indigenous groups in Chile. The largest one is the Mapuche, followed by the Aymara, the Diaguita, the Lickanantay, and the Quechua peoples and includes the Atacameñas [5]. In Atacama Comunidades Atacameñas are indigenous organisations legally constituted. They are in charge of the administration of their territory. Each Comunidad Atacameña is part of the Consejo de Pueblos Atacameños (CPA), as the main organisational body for collectively representing the Atacama's indigenous people.

2.7.2 Summary of Challenges & Opportunities

Opportunities: There is an increasing recognition of the importance of social issues and the willingness of many parties to engage with more open forms of communication. In particular, there is a requirement built into legislation for participation and engagement with the local population. The indigenous peoples (IPs) are empowered to engage with decision-making process and that there are examples where IPs are included in a meaningful way in decision-making process. Alongside there is access to data and information albeit tempered by the ability to interpret these fully. Finally, there is a recognition that jobs, development and training are being offered to both local communities and nationally.

The future can be seen as moving from conflict (Extractivism) to consultation which in itself is not enough and can be seen as a box ticking exercise if real changes are not adopted by the operator. There is a recognition of the need for a considered approach to stakeholder interaction and the ability to make real changes to any mining operation and its environmental and social impact have the potential to reduced confrontation. The use of political ecology and energy justice frameworks can help with this process by providing a more comprehensive understanding of the situation and how effective changes can be implemented (Escosteguy *et al*., 2024).

Stakeholder interactions / conflict: At the heart of social challenges appears to be the relationship between local stakeholders, i.e. Indigenous Peoples (IPs) and the mining companies

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[5] Chile | Indigenous Navigator

/ operators. Local protests by IPs is often in stark contrast to the "slick" corporate campaigns related to CSR and the companies. Further, there is a general fear related to the protests given the history of Human Rights abuses elsewhere in South America, in particular, related to IPs (Lunde Seefeldt, 2022).

But deployment of Free Prior and Informed Consent (FPIC) is seen as not being as widespread as perhaps it should be (Lunde Seefeldt, 2022). Conflict over water is often related to perception of high water consumption of lithium mining (Díaz Paz *et al*., 2023). Commodification of water and lack of access to traditional water rights by local stakeholders, e.g. IPs can amplify the conflict (Jerez *et al*., 2021). Conflict can be exacerbated by the perception of an imbalance due to the global north creating a demand for materials from the global south to achieve the energy transition (Jerez *et al*., 2021).

Over the past years, the mining activities in the Atacama salt flat and the surrounding communities had different phases of conflicts and negotiation processes (Gundermann & Göbel, 2018) argue that the socio-environmental conflict in this region is not as a one-sided constant resistance but the alternance of differing periods of open conflict mixed with periods of dialogue and agreements. According to (Gundermann & Göbel, 2018) the manifestation of this protest in the Atacama salt flat can be more rhetoric than practical and it is linked to the community social licence for mining operations. However, there are interesting examples of how the socioenvironmental conflicts disputes were handled. For instance, in the case of Empresa Minera La Escondida (EMEL), a self-managed development fund was stablished and agreements of direct income transfers to the community of Peine, Atacama. For Argentina, in terms of socioenvironmental conflicts, there are different degrees of opposition/acceptance to lithium mining. The three provinces show striking variations in terms of how the mining projects articulate with local people and organisations, in particular indigenous communities (Gonzalez & Snyder, 2020). In terms of the resistance arguments, they range from territorial claims and the previous and informed consultation process to environmental issues (water, biodiversity, flamingos) and other laws (e.g.Ley de Glaciares and Ramsar sites (understood as wetlands of international importance designated under the Ramsar Convention) (Argento & Puente, 2019).

Justice and equality: The global need for lithium to decarbonise and its occurrence in the Lithium Triangle, in particular Chile, results in a pressure to increase production. One of the main and recurring themes of the workshops is justice and inequality: justice in terms of the environment and its use alongside lack of a level playing field related to all stakeholders to have a voice and the ability to make decisions (power), access to information and wealth. The overall perception of mining in Chile and Argentina is negative, particularly amongst the urban middle classes and rural poor located close to mining activities.

Both the geography of Argentina and Chile (north-south elongated countries) and the governance approach (regional / federal structure) leads to tension between central and local government. There are complexities within the relationship between the central government and the regions, either through the provincial structures in Argentina or through the distance involved from the capital such as the northern territories in Chile. There are also communication challenges which result in the lack of trust developing between institutional stakeholders and those with less power such as NGOs and IPs. There are also difficulties related to conflicts and their management. In general, it is recognised that there is lack of true dialogue leading to change.

Impact of mining and inequalities: Conflict related to mining may be driven by inequalities : how the benefits are distributed, where negative impacts occur and how it affects social, economic and cultural rights (Escosteguy *et al*., 2024). Mining itself is seen as a controversial activity, but it is recognised it brings benefits and a nuanced position is required. Tension between pastoralism (traditional farming) and mining jobs and the pros and cons of both are considered by the local community rather than a straight choice (Escosteguy *et al*., 2024). Differences of behaviour or postering between protesting at open events and more constructive discussions taking place at closed meetings can occur, i.e. "*No a la minera*" more likely to be heard in public forum like conferences. This demonstrates how the differing forum will promote different narratives about mining and its acceptance by communities in which it is undertaken. Locally, mining-based developments are seen as providing access to benefits : jobs and better working conditions, access to basic services and infrastructure development (Escosteguy *et al*., 2024).

Challenges were identified related to labour supply as well as local developments, in particular, those related to infrastructure benefiting local population more generally. There was a recognition that, for example, the requirement to recruit staff from within the country whilst having good intentions places significant pressure on local labour markets.

Openness / communication: In Chile, the definition of brines is related very much to a mining perspective, it is a mineral and, therefore, can be abstracted in arid regions which are water stressed (Flores Fernández & Alba, 2023). This further exacerbates the potential conflict as water rights are seen as being important to IPs, particularly those located close to salars, to provide for their basic needs and, importantly, brines themselves can be viewed as a sacred entity (Lunde Seefeldt, 2022).

Communication of information related to water / environmental issues is seen as an important way of reducing local conflict (Escosteguy *et al*., 2024). In terms of data related to environmental issues, whilst it is available, the understanding and interpretation for a range of non-scientific audiences is limited (Lunde Seefeldt, 2022).

2.7.3 Recommendations and research priorities

- Effective communication between different types of stakeholders (e.g. industry and civil society) on progress, challenges, scientific evidence and other
- Law enforcement and implementation of existing governance frameworks to promote social participation
- Capturing disputes and transparency in processes dealing with them (feedback loops)
- Developing communities and managing demands for resources, infrastructure etc (better holistic approach is required)
- Improve participatory processes
- On the job training - not just from the private sector

2.8 STANDARDS AND CERTIFICATION PROCESSES FOR RESPONSIBLE LITHIUM

2.8.1 Background

A wide range of standards, frameworks and certification processes have emerged that provide auditing and assessment of mining project on sustainable development, responsible supply and environmental, social and governance (ESG) challenges. Whilst this is seen as positive and has raised the profile of sustainability in mining as well as the expectations that governments, communities and supply chains have on mining operations, the plethora of standards with divergent processes and objectives has also created confusion, administrative burden and dilemmas about their effectiveness. Available standards are produced by both private and international organisations and in most cases, they aim to assess the sustainability of single projects. Their adoption varies widely across the mining sector, and their implementation and enforcement can be challenging. In the lithium sector in Chile and Argentina, concerns around sustainability and ESG issues have been highlighted by several authors (Petavratzi *et al* 2023; Escosteguy *et al* 2024; Murguia & Bastida 2024) and they are a key component of national legislation (Government of Chile 2023) (see governance section above), but also operating companies who are seeking to achieve certification through various schemes. For example, in 2023 both Albemarle and SQM in Chile have completed an audit with the Initiative for Responsible Mining Assurance (IRMA) standard for responsible mining (IRMA 2023a; IRMA 2023b). Given that the lithium sector is evolving rapidly, and the development and use of standards is essential for avoiding trade-offs between stages in the value chain. Their development, use and enforcement however should respond to existing challenges, be coordinated and tailored, and provide outcomes that can push the sector towards the right direction.

2.8.2 Summary of Challenges & Opportunities

Mining activities, if not designed and managed from the early stages of exploration with sustainability in mind, can cause adverse social and environmental impacts Over the recent past multiple standards and certification schemes have developed to assess the sustainability of mining projects and to undertake due diligence for identifying environmental, social and governance risks that may inhibit responsible supply (Kramarz 2021). The proliferation of due diligence and sustainability standards provide **opportunities** for identifying challenges early in the process, which can promote environmental protection, avoidance of social conflicts and deliver responsible sourced lithium. Examples of such standards are shown in Table 3.

Initiative	Responsible organisation	Produced by
OECD Due Diligence for responsible Mineral Supply Chain	OECD	International organisation
Initiative for Responsible Mining Assurance (IRMA)	IRMA	Private sector
Responsible Minerals Initiative	Responsible Business Alliance (RBA)	Private sector (industry coalition)
LME approach to responsible sourcing	London Metal Exchange	Private sector
Sustainability Accounting standards (SASB)	IFRS Foundation	Not-for-profit organisation
Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains	China Chamber of Commerce of Metals, Minerals and Chemicals Importers & Exporters (CCCMC) in collaboration with OECD	Not-for-profit
IFC Performance Standards on Environmental and Social Sustainability	International Finance Corporation (IFC) part of World Bank	International organisation
Towards Sustainable Mining (TSM)	Mining Association of Canada (adopted by Cámara Argentina de Empresarios Mineros (CAEM))	Private – industry association
ISO TC333/ Lithium	International Organisation for standardisation	International organisation
ICMM Sustainable Development Framework	International Council on Mining and Metals (ICMM)	International – industry association
CERA 4in1 certification scheme	DMT Group	Private sector
United Nations Resource Management System (UNRMS)	UNECE	International organisation
Global Reporting Initiative (GRI)	GRI	International non-governmental organisation
Ecovadis sustainability rating for global supply chains	Ecovadis	Private sector
Strategic Environmental and Social Assessment	World Bank	International organisation

Table 3. Examples of sustainability standards

The energy transition has been linked with inequalities and injustices associated with the extraction of lithium brines. This is because our systemic understanding of the social, economic and environmental impacts within rapidly evolving supply chains is poor. The proliferation of various sustainability standards and certification schemes has been advantageous for the mining and minerals sectors including the lithium market, as they raised awareness globally about environmental, social and governance issues that may relate to the lithium extraction sector. In addition, operators have taken them seriously and followed up routes to assessment, release of sustainability information and certification. For example, SQM in Chile they have been releasing sustainability reports following the Global Reporting Initiative (GRI) principles, which also include the SASB indicators report, and they have been involved in a range of sustainability certification schemes including IRMA, the Dow Jones Sustainability Index, Ecovadis sustainability ratings and others (SQM 2022). Other operators, such as Albemarle (Albemarle 2024) and Arcadium Lithium (Arcadium Lithium 2024) have followed similar strategies with certification undertaken with at least one organisation.

The plethora of sustainability standards and certification schemes despite being generally positive, they also come with challenges and questions about their suitability for the lithium brines sector. Some of the key challenges identified include:

Which standard and for what purpose? Currently, it is difficult to navigate through the various standards, their purpose, focus and assessment process, and their relevance to the sustainability questions associated with lithium brines. Typically, they are corporately orientated and are not designed to deal with the full range of challenges posed by the situation, e.g. (Obaya *et al*., 2024). Operators committed to sustainable development have allocated resources to exploring several of them, so that they can showcase their credentials, but also to identify potential issues within their operations that require addressing. The independent view of their projects is positive, but the question as to whether these standards are fit-for-purpose remains unanswered. A move towards interoperability and harmonisation of the many standards available would be highly beneficial, as it would allow for a common terminology and aligned methodological procedures reducing some of the heterogeneity seen at present.

Whilst the various sustainability standards can help companies to meet their own sustainability goals, protect their brand, engage with local communities and communicate better their practices to multiple stakeholders, they cannot resolve systemic issues that are inherently complex (Franken and Kikler 2017; Franken 2019). One of the most important issues with assessing the sustainability and environmental impact of lithium brine abstraction is the scale of the assessment. The co-location of lithium brines projects within a single salar (e.g. Atacama or Hombre Muerto) demands for the identification and quantification of interdependencies and cumulative impacts associated with multiple operations at the basin scale. This would require several operators working side by side and providing data to an independent body, so that cumulative environmental impacts can be quantified. Basin scale modelling of salars and brine abstraction is still lacking and therefore current certifications schemes are unlikely to provide a proper rating.

Implementation of standards and enforcement of recommendations – alignment with national governance frameworks: Although some of the producing companies can undertake independent assessments and try to implement the recommendations provided by certification schemes, unfortunately this is not the case for the wider lithium sector and the many exploration projects developing in Argentina and Chile. Ideally, sustainability should be an integral part of a mining project in development, but the cost and resource implications are often significant for projects in early exploration stages. However, the exclusion of sustainability and ESG reporting may inhibit its development and timeline. Currently there is no legal requirement for any of these standards to be used, neither any enforcement following sustainable development principles. The voluntary adoption of them is not, however, sufficient for ensuring environmental and social protection. Implementation and enforcement have an important role to play, and they would require the reform of national governance frameworks to account for their inclusion, but also to enable enforcement and ongoing monitoring. Standards cannot replace national regulatory frameworks nor substitute for the government’s role in ensuring sustainable development. They can, however, work side-by-side and complement the role of national government in developing a sustainability strategy for lithium. Data, information and recommendations outlined in these schemes can provide important insights into issues e.g. environmental impacts that can help governments to develop and adapt their policy and legislation.

2.8.3 Recommendations for Research Priorities

- Monitoring of standards and their applicability to lithium brines to avoid unnecessary proliferation and bad practice.
- Harmonisation and interoperability of standards to ensure common terminology and alignment between different schemes.
- Good practice guidance based on existing industry (e.g. technical standards tailored to Li brines)
- Resource and reserves reporting standards for lithium brines. This aspect is still lagging behind, but it is critical for considering the economic lithium brine resources at basin level and with sustainability in mind.
- Implementation of sustainability frameworks such as Strategic Environmental and Social Assessment (SESA) and the UN Resource Management System (UNRMS).

2.9 GLOBAL LITHIUM MARKET AND ECONOMICS

2.9.1 Background

Lithium demand is driven by the electrification transition and the use of lithium-ion batteries (LIB) in electric vehicles (EV) and energy storage systems. The forecasts for lithium demand suggest exponential growth across various different scenarios and projections produced (IEA, 2024). For example, the IEA suggests that total lithium demand for all uses will be between 471kt and 705kt of lithium by 2030 and between 1196kt and 1728kt by 2050 (IEA, 2024). The global lithium production in 2022 was around 149kt of lithium (BGS, 2024), so unless new supply comes to on-stream over the next few years, then the lithium market may operate under significant pressures, with a deficit being very likely.

The high demand projections are beneficial for the lithium sector as they provide new opportunities for development. However, several interconnected and complex challenges exist, such as price volatility, supply chain bottlenecks, geopolitical tensions, which could increase supply risk and slow the pace of the energy transition.

Chile and Argentina, with their rich lithium resource base, have a major role to play in lithium supply and there is significant industry activity in the region. Multiple new projects are in development and producing projects are scaling up. However, the dynamic landscape in the global lithium and LIB markets influence these projects and their future success is uncertain.

2.9.2 Summary of Challenges & Opportunities

The **opportunity** for the lithium sector in Chile and Argentina arises from the global objective to decarbonise our economies, in which the use of battery systems and specifically LIB play a major role. Lithium supply shortages are estimated in the near future (before 2030) (Shan, L. Y. 2024), therefore new supply would be essential to meet projected demand. The global lithium market economic landscape is very positive. It is estimated that revenues from the rapid expansion of the LIB value chain will increase from about $85 billion in 2022 to over $400 billion in 2030, where mining is likely to have a share of 9% in these revenues (about $34 billion in 2030 compared to $8 billion in 2022) (McKinsey & Company and Global Battery Alliance 2023). The increase in spending on lithium mining was considerable in 2022, for example, a 50% rise has been recorded in 2022 compared to the previous year. Exploration activity for lithium projects has also been strong with a spending increase by 90% in 2022 compared to the previous year, whilst there has been several major merging and acquisition activities, for example the merger between Livent and Alkem ($10.6 million) and the acquisition by Rio Tinto of the Rincon Lithium Project ($ 825 million) (IEA, 2024). Finally, in an attempt to secure lithium supply, the downstream sector (automakers and battery cell manufacturers) is getting more involved in the Tier 4 (raw material supply) value chain through long-term offtake agreements and direct investment activities. A noticeable example includes the General Motors investment in Lithium Americas (Thacker Pass project) and the “Responsible Lithium Partnership” project initiated in 2021 by BASF, the Mercedes-Benz Group AG, BMW Group, Daimler Truck AG, Fairphone and the Volkswagen Group to develop a common framework in collaboration with local stakeholders for the responsible and sustainable management of lithium mining in Salar de Atacama, Chile. All the above provide evidence of the global interest in lithium mining and commitment to grow the sector to meet the decarbonisation targets.

Despite the strong demand projections and increased activity (e.g. on exploration, new investment), challenges remain and their impact on the lithium sector in Argentina and Chile can be detrimental. The key **challenges** identified are:

Supply chain development timescales: The different elements of the supply chain need to develop in parallel, to form a coherent ecosystem that permits the timely flow of adequate quantities of raw materials into battery manufacturing. The challenge is that development timescales in the mining sector are traditionally much slower than the pace of change that is being observed in the LIB industry and the EV value chain. For example, the timeline for developing the Tier 4-raw material supply chain in the EV value chain may take 20 years, compared to Tier 1 to 3- downstream EV supply chain, which is around 10 years (Petavratzi & Gunn 2023). Conflicting messages sent to the lithium sector about long-term demand, for example, due to the rise of alternative battery technologies, the role of recycling in supply, or environmental, social, governance (ESG) and security of supply issues, result in increased uncertainty in the lithium market outlook, unfavourable investment conditions and prolonged timelines for new mining projects to emerge. The implication of the latter is increased risk for new mining projects reaching the production stage on time and the likely deficit in future lithium supply.

Price volatility in the lithium market: The lithium market has seen significant price volatility over the past 3 years (Figure 5). This is influenced by several factors, including demand and supply imbalances, changes in national regulations, new mining projects, ESG factors and many more. The lithium price has dropped considerably in 2023, since 2022. The price volatility is attributed to additional supply becoming available from stocks in China and increase in supply primarily from existing operators (IEA, 2024). The lithium price volatility impacts investors' confidence and therefore the diversification of lithium supply may become challenging. The recent drop in lithium prices has managed to reduce the battery price but has also reduced the rate of investment in new projects in 2023 compared to 2022. However, an overall rise in investment in lithium mineral supply (mining, refining) is still present despite the low prices (IEA, 2024). The impact of high price volatility can be significant for junior companies that are in early stages of exploration as they are trying to prove the economic viability of their project. However, producing mines and advanced exploration projects are likely to be less impacted by current prices because the long-term projections of the lithium market remain strong.

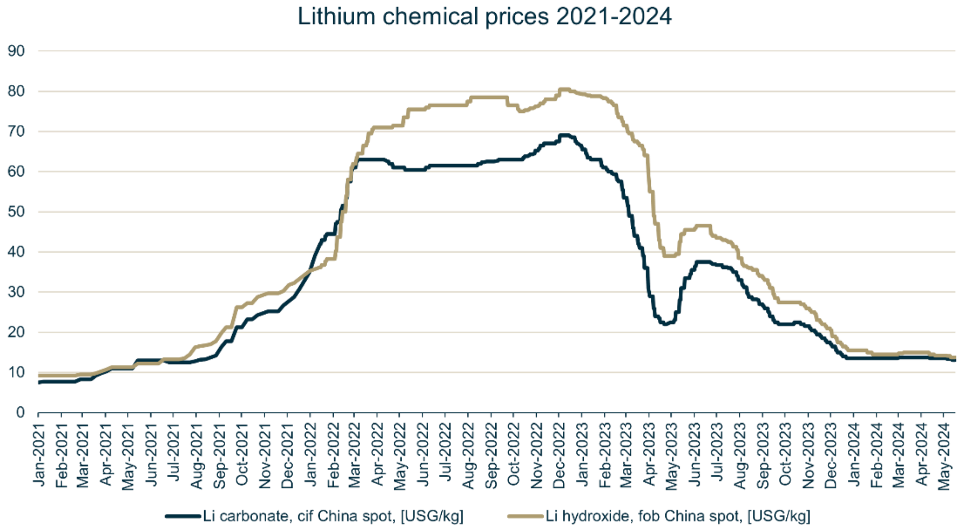


Figure 5. Lithium chemical prices 2021-2024, data from Argus Media (www.argusmedia.com).

Responsible and secure supply of lithium: The importance of responsible, sustainable and secure lithium supply has increased over the years. This is driven by investors and OEMs who are interested in understanding and quantifying the environmental, social and governance impacts of project they invest into and supply chains they operate, but also from global instruments such as the sustainable development goals (SDGs), which aim to improve the sustainability in raw materials supply chains and in the locations that mining activity takes place. Despite the drive for change, significant unquantified challenges and risks associated with the sustainable and responsible supply of lithium exist, for which resolution can only be achieved through in-depth, holistic investigations and identification of impacts. However, developments such as the EU Battery Regulation (2023) provide an ambitious framework that seeks to provide transparency and higher standards for critical minerals in Li-ion batteries.

Complex global interactions landscape: Rising lithium demand has result to global competition for access to resources and geopolitical tensions (Sanchez-Lopez 2023). These become apparent both in lithium producing countries, for example the nationalisation of lithium resources in Chile and in consuming countries, which try to ensure security of raw materials supply through national instruments, such as the Inflation Reduction Act in the United States, or the Critical Raw Materials Act int the European Union. Both are seen as protectionist activities that influence the future of the lithium market. The role of China in the lithium value chain should not be underestimated, as they secure the majority of lithium raw materials, and they actively invest into new mining and refining projects. They hold the largest refining capacity globally, and they are vertically integrated to establish themselves as the primary producer of lithium-ion batteries. It is therefore the supply chain concentration and uneven distribution of lithium raw materials supplied from China that often leads to geopolitical challenges.

Global capacity for lithium conversion and refining: Even if lithium mining supply increases, the development of new conversion capacity to turn lithium brine to compounds, such as lithium carbonate and lithium hydroxide is essential. The differentiation between battery grade and non-battery grade compounds should be highlighted. While some lithium brine assets can produce battery grade lithium compounds, this is not the case for all (BM Review 2024). This is due to the physical and chemical properties of the lithium brine, which varies considerably between salt flats, but also the processing and concentration approaches. The use of direct lithium extraction is expected to increase the quantity of material produced that falls into the battery grade category, but this is still only operational at pilot scale. Existing upgraded refining capacity to convert non-battery grade material to battery grade is currently monopolised by China. There are a lot of technical complexities with upscaling conversion and refining capacity, and these are not often taken into account in lithium supply forecasts, so the likelihood that battery grade lithium supply is overestimated is significant.

2.9.3 Recommendations & Research Priorities

- Ongoing monitoring of the global lithium value chain, including ESG trends, economic value, geopolitical factor to inform effective decision making at local, national and global levels.
- Development of forecasts and scenario analysis to estimate the future lithium market
- Introduction of instruments that can improve economic resilience and attract new investment.
- Developing opportunities for domestic midstream and downstream value chains to add value to lithium resources.

3 Research Roadmap

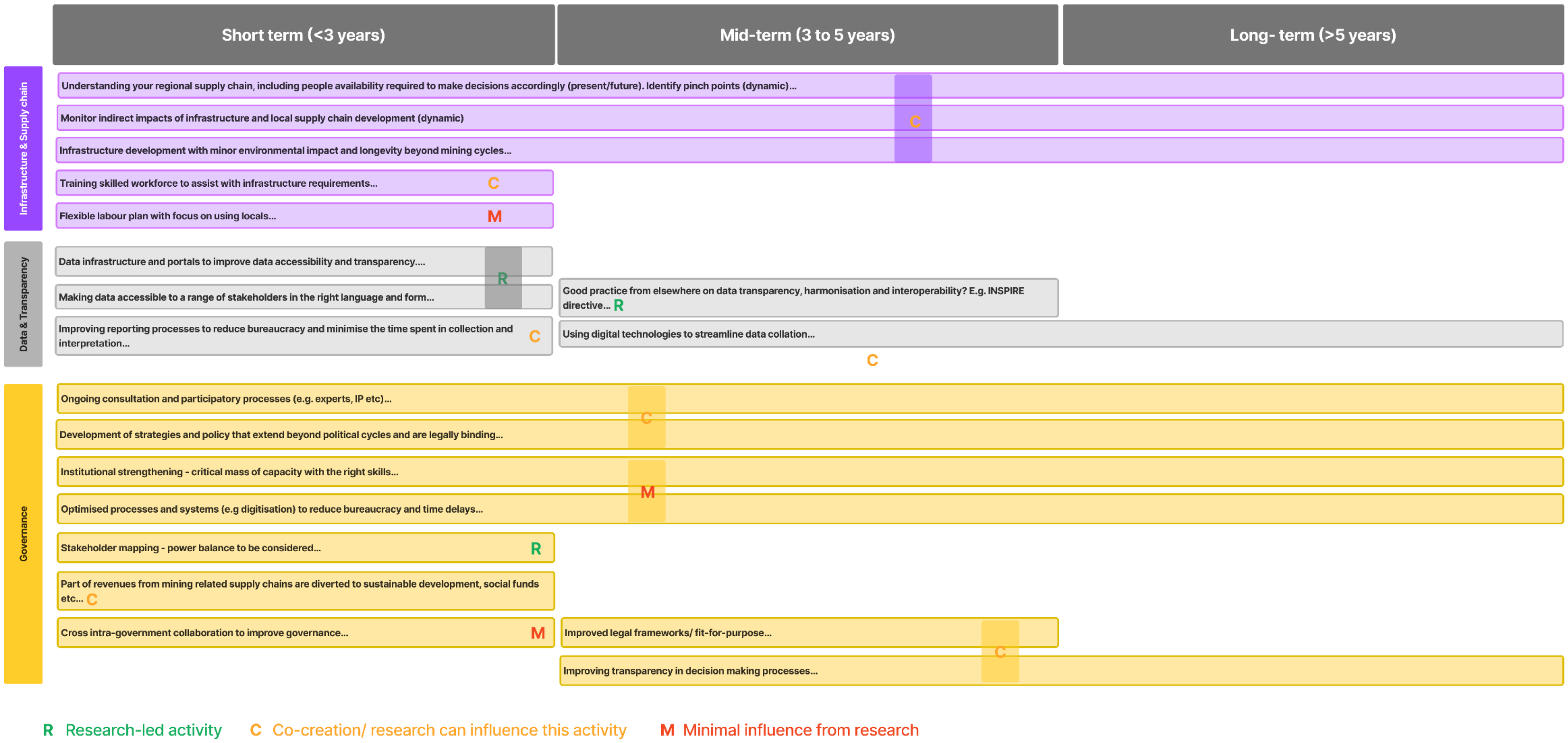
3.1 PRIORITIES AND TIMESCALES

The nine themes identified above and the recommendations listed at the end of each section have been collected and presented in Table 4. The themes have been reordered by scale in order to start from the local scale (the salar itself) and widen to the global supply chains and associated markets. The activities have been ordered by timescale with the most urgent ones given the priority.

Three timescales have been considered from short (less than 3 years), mid-term (3-5 years) and long term (greater than 5 years). There are a number of activities that need to be started as soon as possible and continued such as on-going development of salar conceptual models along with feeding back new understanding into the research community and operators. However, work on the longer time-scale activities should not be neglected to ensure that progress on meeting the overall challenges still occurs. Further, there is a need to reassess the periodic situation as it is a dynamic, fast-changing one and proposed activities will solve some problems but also identify gaps that need to be addressed

	Short term (<3 years)	Mid-term (3 to 5 years)	Long- term (>5 years)
Salar Processes	Development of agreed conceptual model R	Ongoing development of conceptual model R	
	Geological and hydrogeological understanding R	Understanding of lithium 3D distribution and changes with time Microbiological and geochemical processes Vertical heterogeneity and lithium dilution over time due to inputs and outputs Development of integrated understanding and simulation of laguna processes Understanding impact of other riparian users on watershed Quantification of recharge processes R	Ongoing research to cover gaps identified in mid-term activities R
Environmental Challenges	Ongoing monitoring of environmental impacts with life cycle thinking (with capacity building and people/ data to enable this)... C		
	Monitoring baseline (development of schemes in pristine areas/ existing techniques with novel techniques e.g earth observation)... C		
	Reinjection - how to use effectively to minimise environmental impacts R		
	Assessing the impact of wellfield and key environmental receptors R		
		Assessing cumulative impacts... R	Integration of findings into new environmental regulation and policy and integration with mining regulation C
		Quantification of waste and opportunities for valorisation... R	
		Develop mine closure plans and assess potential impacts/ rehabilitation options... C	
		Producing good practice based on other schemes e.g. EU water framework directive... C	
New technologies for Li extraction & processing	Dynamic technology roadmap for Li extraction and processing... C		
	Green energy for lithium extraction (e.g. PV opportunities)... M		
	DLE understanding and assessment of environmental impacts; transparency of information on DLE... R		
	DLE pilot testing facility for research and development purposes... C		
		Investigate opportunities for recovering co-and by-products C	
			Horizon scanning for new technologies in brine extraction and processing R

R Research-led activity C Co-creation/ research can influence this activity M Minimal influence from research



Short term (<3 years)
Mid-term (3 to 5 years)
Long- term (>5 years)
Infrastructure & Supply chain
Understanding your regional supply chain, including people availability required to make decisions accordingly (present/future). Identify pinch points (dynamic)...
Monitor indirect impacts of infrastructure and local supply chain development (dynamic)
Infrastructure development with minor environmental impact and longevity beyond mining cycles...
C
Training skilled workforce to assist with infrastructure requirements... C
Flexible labour plan with focus on using locals... M
Data & Transparency
Data infrastructure and portals to improve data accessibility and transparency....
Making data accessible to a range of stakeholders in the right language and form...
R
Good practice from elsewhere on data transparency, harmonisation and interoperability? E.g. INSPIRE directive... R
Improving reporting processes to reduce bureaucracy and minimise the time spent in collection and interpretation... C
Using digital technologies to streamline data collation...
C
Governance
Ongoing consultation and participatory processes (e.g. experts, IP etc)...
Development of strategies and policy that extend beyond political cycles and are legally binding...
C
Institutional strengthening - critical mass of capacity with the right skills...
Optimised processes and systems (e.g digitisation) to reduce bureaucracy and time delays...
M
Stakeholder mapping - power balance to be considered... R
Part of revenues from mining related supply chains are diverted to sustainable development, social funds etc... C
Cross intra-government collaboration to improve governance... M
Improved legal frameworks/ fit-for-purpose...
Improving transparency in decision making processes...
C
R Research-led activity
C Co-creation/ research can influence this activity
M Minimal influence from research

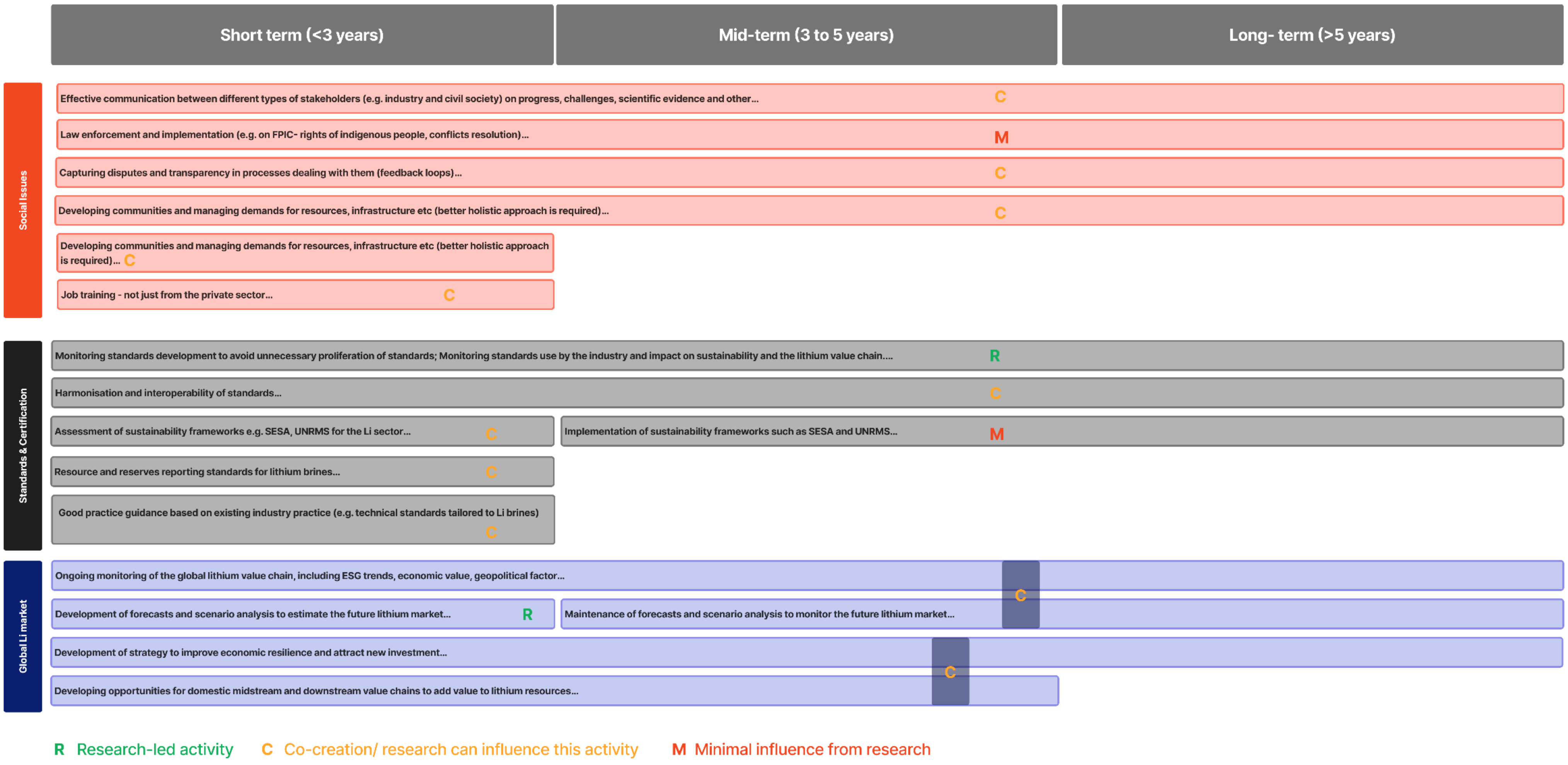


Table 4. Summary of research roadmap for the short, medium and long-term

3.2 POTENTIAL SOURCES OF FUNDING

There are many potential funders which regularly release relevant calls or could be approached to design specific ones. The aim would be to address the research challenges detailed in this report by bidding into existing calls or to present to organisations to influence their funding calls. Given the global nature of the challenges then both country specific calls as well as international collaboratively-based funding should be considered. This will enable organisations in their own country to develop programmes of work as well as collaborative programmes linking groups of organisations around the world.

It is anticipated that this roadmap will be useful to all partners to enable them to seek funding with their own consortium and from their own funding bodies that they are eligible. Further, a method of keeping track of potential funding should be sought.

The following sections list the main funding sources currently identified.

3.2.1 Regional: Chile / Argentina

- Funding from national bodies such as CONICET
- Mercosur countries and links to external funding
- Regional banks such as the Inter-American Development Bank (IADB / BID)
- Industry bodies and their members
- Operators who are exploiting the salars as part of their R&D spend
- Others as appropriate

3.2.2 UK-led

- UK Government departments: FCDO, DSIT, Defra
- UK Research and Innovation including BGS' parent body NERC
- Royal Society grants or similar
- Industry bodies and their members
- Operators who are based in the UK or have offices here
- Others as appropriate

3.2.3 International

There are several funding bodies who operate at a global scale and that could allow consortium of international organisations to bid for larger-scale projects, which include:

- Horizon programme (EU)
- Belmont Forum
- World Bank
- Gates Foundation
- Others as appropriate

4 Conclusions and next steps

Given the need for a rapid expansion of lithium production in a responsibility sourced manner to meet the energy transition, then work to develop a research roadmap to meet these requirements has been undertaken. To achieve this, a series of workshops have been undertaken in Argentina and Chile using a PESTLE analysis (Political, Economic, Social, Technical, Legal and Environmental) as their basis. The results from six workshops held in Buenos Aires, Salta, Santiago and Copiapó have been collated and analysed. The PESTLE analysis identified a series of "enablers" and "blockers" for each of the areas and nine themes have been identified emerging from this analysis:

1. Salar processes
2. Environmental challenges
3. New technologies for Li production
4. Infrastructure, supply chains and development
5. Data & Transparency
6. Governance
7. Social issues
8. Standards & Certification
9. Global Li market

For each of the themes then recommendations as to how to address the "blockers" have been made. These recommendations have been related to three timescales: short (<3 years), mid-term (3-5 years) and long-term (>5) years and research priorities have been identified based on these recommendations and funding sources suggested.

4.1 IMMEDIATE NEXT STEPS

Given the urgency for lithium and the short time scales needed to meet the demands of the energy transition, we have summarised the short-term (<3 year) priorities (see Figure 6). The rapidly changing landscape means that these activities are the foundation on which the rest of the research roadmap can be built upon. We have aimed to portray the issues starting from the scale of the salar itself and up through country scale to the global markets. The issues are presented in Figure 6 and are outlined in the following text. Whilst not all the suggested activities are research-based, many of them require joint working / co-creation between the stakeholders involved and researchers.

Further, no one organisation can take on these tasks and provide the outcomes required. Given the number of stakeholders involved and the complexity of the proposed activities then a combination of regional (South American) and international organisations are required to work together. An example would be the assessment of Direct Lithium Extraction alongside reinjection (DLE/R) which would require a range of organisations from different disciplines such as engineers, environmental specialists, geologists, hydrologists and hydrogeologists working alongside social scientists. Likewise for participatory processes which require a combination of different stakeholders including IPs working alongside social and biophysical scientists in conjunction with government organisations and industry partners.

Salar processes require a fundamental scientific understanding and the data on which to build this is still lacking. Developing this understanding along with a salars observatory for the region alongside the international community is, therefore, required. The environmental challenge related to wellfield operation and the impact on key environmental receptors needs to be established. New technology such as DLE/R or Direct Lithium Extraction, used in combination with reinjection requires understanding and investigation. A technology roadmap would enable the novel lithium processing techniques to be characterised and understood. A pilot facility for DLE in the region available to researchers from various organisations to assess different technologies would be beneficial.

Infrastructure that is fit for purpose for development of multiple operations is key, along with developing shared infrastructure in collaboration with local communities to facilitate production whilst ensuring the least environmental harm and maximum benefit. An understanding of local supply chains would enable current facilities to be determined and gaps to be identified. A holistic view of data and information availability is required. By bringing together different sources and making them available to stakeholders with different backgrounds and scientific training has the potential to reduce conflict as well as facilitating access to information in an efficient manner. This would be combined with enabling all stakeholders to view the available information in a form that's appropriate to their background and training.

Stakeholder mapping needs to be undertaken, ensuring that the interactions between stakeholders are understood and their power balance characterised. This enables consultation and participatory processes to be developed that are fit for purpose. To reduce social conflict, participatory processes need to be put in place, and measures implemented to reduce disputes and increase transparency in the decision-making process. To address the potential skills gaps in the mining sector, then “on the job” training across a range of organisations needs to be enhanced.

Ensuring that good practice for standards and certifications are disseminated, including development of resources and reserves estimations for lithium brines, is important. Assessment of existing sustainability frameworks is required to identify the ones that are fit-for-purpose as well as a need to have a watching brief kept on standards and certification schemes to avoid unnecessary proliferation and duplication. Further, it is necessary that interoperability of standards and their joint use is possible.

It is important that an overview of the lithium market, enabling tracking of lithium prices and mass balance to provide feedback on supply/demand balance is maintained and made easily available. This will ensure that an understanding of market volatility is available to all the relevant decision-makers, enhancing investment stability. Developing an understanding of the global value chain and identifying where opportunities exist for mid-stream activities (between mineral operators and battery producers) exists thus facilitating technology development and manufacturing growth in the region is required.

Figure 6. Short-term research priorities to support responsible lithium supply.

To meet these challenges then potential funding sources have been identified in South America (regional), UK and internationally:

Regional	UK-led	International
• Funding from national bodies such as CONICET • Mercosur countries and links to external funding • Regional banks such as the Inter-American Development Bank (IADB / BID) • Industry bodies and their members • Operators who are exploiting the salars as part of their R&D spend	• UK Government departments: FCDO, DSIT, Defra • UK Research and Innovation including BGS' parent body NERC • Royal Society grants or similar • Industry bodies and their members • Operators who are based in the UK or have offices here	• Belmont Forum • World Bank • Gates Foundation

The final point to consider is the inter-connectedness and integrated nature of these challenges where progress in one area can lead to positive impacts in others. However, the reverse is also true and only by moving forward on meeting of a number of these challenges and opportunities will rapid uptake of lithium production from brines in a responsible manner be achieved.

Appendix 1 Sample agendas for events

Round table (half-day event)

Time	Activities
9.30-9.45	Welcome, Introductions, Scope of roundtable
9.45 - 10.15	Introductory presentation - Lithium mining and opportunities landscape
10.15-10.45	BGS Li work
	What are the challenges faced by the Li sector (political, economic, social, technical, legal, environmental)?
	What progress has been made to date to address these challenges?
10.45 - 12.00	How can research help address these challenges?
12.00-12.15	Wrap up
12.15-12.30	Lunch

Full day events (with PESTLE analysis)

Time	Activities
9.00-9.30	Registration & Coffee
9.30-9.45	Welcome, Introductions, Aims of the workshop
9.45 - 10.15	Keynote presentation - Lithium mining and opportunities landscape
10.15 - 10.30	Why are we here? BGS introduction
10.30 - 11.00	BGS Li work
11.00 - 11.30	Coffee break
11.30 - 12.30	Regional perspective: - Geological perspective - Social Impacts - Environmental impacts
12.30 - 13.30	Lunch
13.30-13.45	Introduction to interactive session
13.45-14.30	Interactive workshop - session 1: break out groups - PESTLE analysis
14.30-14.45	Summary of PESTLE analysis
14.45-15.15	Break
15.15-1600	Interactive workshop - session 2: prioritisation of challenges to contribute to the roadmap
16.00-16.15	Summary of prioritisation
16.15 - 16.30	Wrap up. What is next?

Appendix 2 Methods and materials

The following section describes the workshops undertaken and the methods used to draw out nine overarching themes resulting from the work. These themes are used as the basis to produce a research roadmap.

WORKSHOPS

Aims

BGS has undertaken a series of visits and workshops in the region since 2019 but the situation is dynamic and fast-changing. Therefore, the understanding developed as a result of previous projects, undertaken during the pandemic (https://link.springer.com/article/10.1007/s13563-022-00332-4), required updating.

The aim of the project and workshops is to identify challenges and develop a research roadmap to meet these. So that all organisations active in the field could use this as part of their research agenda as well as guide and aid future research efforts.

Itinerary

The workshops took place over two weeks: week 1 in Argentina (11th to 14th March) and week 2 in Chile (18th to 22nd March). For each location (Buenos Aires, Salta and Santiago) two pairs of events took place a one-day workshop with PESTLE analysis and a shorter, round table event (see Table 5). An additional workshop was held at the University of Atacama, Copiapó. These series of workshops enabled different types of stakeholders to attend the events based on their location and availability.

Day	Date	Activity	Location	Stakeholder group
Week 1 - Argentina				
Monday	11/03/2024	Academic workshop - CONICET	Buenos Aires	Academics and NGOs
Tuesday	12/03/2024	Round Table : Policy-makers (morning only)	Buenos Aires	Policy-makers
Wednesday	13/03/2024	Workshop: Operators	Salta	Operators
Thursday	14/03/2024	Round Table: Provincial Governments (morning only)	Salta	Policy-makers
Week 2 - Chile				
Monday	18/03/2024	Round Table: Policy-makers (afternoon only)	Santiago	Policy-makers and operators
Tuesday	19/03/2024	Workshop: Academics	Santiago	Policy-makers, operators and academics
Wednesday	20/03/2024	Meetings	Santiago	SERNAGEOMIN, SQM, WSP
Thursday	21/03/2024	Workshop : Academics	Copiapó	Academics and NGOs

Table 5. Itinerary for in-country workshops

Agenda

Two types of events were undertaken: a half day roundtable and full day which included a PESTLE analysis. Both types of events consisted of presentations by all parties followed by questions and discussion. Sample agendas for both types of events are provided in Appendix 1.

Attendees

A summary of the different types of organisations represented at the events are provided in Table 6 below.

Workshop	Location	Organisations represented
Academic workshop - CONICET	Buenos Aires, Argentina	Universities, CONICET Staff, NGOs, Operators
Round Table : Policy-makers (morning only)	Buenos Aires, Argentina	Ministry of Mines, Ministry of Environment, SegemAR
Workshop: Operators	Salta, Argentina	Operators, SegemAR
Round Table: Provincial Governments (morning only)	Salta, Argentina	Provincial (Salta, Catarmarca, Jujuy) government officials
Round Table: Policy-makers (afternoon only)	Santiago, Chile	Ministry of Mines, Ministry of Economics, Universities, Sernageomin, Operators
Workshop: Academics	Santiago, Chile	Ministry of Mines, Ministry of Economics, Ministry of Environment, Universities, Sernageomin
Workshop : Academics	Copiapó, Chile	Universities, NGOs, IPs, Sernageomin, Local government officials

Table 6. Summary of organisations attending the events

PESTLE ANALYSIS

As outlined above for the one-day workshops, a PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis was undertaken. During the afternoon "break-out" sessions workshop participants were split into small groups (6-8 people) and worked through each factor of the PESTLE analysis examining both "blockers" and "helpers" for each one. They then prioritised the work required to address the "blockers" or enhance the "helpers". The outcomes from this process were then presented back to all the workshop participants in a plenary session.

The results from the PESTLE analysis presented in this report combine those undertaken in four workshops : Buenos Aires, Salta, Santiago and Copiapó. They were then collated and analysed by the BGS team after they returned to the UK. The main "blockers" and "helpers" for each country were summarised and then further analysed to pull out overarching themes (see Table 2).

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