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Trade-Offs and Impact Redistribution in Lithium Extraction: Toward a Systemic Analysis of Technological Configurations in Hydrogeological Systems, with Evidence from Chile

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Abstract

Lithium has become a critical resource in the global energy transition; however, its sustainability assessment remains fragmented, as technological performance, environmental impacts, and governance dimensions are typically evaluated independently. This fragmentation constrains the understanding of systemic trade-offs and limits the recognition of sustainability as an emergent property arising from the interaction of technological, hydrogeological, and territorial configurations. This study proposes a systemic approach that conceptualizes lithium extraction technologies as interdependent configurations rather than isolated technical solutions. Based on a structured review of scientific literature and operational evidence, the analysis integrates resource efficiency, technological performance, environmental impacts, and governance dimensions to identify patterns of impact redistribution across water consumption, energy use, production efficiency, and hydrogeological stability. The findings indicate that Direct Lithium Extraction (DLE) should not be interpreted as a universally superior alternative but rather as a reconfiguration of the extraction system that reduces brine withdrawal while increasing dependence on freshwater resources, energy consumption, and uncertainties associated with reinjection processes. Furthermore, evidence from Chile demonstrates that favorable geological conditions do not necessarily translate into sustainability outcomes because of persistent water constraints and socio-environmental tensions. Overall, the sustainability of lithium extraction depends less on the characteristics of individual technologies than on the degree of alignment between technological configuration, hydrogeological conditions, and governance arrangements. These findings shift the focus of assessment from linear comparisons among technologies toward a systemic evaluation of configurations that is better suited to contexts characterized by high socio-hydrogeological complexity.

Keywords: lithium extraction; systemic analysis; trade-offs; impact redistribution; hydrogeological systems; technological configurations; socio-environmental governance

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1. Introduction

Lithium (Li) has become a strategic resource in the global energy transition owing to its essential role in energy storage systems, particularly lithium-ion batteries used in electronic devices and electric vehicles. Its low weight and high energy density have facilitated its widespread adoption in key decarbonization technologies within a context in which greenhouse gas (GHG) emission reduction and carbon neutrality have emerged as priority objectives [1,2]. In this context, global lithium demand is projected to increase by up to fivefold by 2050 [3], transforming lithium extraction into both a production challenge and a critical sustainability issue of global relevance.

Concurrently, the scientific literature related to lithium has expanded substantially over the last decade, focusing primarily on technological applications, global supply and demand dynamics, price volatility, supply-chain security, and the governance of critical minerals [4]. Nevertheless, recent reviews have identified significant gaps in sustainability-related research. Through an analysis of 395 publications, Agusdinata et al. [5] reported limited attention to water scarcity, water quality, and territorial socio-environmental impacts. Similarly, Watari et al. [6] demonstrated that many studies do not adequately integrate the social and environmental consequences associated with increasing demand or the effects of technological innovations on these impacts. Chabchoub et al. [7] further identified insufficient integration among technological performance, environmental sustainability, governance, and decision-making processes. Collectively, these findings highlight the need for more integrative and systemic frameworks for assessing lithium sustainability.

Globally, lithium is primarily extracted from two conventional sources: hard-rock deposits (spodumene) and continental brines. Whereas hard-rock extraction requires energy-intensive processing and acid leaching, brine deposits, which dominate production in South America, are exploited through solar evaporation. These geological differences give rise to extractive systems with distinct environmental and operational characteristics that have traditionally been examined separately.

In recent years, increasing attention has been directed toward unconventional lithium sources. These include brines associated with oil fields (produced water), a by-product of hydrocarbon extraction from deep geological formations, with lithium concentrations ranging from 30 to 500 mg/L in regions such as Smackover (USA), Williston, and Qianjiang (China) [8,9]. In particular, oil and gas field produced water represents a promising resource because of its broad geographical distribution and lithium concentrations that may exceed industrial thresholds [9]. Furthermore, low-grade brines, geothermal fluids, seawater, industrial groundwater, and marginal salt flats exhibit considerable potential due to their abundance, although technical constraints remain because of low lithium concentrations and elevated Mg/Li ratios [10]. Overall, the lithium resource base encompasses pegmatites, continental and geothermal brines, as well as clays, seawater, and industrial waters, creating a highly heterogeneous extraction landscape [11].

The Puna de Atacama region, which hosts the "Lithium Triangle" (Chile, Argentina, and Bolivia), contains a substantial proportion of global lithium resources. Chile is distinguished by exceptional geological and climatic conditions, characterized by high lithium concentrations and elevated evaporation rates [4], which have historically enabled low-cost production. In particular, the Salar de Atacama is considered one of the most competitive lithium-producing systems worldwide because of its high-grade brines, low impurity content, and reliance on solar evaporation, which reduces both energy requirements and technological complexity [12].

Salt flats are also complex hydrogeological systems in which brines constitute an essential component of aquifer and ecosystem equilibrium [13]. Consequently, their exploitation directly affects interconnected water systems and associated ecological processes.

However, increasing global demand has intensified pressure on these systems, particularly within the fragile ecosystems of northern Chile. The solar evaporation method requires the extraction of large volumes of brine—exceeding two million liters per ton of lithium carbonate equivalent (LCE) [14]—thereby exerting significant pressure on scarce water resources, a phenomenon commonly described as "water mining" [15]. This process exhibits low water-use efficiency, with losses exceeding 80% of the extracted volume [16], thereby highlighting a structural tension between global decarbonization objectives and local environmental impacts.

Several studies have documented associated impacts, including groundwater depletion, vegetation loss, and ecological alteration [17,18]. These impacts are particularly significant because salt flats provide essential ecosystem services, including hydrological regulation and biodiversity support [19], while simultaneously constituting interconnected systems whose dynamics are not always adequately represented by conventional hydrological models [20,21]. As a result, the impacts associated with lithium extraction tend to be systemic and cumulative rather than localized.

At the same time, these effects have generated substantial socio-environmental tensions. In northern Chile, Indigenous communities have reported reductions in water availability that affect traditional livelihoods and contribute to conflicts with the mining sector [22,23]. Although compensation mechanisms have been implemented, they do not resolve the structural tensions associated with water use [15]. Moreover, these conflicts arise not only from material impacts but also from limitations in participation processes and insufficient recognition of territorial knowledge [24].

In response to the limitations of the conventional extraction model, technologies such as Direct Lithium Extraction (DLE) have emerged, offering potential improvements in efficiency through recovery rates of 80–95%, reduced water consumption, and shorter production times [18,25]. Nevertheless, significant uncertainties remain regarding their hydrogeological implications, particularly with respect to brine reinjection and aquifer stability [26].

Despite the expansion of the literature, sustainability assessments continue to rely predominantly on isolated indicators, including water use, carbon emissions, and recovery rates, often assuming direct attribution of impacts to individual technologies. Moreover, studies frequently examine technological performance, environmental impacts, and policy dimensions independently, without systematic integration [27]. Although a substantial body of research addresses applications, supply, pricing, and supply chains, integrated socio-environmental analyses remain limited [4]. In particular, dimensions such as water scarcity and local impacts continue to be underrepresented [5]. Consistent with these findings, systematic reviews have shown that the implications of demand growth and technological innovation are not adequately incorporated into sustainability assessments [6].

However, this approach overlooks the fact that lithium extraction systems are both hydrogeologically interconnected and operationally complex, such that impacts do not disappear but are redistributed across different system components. This limitation constrains the understanding of trade-offs and may lead to misleading interpretations of relative sustainability.

Consequently, current assessment approaches fail to capture the systemic nature of trade-offs, the interdependence between brine and freshwater systems, and sustainability as an emergent property of technological, hydrogeological, and territorial configurations.

Consistent with these limitations, the existing literature evaluates resource efficiency, environmental impacts, and technological performance in a fragmented manner, without adequately integrating water-related trade-offs, hydrogeological connectivity, or territorial and governance dimensions.

To address this gap, the present study develops a systemic framework in which sustainability is conceptualized as an emergent property arising from the interaction among extraction technology, hydrogeological conditions, territorial context, and governance. The proposed framework integrates hydrogeological connectivity, technological systems, territorial impacts, and governance within a unified analytical structure, interpreting outcomes as the result of interactions rather than independent variables. Unlike conventional approaches, it emphasizes mechanisms of impact redistribution across environmental, technological, and social dimensions, thereby enabling the identification of trade-offs that remain largely invisible in traditional analyses.

Within this study, a systemic configuration is defined as the combination of extraction technology, hydrogeological conditions, territorial context, and governance mechanisms. This definition enables the analysis of how different combinations of these elements generate distinct sustainability outcomes. The same technology may exhibit different levels of performance depending on freshwater availability, hydrogeological connectivity, territorial conditions, or institutional arrangements. Sustainability is therefore attributed not to technology itself but to the interactions and trade-offs that emerge within the broader system.

Systemic coherence is defined as the degree of compatibility among technology, hydrogeology, territory, and governance, whereby an intervention is considered coherent when its effects are integrated without generating interdependent imbalances. Within this framework, impact redistribution refers to the displacement of environmental, water-related, energy, economic, or social pressures among system components without a net reduction in overall burden, allowing improvements in one domain to be interpreted as potential transfers of impacts to others. Territorial legitimacy, in turn, refers to the degree of social and institutional acceptance of extractive activities, conditioned by the distribution of benefits, participation mechanisms, and recognition of territorial knowledge.

These concepts constitute the foundation of the proposed systemic framework, which interprets sustainability as the outcome of interactions among physical, technological, territorial, and institutional dimensions.

This study contributes to the literature by developing a systemic framework that integrates hydrogeology, technology, territory, and governance while explicitly incorporating impact redistribution, brine–freshwater interdependence, and knowledge co-production.

Furthermore, the framework operationalizes trade-offs among water-related, technological, environmental, and territorial variables, revealing dynamics that often remain invisible in conventional assessments, including impact redistribution, tensions between efficiency and hydrogeological stability, and relationships between performance and territorial legitimacy.

From a practical perspective, the framework supports decision-makers and regulators by extending sustainability assessments beyond conventional indicators and highlighting the interdependencies among sectoral decisions.

Accordingly, this study proposes an alternative framework in which sustainability is understood as an emergent property of the system. The findings indicate that performance depends on the interaction among technology, hydrogeology, territory, and governance. Figure 1 summarizes these interdependencies.

The conventional approach represents variables such as water use, carbon emissions, recovery rates, costs, and conflicts as independent factors, reflecting a fragmented perspective in which these dimensions are examined in isolation. In contrast, the systemic approach integrates these dimensions through interdependencies among hydrogeology, technology, territory, and governance. The arrows represent feedback mechanisms, trade-offs, and processes of impact redistribution, while territory functions as the central node. Within this framework, sustainability is interpreted as an emergent property of systemic configurations.

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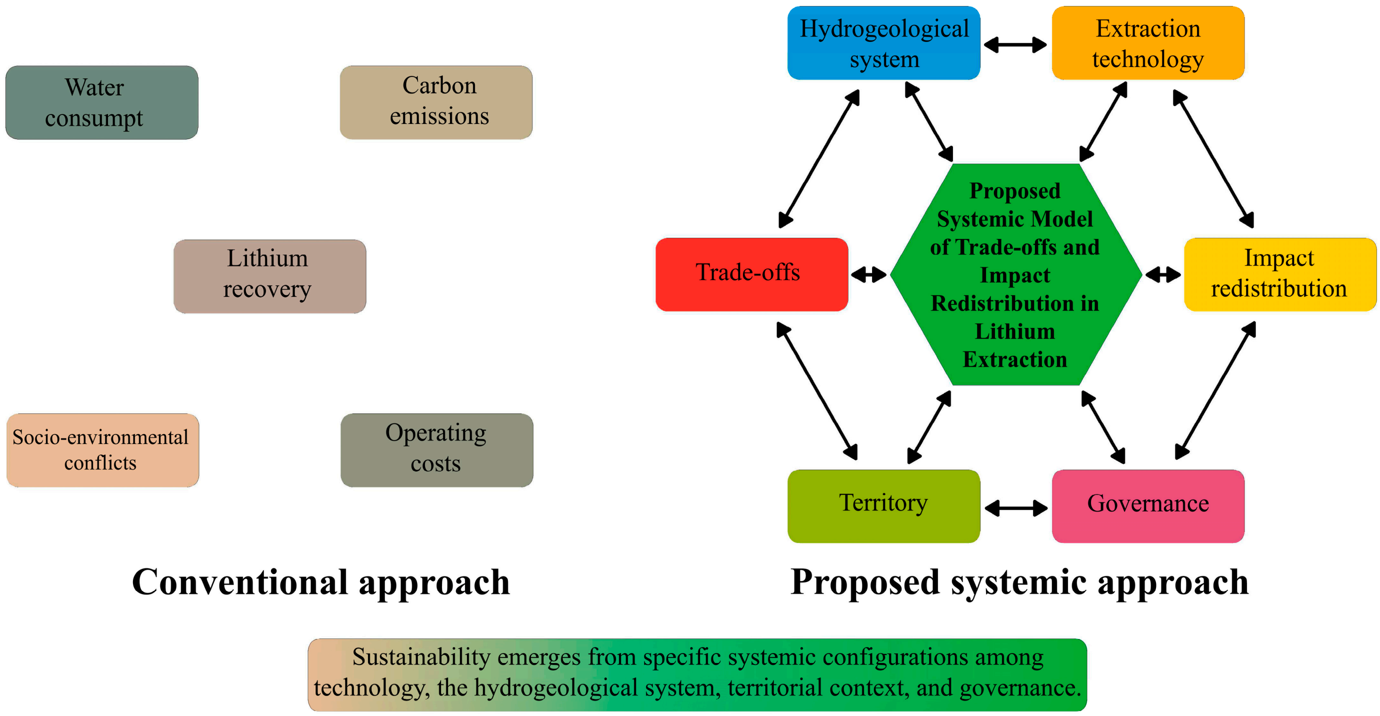

Figure 1. Systemic conceptual framework for the analysis of trade-offs and impact redistribution in lithium extraction systems.

2. Methodology

This study adopted a structured review and comparative analysis approach to evaluate lithium extraction technological configurations based on available scientific and technical evidence. Unlike conventional descriptive reviews, it proposes an analytical framework that extends beyond the comparison of individual indicators by interpreting these indicators through their interdependencies, thereby enabling the assessment of extraction-system performance from a systemic perspective.

The systemic approach was implemented through an analytical scheme integrating interdependent indicators of resource efficiency, environmental impact, and technological performance, which were jointly evaluated under specific hydrogeological conditions and operational contexts. Rather than examining metrics independently, the analysis focused on their functional relationships, enabling the identification of structural trade-offs and patterns of impact redistribution across water, energy, environmental, and territorial dimensions.

Operationally, the results were interpreted not as absolute values but as outcomes conditioned by technological, hydrogeological, and territorial configurations, considering variables such as deposit type, brine composition, freshwater requirements, energy consumption, and operating conditions. This approach enabled the comparison of extraction methods not as isolated alternatives but as systemic configurations operating under specific constraints, facilitating the identification of impact displacement mechanisms and critical dependencies within the production system.

The study was conducted using a structured evidence-synthesis approach designed to integrate information from multiple sources and technological contexts. The methodological strategy did not follow a formal systematic review protocol; instead, it was designed as a process of collection, selection, and comparative interpretation of scientific and technical information suitable for addressing the complexity and heterogeneity of lithium extraction systems. This approach enabled the analysis of relationships among variables and technological configurations without restricting the assessment to homogeneous metrics or predefined evaluation criteria.

Information was collected through a structured literature search in international scientific databases, primarily Web of Science and Scopus, complemented by technical reports, institutional documents, and specialized industry publications. The search strategy included combinations of terms related to lithium extraction, DLE, brines, sustainability, water use, energy consumption, environmental impacts, trade-offs, and governance. Documents from international organizations, governmental agencies, industry associations, and private companies were also reviewed.

Source selection was guided by inclusion criteria designed to prioritize empirical evidence, quantitative information, technological performance analyses, case studies, advanced pilot experiences, and sustainability assessments applied to real-world lithium extraction systems. Conversely, documents lacking sufficient information to characterize technological processes, publications unrelated to extraction systems, and studies that did not permit the establishment of relationships among relevant variables were excluded. In addition, studies representing diverse geographical and technological contexts were prioritized to capture the variety of configurations present across the industry.

Given the heterogeneity of the sources and the lack of standardization in reported data, a common analytical framework was adopted to improve comparative consistency. Within this framework, a cradle-to-gate system boundary was established, encompassing the process from primary resource extraction (brines or hard rock) to the production of lithium compounds at the plant gate. Furthermore, all quantitative indicators were expressed per 1 t of LCE as a common functional unit, providing a standardized basis for comparing resource consumption, GHG emissions, and other sustainability parameters.

Within this framework, the literature identifies recurring technical indicators, including recovery rate, water consumption per unit of product, energy intensity, lithium concentration, and supply projections. However, owing to methodological differences and data availability, these indicators were not applied as a homogeneous dataset but rather as interpretative inputs for identifying trends and trade-offs among technologies.

To improve evidence traceability, indicators were contextualized according to their geographical and temporal origins. Data on conventional evaporative systems and DLE technologies were derived primarily from the Lithium Triangle in South America, with particular emphasis on the Salar de Atacama (Chile) and Argentine salt flats, and were published between 2020 and 2026. Hard-rock indicators originated mainly from Australia and processing chains in China, with studies published between 2018 and 2026. Additional sources from North America, Asia, and international organizations were incorporated to contextualize governance and regulatory aspects. In all cases, the data were interpreted according to their spatial and temporal contexts, avoiding extrapolation across structurally different systems.

Accordingly, indicators were not treated as independent variables or directly comparable metrics but rather as elements for characterizing technological configurations operating under specific geological, operational, and hydrogeological conditions.

The methodological analysis was structured on the premise that sustainability cannot be adequately assessed through isolated indicators but rather through the relationships among them. In particular, the study incorporated trade-off analysis, understood as the identification of structural compensations among system dimensions that reveal mechanisms of impact displacement across technological configurations.

Trade-offs were identified through a comparative analysis of relationships among variables reported in the literature. Cases were examined in which improvements in specific indicators were simultaneously associated with adverse effects in other dimen-

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sions. This procedure enabled the identification of trade-offs between lithium recovery and by-product generation, between reduced brine extraction and hydrogeological risks associated with reinjection, and between production efficiency and increased energy or chemical requirements. Trade-offs were therefore interpreted as manifestations of systemic interdependencies rather than isolated effects.

Recent literature confirms that trade-offs are inherent to lithium extraction systems. DLE technologies achieve recovery rates ranging from 70% to 90%, and in some cases exceeding 92%, compared with conventional evaporative systems, which report values between 42% and 49% in Chile [28,29]. These technologies also reduce brine consumption, land occupation, and processing times. However, such improvements are not interpreted as net sustainability gains but rather as alternative configurations involving trade-offs in other dimensions, including the loss of by-products (e.g., potassium) and increased dependence on chemical inputs and more complex operating conditions [29].

Similarly, brine reinjection introduces hydrogeological uncertainty. Available evidence indicates risks associated with brine mixing, resource dilution, and alterations to aquifer equilibrium, creating a trade-off between operational efficiency and hydrogeological stability [18,30]. In this context, technological innovation does not eliminate system constraints but instead reconfigures them.

At the macro level, trade-offs were identified between economic development and environmental sustainability. Water overexploitation may constrain economic growth in water-scarce regions [14], whereas local-scale impacts include ecosystem degradation and adverse effects on communities, such as vegetation loss, reduced water availability, and declining living conditions [17,22]. These findings demonstrate that impacts are redistributed across water-related, environmental, and social dimensions.

Accordingly, the comparative analysis does not constitute a standardized quantitative assessment or a ranking of technologies; rather, it provides an interpretation of technological configurations operating under specific constraints. This approach enables the identification of dynamics that are not captured by conventional assessments, including impact redistribution between brine and freshwater systems, tensions between production efficiency and hydrogeological stability, and trade-offs between economic benefits and territorial sustainability.

In this manner, the methodological approach links technical and environmental indicators through dependency relationships, enabling the analysis of their combined behavior. Rather than evaluating isolated metrics, the analysis focuses on interactions among variables, facilitating the identification of performance patterns associated with specific technological and hydrogeological conditions.

Finally, the study relied on secondary information derived from scientific literature, technical reports, and databases, which entails limitations associated with data heterogeneity and availability, particularly for emerging technologies such as DLE, where evidence frequently originates from pilot-scale or pre-commercial applications. These limitations further reinforce the need for contextual and systemic interpretation.

Scope and Nature of the Analysis

This study is framed as a structured and conceptual comparative analysis based on the systematic integration of secondary evidence derived from scientific literature, technical reports, and case studies. It does not constitute an experimental investigation or a standardized quantitative assessment based on primary data; rather, it represents an analytical exercise aimed at interpreting patterns within complex systems.

The scope of the analysis focuses on evaluating lithium extraction technological configurations in interaction with hydrogeological, operational, and territorial conditions.

Consequently, the results are not intended to establish universal metrics or direct comparisons across all cases but rather to identify interdependencies, performance patterns, and structural trade-offs.

Consistent with this approach, no formal quantitative model or standardized multicriteria framework was developed because of data heterogeneity and structural differences among systems. Comparative interpretation was based on qualitative evidence synthesis to identify trade-offs, interdependencies, and recurring patterns across technological, hydrogeological, environmental, territorial, and governance dimensions. Accordingly, the results do not constitute a ranking of technologies but rather an analytical contribution toward understanding how different configurations redistribute impacts among system components.

Finally, the study acknowledges the inherent limitations associated with the use of secondary information and heterogeneous sources. Nevertheless, these conditions are consistent with the current state of knowledge in the lithium industry and align with the objective of capturing system complexity under conditions of uncertainty and rapid technological evolution.

3. Global Context and Fundamentals of Lithium Extraction

3.1. Lithium Resources and Global Distribution

Lithium (Li) is a key element in energy storage systems owing to its high electrochemical potential, low density, and high energy storage capacity per unit mass, making it a strategic input for rechargeable battery technologies. Its importance extends beyond its physicochemical properties, as it has become a central component of the global energy transition, particularly in electromobility and renewable energy storage applications. Globally, lithium resources are distributed primarily in brines (60%), followed by clays (25%) and hard-rock deposits (15%). Despite this distribution, hard-rock mining remains the dominant production route, although it presents structural limitations, including moderate recovery rates, higher operating costs, and greater environmental impacts. In contrast, lithium extraction from brines through solar evaporation, which predominates in South America, is characterized by long production cycles (12–24 months), lower recovery rates, and intensive water and land use [8].

Lithium is not produced in elemental form but mainly as industrial salts, including lithium carbonate, lithium hydroxide, and lithium chloride [31,32]. Geologically, lithium is extracted primarily from two deposit types: (i) hard-rock deposits, particularly pegmatites containing minerals such as spodumene, and (ii) brines found in continental salt flats, geothermal systems, and oil fields [33]. Additional potential sources have recently gained attention, including lithium-rich clays and secondary resources derived from mining and industrial waste streams, reflecting the ongoing diversification of global supply sources [34–37].

In Chile, lithium production from brines involves a sequential process of evaporation and salt precipitation. Initially, halite (NaCl) precipitates due to natural brine saturation. Subsequently, sylvinite (NaCl–KCl) and potassium chloride (KCl) precipitate, the latter being marketed as an industrial fertilizer. This stage is followed by the precipitation of potassium carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$), a double potassium–magnesium chloride, and bischofite ($MgCl_2 \cdot 6H_2O$), a hydrated magnesium chloride. The process ultimately culminates in the precipitation of lithium carnallite ($LiCl \cdot MgCl_2 \cdot 7H_2O$), a double lithium–magnesium chloride [38].

Lithium resources are highly concentrated geographically. The largest resources are located within the so-called "Lithium Triangle" (Chile, Argentina, and Bolivia), together with Australia, China, and the United States [39]. According to the World Resources section of the Lithium chapter published by the U.S. Geological Survey [33], global measured and indicated resources total approximately 115 million tonnes. Within this total, Argentina and Bolivia each account for 23 million tonnes, Chile for 11 million tonnes, and Australia for 8.9 million tonnes. Complementarily, the World Mine Production and Reserves section of the same report estimates global reserves at approximately 30 million tonnes [33]. This distribution reveals a strong geographical concentration of lithium resources within a limited number of countries, with significant geopolitical, strategic, and economic implications for global supply chains.

From a geological and operational perspective, brine systems are complex hydrogeochemical environments typically located in endorheic basins within arid regions, where intense evaporation promotes the concentration of dissolved salts, including lithium [40]. Representative examples include the Salar de Atacama in Chile and the Hombre Muerto and Olaroz salt flats in Argentina. By contrast, hard-rock deposits contain minerals such as spodumene, lepidolite, and petalite, with lithium contents ranging from 1% to 4% and recovery rates between 60% and 70% [40]. Australia has consolidated its global leadership through the intensive exploitation of these deposits, although this pathway requires greater energy inputs and involves higher operational complexity [41].

More broadly, lithium occurs in a wide range of geological formations, including hard-rock pegmatites [36], salar brines [42], sedimentary deposits, oilfield brines [34], geothermal brines [37], and seawater [35]. Nevertheless, only salar brines and hard-rock deposits are currently exploited at a commercial scale.

Despite the extensive literature on lithium resource distribution, a critical gap remains. Existing studies are largely descriptive and rarely examine how geological conditions influence technological configurations, resource consumption patterns, and environmental impacts. In particular, geology and technology have often been treated as separate dimensions, despite constituting interdependent components of the same production system. This limitation hinders consistent comparisons among extraction pathways and forms part of the research gap addressed in this study.

3.2. Lithium Uses and Global Demand Dynamics

Lithium plays a strategic role across multiple industrial applications; however, its principal contemporary use is in lithium-ion batteries for electronic devices, energy storage systems, and, most notably, electric vehicles. This latter segment has driven a structural transformation in global demand, positioning lithium as a critical resource for energy transition and decarbonization strategies. Accordingly, lithium has been classified as a "near-critical" element in the short term (2020–2025) and as a critical material in the medium term (2025–2030) with respect to energy storage applications [43].

Although lithium continues to be used in traditional sectors such as glass, ceramics, lubricants, metal alloys, refrigeration, nuclear energy, and pharmaceuticals, sustained demand growth has been driven primarily by the rapid expansion of electromobility and energy storage technologies [41]. This transformation has substantially altered the structure of lithium consumption. Whereas batteries accounted for less than 5% of total lithium use during the 1990s, more than 80% of global lithium production is currently directed toward secondary battery manufacturing [43], evidencing a profound shift in demand patterns.

From a prospective perspective, the global electric vehicle market is projected to reach approximately 130 million units by 2030, accompanied by a substantial increase in end-of-life battery generation [44]. This scenario not only intensifies pressure on lithium supply expansion but also raises challenges related to sustainability, recycling, and resource management at the global scale.

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Consistent with this trend, recent scenario analyses project rapid growth in lithium demand, ranging from a fourfold increase by 2030 to nearly tenfold growth by 2050 under intensive electrification pathways [45]. According to the International Energy Agency's net-zero emissions scenario, annual lithium demand could reach between 3 and 4 million tonnes of LCE by 2030, compared with approximately 500,000 tonnes in 2022. More ambitious projections suggest that demand may exceed 6 million tonnes of LCE by 2050, driven by accelerated electric vehicle adoption, large-scale energy storage deployment, and the development of the hydrogen economy [27]. Similarly, global demand is expected to range between 3.6 and 5.2 million tonnes of LCE by 2040, underscoring the magnitude of anticipated growth [27].

This increase in demand has been accompanied by substantial growth in global production, which reached approximately 240,000 tonnes in 2024, representing an 18% increase compared with the previous year [33]. Nevertheless, fluctuations in electric vehicle markets continue to generate demand and price volatility, introducing uncertainty into the development of new lithium projects.

Conventional analyses have largely addressed this phenomenon through supply-and-demand models focused on resource availability and production expansion capacity. However, these approaches often disconnect demand growth from the material and environmental conditions that underpin extraction processes, thereby limiting their explanatory power regarding sustainability outcomes.

Projected demand growth implies not only expanded production but also intensified pressures on extraction systems, particularly within hydrogeologically fragile environments. These pressures amplify trade-offs related to water consumption, energy use, and land occupation, demonstrating that demand dynamics cannot be assessed independently of technological configurations and production-system constraints.

Consequently, the expansion of lithium as a strategic resource cannot be understood solely through its contribution to decarbonization. It must also be examined in relation to the environmental and operational constraints associated with extraction. This issue is particularly relevant in northern Chilean salt flats, where increasing pressure on water resources highlights the limitations of fragmented analytical approaches.

Accordingly, the literature reveals a structural disconnect between analyses of global demand and assessments of production-system sustainability, frequently treating these processes as independent dimensions. Although the present study does not explicitly model demand dynamics, the reviewed evidence indicates that projected production growth acts as a driver that intensifies and reconfigures pressures on extraction systems, particularly in terms of resource use, operational conditions, and territorial conflicts.

This fragmentation constrains understanding of how such pressures are translated into redistributed impacts throughout the system, reinforcing the research gap identified in this study.

To address this limitation, the present work integrates both dimensions within a systemic framework that enables analysis of how demand expansion interacts with technological configurations, hydrogeological constraints, and the trade-offs associated with lithium production systems.

3.3. Technological Extraction Configurations and Their Implications for Lithium Sustainability

Lithium extraction is governed by technological decisions that are strongly conditioned by deposit characteristics, which in turn influence recovery efficiency, resource consumption, and environmental impacts [46–48]. Technologies should therefore be understood not as isolated solutions but as components of complex systems whose performance depends on interactions with hydrogeological, operational, and territorial conditions.

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In hard-rock systems, production follows a conventional mining pathway involving extraction, comminution, flotation, and thermochemical processes such as calcination and acid leaching. These configurations produce spodumene concentrates containing approximately 6% Li_2O, with recovery rates ranging from 60% to 70% [18]. However, they require substantial energy inputs and intensive processing, shifting impacts toward energy consumption and emissions and illustrating a redistribution of trade-offs within the production system.

Brine-based systems, by contrast, rely on solar evaporation to concentrate lithium under favorable climatic conditions [46]. Nevertheless, they exhibit structural limitations, including recovery rates of only 40–50%, long processing times (10–24 months), and intensive water use accompanied by substantial evaporative losses [18,25]. In these systems, impacts are concentrated primarily on hydrogeological equilibrium, reflecting a different configuration in which pressure is transferred to water resources.

To address these limitations, DLE technologies have emerged, employing processes such as adsorption, ion exchange, membrane separation, and solvent extraction [49,50]. These technologies can substantially reduce processing times and achieve recovery rates exceeding 80–90% [18,51]. However, their performance does not constitute a universal improvement, as it depends heavily on brine chemistry and site-specific operating conditions, thereby limiting transferability and scalability [25].

Moreover, DLE does not eliminate environmental impacts but rather redistributes them. Compared with conventional brine extraction, DLE may require greater freshwater consumption, increased use of chemical reagents, and introduces uncertainties associated with brine reinjection [52,53]. This behavior demonstrates that improvements in recovery rates and processing efficiency are often accompanied by new dependencies and pressures within the system, reinforcing the existence of structural trade-offs.

Despite these advances, evaporative methods remain the dominant extraction route due to their technological maturity and comparatively lower operating costs. This persistence highlights that technology adoption is shaped not only by technical performance but also by broader economic, regulatory, and territorial conditions.

The literature has generally evaluated extraction technologies in a fragmented manner, separately examining technological performance, environmental impacts, or policy dimensions without integrating these elements within a common analytical framework [27]. This tendency is consistent with the widespread use of isolated indicators in sustainability assessments, limiting understanding of how impacts are redistributed throughout the production system [4,6].

Collectively, this evidence reveals a fundamental limitation: extraction technologies have frequently been assessed as independent units, implicitly assuming that their impacts can be directly attributed and evaluated in isolation. Such an assumption neglects their systemic character and their dependence on geological and hydrogeological contexts. This limitation is particularly critical in hydrogeologically interconnected environments, where technological interventions can generate indirect effects and impact displacement that remain invisible to conventional assessment approaches.

In contrast, the present study conceptualizes extraction technologies as integrated configurations whose sustainability depends not on the intrinsic superiority of a particular method but on its coherence with the system in which it is implemented. From this perspective, impacts are not eliminated but redistributed across water-related, energy-related, environmental, and territorial dimensions according to the adopted technological configuration.

This approach addresses the identified research gap by shifting the analysis from linear technology comparisons toward an assessment grounded in interdependencies,

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trade-offs, and impact redistribution. These elements are essential for understanding lithium sustainability in highly complex contexts and provide a conceptual foundation for analytical frameworks capable of capturing the systemic nature of lithium extraction systems.

4. Sustainability Challenges in Lithium Extraction: A Systemic Perspective of Interdependencies and Impact Redistribution

The sustainability challenges associated with lithium extraction cannot be understood as isolated dimensions—such as water consumption, environmental degradation, technological performance, or social conflict—but rather as interconnected manifestations of a complex system in which hydrogeological, technological, and territorial factors interact. Within this framework, water represents a structuring component due to its central role in extraction processes and impact generation, although it does not fully explain the observed sustainability outcomes.

Available evidence indicates that pressures on water resources are closely linked to energy requirements, chemical inputs, operational performance, and governance arrangements. Consequently, sustainability outcomes should be interpreted as emergent properties arising from the interaction between technological configurations and environmental conditions, introducing a strong contextual dependency into the performance of extraction systems.

This perspective is consistent with the research gap identified in the literature, as it challenges assessments based on isolated indicators and redirects attention toward interdependencies, trade-offs, and systemic configurations as the principal determinants of sustainability.

4.1. Water Stress and Hydrogeological Alterations

In brine-based systems located in arid environments such as northern Chile, solar evaporation requires the extraction and irreversible loss of substantial water volumes, estimated at approximately two million liters per ton of LCE [14]. Freshwater consumption associated with evaporation-based technologies reaches 22.5 m^3/t LCE in the Salar de Atacama and 50 m^3/t LCE in the Salar de Olaroz [25]. This production model is characterized by a predominantly linear extraction logic, with limited opportunities for water recirculation.

The resulting alterations extend beyond the brine reservoir itself and affect interconnected freshwater systems, generating consequences for vegetation and ecosystem functioning [17]. These effects demonstrate that hydrogeological disturbances propagate through interconnected networks rather than remaining confined to localized extraction zones.

From a hydrogeological perspective, brine pumping modifies pressure gradients and induces compensatory flows that may affect freshwater reserves. Evidence from the Salar de Olaroz in Argentina highlights the risks associated with disruptions to surface-water networks within alluvial environments [54]. The absence of robust long-term monitoring systems further increases uncertainty regarding the magnitude and spatial extent of these processes at the basin scale.

4.2. Redistribution of Environmental Impacts in Lithium Extraction Systems

Evidence from different producing regions indicates that environmental outcomes are determined primarily by the technological configuration of extraction systems rather than by national context alone. In Qinghai, China, lithium production from brines has generated impacts on aquatic ecosystems associated with by-product discharges [55], whereas in Nevada, concerns have focused on water consumption and potential contamination pathways.

More broadly, the literature shows that all extraction methods involve trade-offs related to water use, emissions, and ecological sustainability [27], indicating that environmental pressures are structurally embedded within lithium production systems rather than representing isolated operational failures.

Hard-rock mining, for example, concentrates environmental burdens in GHG emissions, particulate matter generation, and localized disturbances to soils and water resources [56,57]. These pressures do not disappear in comparison with brine extraction; instead, they are displaced toward energy-intensive processing stages and greater industrial complexity.

From this perspective, sustainability is determined not by the elimination of impacts but by how they are distributed and managed across the socio-technical system.

4.3. Technological Reconfiguration and Trade-Offs Associated with Direct Lithium Extraction

DLE technologies have emerged as alternatives capable of reducing brine consumption and land occupation. However, current evidence suggests that these technologies do not eliminate environmental pressures but rather redistribute them across different components of the extraction system.

Several DLE processes require freshwater inputs for elution and regeneration stages [25], while large-scale brine reinjection introduces uncertainty regarding long-term hydrogeological responses [30,58,59]. As a result, improvements in certain performance indicators may be accompanied by the emergence of new dependencies and operational risks.

Freshwater requirements in DLE systems exhibit considerable variability, ranging from 30 to 150 m^3/t LCE, with extreme cases exceeding 500 m^3/t LCE [25,60]. At the same time, reinjection of 50–60% of extracted fluids may contribute to maintaining salar equilibrium, although it also introduces potential risks related to dilution processes and structural modifications of aquifer dynamics [61,62].

These findings indicate that technological innovation primarily reconfigures the location and nature of environmental pressures rather than producing a straightforward reduction in overall impacts.

4.4. Social Dimension and Socio-Environmental Conflicts

Socio-environmental tensions associated with lithium extraction reflect the uneven distribution of costs and benefits across territories and stakeholder groups. In northern Chile, communities in the Atacama Desert have reported concerns regarding water availability and ecosystem degradation [22], demonstrating that extraction-related pressures extend beyond technical and environmental dimensions to encompass social and territorial dynamics.

In this context, the development of new projects increasingly faces resistance associated with water demand, ecological impacts, and perceived threats to local economic activities. These concerns have contributed to project delays and prolonged environmental assessment processes [27].

Such dynamics reveal that sustainability challenges are redistributed not only across biophysical systems but also among social actors, introducing questions of equity, legitimacy, and territorial governance into the extraction process.

4.5. Systemic Synthesis of Interdependencies and Impact Redistribution

Taken together, the reviewed evidence indicates that the sustainability challenges associated with lithium extraction cannot be adequately addressed through fragmented analytical approaches. Water consumption, environmental degradation, technological performance, and socio-environmental conflicts constitute interdependent dimensions of a single socioecological system.

Under this perspective, sustainability depends not on minimizing individual impacts in isolation but on achieving coherence between technological configurations, resource availability, hydrogeological conditions, and territorial contexts. This finding reinforces the notion that sustainability should be understood as an emergent property arising from systemic interactions rather than as an intrinsic attribute of any particular technology.

Accordingly, lithium extraction can be conceptualized as a process that simultaneously transforms hydrological, ecological, and social systems. Its assessment therefore requires integrated analytical frameworks capable of capturing interdependencies, trade-offs, and impact redistribution mechanisms, thereby overcoming the analytical fragmentation that characterizes conventional sustainability assessments.

5. Comparative Analysis of Lithium Extraction Methods

The comparative analysis conducted in this study confirms that differences among lithium extraction methods cannot be interpreted as independent variations in performance indicators but rather as the outcome of technological configurations embedded within specific hydrogeological and territorial systems. Consistent with the research gap identified in the literature, the results demonstrate that conventional assessments based on isolated indicators are insufficient to capture the systemic nature of sustainability outcomes, particularly the redistribution of pressures and impacts across interconnected system components.

Accordingly, the comparison is not structured as a linear ranking of technologies but as an examination of patterns of interdependence and structural trade-offs through which sustainability emerges from the behavior of the system as a whole. From this perspective, performance indicators are better understood not as absolute measures of sustainability but as expressions of specific technological and environmental configurations.

5.1. Comparison in Terms of Resource Efficiency

The results indicate that resource efficiency is not an intrinsic property of lithium extraction methods but an emergent outcome of specific technological, hydrogeological, and territorial configurations. Indicators such as water consumption and operational efficiency therefore do not represent absolute measures of performance but rather partial manifestations of underlying trade-offs and interactions within the system. Consequently, direct comparisons among technologies that neglect contextual conditions and interdependencies may lead to misleading conclusions regarding relative sustainability. Within this framework, the technical feasibility of lithium extraction projects in salars depends heavily on access to freshwater resources [4].

In evaporation-based systems, the extraction of approximately 2200 m^3 of brine per ton of LCE [63] reflects a linear production model characterized by water losses approaching 95% of the extracted volume [64,65]. However, this pattern should not be interpreted solely as a volumetric issue. Instead, it reflects a technological configuration that relies on highly specific hydrogeological conditions, where apparent operational advantages—such as low costs and technological simplicity—are accompanied by persistent pressure on fragile water systems. Under these circumstances, geological advantages do not eliminate impacts but concentrate them within the hydrogeological dimension.

When the analysis is expanded beyond extraction volumes alone, it becomes evident that DLE systems also require substantial freshwater inputs, typically ranging from 30 to 150 m^3/t LCE and exceeding 500 m^3/t LCE in some cases [25,66]. This finding demonstrates that water-related pressures are not eliminated but redistributed throughout the broader hydrological system, creating new dependencies on continental freshwater resources. Such behavior is particularly relevant to the framework proposed in this study because it illustrates how sustainability outcomes emerge through interactions among multiple system components rather than within isolated compartments.

Hard-rock mining represents a different configuration in which higher levels of water recirculation do not necessarily translate into overall systemic improvement. Instead, environmental burdens are shifted toward greater energy requirements and more intensive transformation processes [65]. This pattern reinforces the notion that efficiency cannot be evaluated through a single dimension, as reductions in pressure within one component of the system are often accompanied by increases in others, including energy consumption, emissions, and waste generation.

DLE technologies represent a further reconfiguration of these relationships. Although they eliminate evaporation as the dominant processing stage, they introduce substantial variability in freshwater demand, ranging from 30 to 150 m^3/t LCE and surpassing 500 m^3/t LCE under certain conditions [25,60]. Rather than constituting a straightforward improvement, this behavior exemplifies the displacement of pressures from brine resources toward freshwater systems while simultaneously creating new chemical and operational dependencies. The reinjection of 50–60% of processed brine provides a mechanism for partial compensation but also introduces hydrogeological uncertainties, reinforcing the importance of system-level coherence over technological attributes alone [61].

Empirical evidence from Argentina illustrates these dynamics. Paz et al. [67] estimated freshwater consumption of 51.0 m^3/t LCE in Olaroz (46.7 m^3/t LCE of freshwater and 4.3 m^3/t LCE of grey water), whereas the Fénix operation reached 135.5 m^3/t LCE. Similar findings were reported by Halkes et al. [68], who identified higher freshwater consumption intensities in DLE systems. Likewise, Vera et al. [25] emphasized that these technologies require reliable and sustainable freshwater supplies and warned that expanded lithium production may intensify competition for local water resources.

From a temporal perspective, DLE offers a substantial advantage over evaporation-based systems, reducing processing cycles to approximately 6–8 h [25,69], compared with the 12–24 months typically required for conventional evaporation.

Collectively, these findings demonstrate that resource efficiency should be interpreted as the outcome of specific systemic configurations in which pressures are redistributed among hydrological, energy, technological, and territorial dimensions. This conclusion directly supports the central argument of the study by showing that approaches based on isolated indicators fail to capture the interactions and trade-offs that ultimately shape sustainability outcomes.

5.2. Comparison in Terms of Environmental Impact

The analysis demonstrates that environmental impacts cannot be attributed to extraction technologies as intrinsic properties. Instead, they emerge from configurations in which technological, hydrogeological, energy, and territorial variables interact. Environmental performance should therefore be understood as a systemic outcome shaped by the redistribution of pressures across interconnected dimensions rather than as a direct consequence of a particular extraction method.

In brine systems, impacts are expressed primarily through alterations to hydrogeological equilibrium. Continuous extraction modifies hydraulic gradients and may affect freshwater reserves through hydrodynamic compensation processes [5]. Rather than constituting localized disturbances, these effects propagate through interconnected hydrological networks, influencing ecosystems, water availability, and territorial dynamics. As a result, assessments focused solely on extraction volumes or local water balances tend to underestimate the cumulative and spatially distributed nature of these impacts.

Hard-rock mining generates more visible and localized environmental pressures, including particulate emissions, tailings production, and risks of soil and water contamination. However, from a life-cycle perspective, many of these burdens are transferred to energy and climate dimensions due to the intensive requirements of extraction, crushing, grinding, concentration, and refining processes. Existing studies report substantial variability in carbon footprint estimates, largely reflecting differences in technological configurations, energy sources, and system boundaries [70,71].

While some assessments estimate emissions close to 2 t CO_2-eq/t LCE for mining and spodumene concentration stages in Australia, values increase considerably when chemical refining is included, reaching averages between 9.6 and 11.9 t CO_2-eq/t LCE and, in some cases, up to 20.4 t CO_2-eq/t LCE [70,72]. Several studies further indicate that more than 80% of life-cycle emissions from hard-rock production are concentrated in processing and refining stages, particularly when supported by fossil fuel-intensive energy systems [72]. In contrast, lithium production from brines generally exhibits lower emissions due to the use of solar evaporation, with reported values of approximately 4.13 t CO_2-eq/t LCE in Chilean operations, albeit accompanied by significant impacts on water systems [71,72]. These findings demonstrate that environmental performance depends not only on extraction methods but also on the broader operational and energy context.

The environmental profile of DLE technologies is similarly context dependent. Emissions vary substantially according to the energy source employed. When powered by solar energy, emissions may reach approximately 7.6 t CO_2-eq/t LCE, whereas operation under the Nevada electricity grid may generate around 17.3 t CO_2-eq/t LCE and diesel-based systems up to 22 t CO_2-eq/t LCE. Overall, reported values range between 2.5 and 7.0 t CO_2-eq/t LCE depending on the energy matrix [73]. Under certain conditions, DLE may therefore generate significantly higher emissions than conventional evaporation-based systems, highlighting a direct trade-off between water efficiency and carbon intensity.

Moreover, DLE technologies reduce pressures associated with large-scale brine evaporation while introducing new demands for freshwater, energy, and chemical reagents [25,60]. These changes illustrate how technological innovation modifies the distribution of environmental pressures rather than eliminating them. Similar dynamics are observed during downstream refining processes, where products such as lithium hydroxide exhibit larger water and carbon footprints than lithium carbonate, extending environmental burdens beyond the extraction stage.

The results further indicate that environmental performance is highly dependent on implementation context. Factors including brine chemistry, freshwater availability, energy sources, and regulatory conditions directly influence sustainability outcomes, limiting the transferability of results across locations and challenging generalized comparisons among extraction pathways.

Overall, the analysis confirms that no environmentally neutral or inherently superior extraction method exists. Instead, different technological configurations generate distinct patterns of environmental pressures distributed across hydrological, energy, climate, and territorial dimensions. This finding shifts the focus from identifying supposedly cleaner technologies toward evaluating their coherence with the systems in which they operate. Environmental sustainability should therefore be interpreted as the management of trade-offs among interconnected system components rather than the minimization of impacts within a single dimension.

5.3. Technological Performance and Limitations

The results indicate that technological performance is not an intrinsic property of lithium extraction methods but an outcome determined by their compatibility with hydrogeological, geochemical, and territorial conditions. Consequently, conventional indicators such as recovery rate, processing time, and operational efficiency provide only a partial representation of performance when interpreted independently of system context.

Evaporation-based technologies exhibit high technological maturity and operational reliability. However, their performance remains strongly dependent on external factors, including solar radiation, evaporation rates, and brine composition. This dependency limits their transferability and demonstrates that apparent efficiency reflects favorable environmental conditions rather than universally applicable technological advantages.

DLE technologies achieve substantial improvements in operational indicators, with reported recovery rates between 80% and 95% and significant reductions in processing times [62]. Nevertheless, these advantages must be interpreted within a broader framework of trade-offs, as performance depends critically on factors such as brine chemistry, freshwater availability, sorbent characteristics, and reagent requirements [60,74]. Technological efficiency is therefore highly context dependent rather than universally transferable.

A particularly important issue concerns brine reinjection, which embodies a central trade-off between operational efficiency and hydrogeological stability. Although reinjection reduces net brine losses, recent studies suggest that it may alter hydraulic gradients, promote mixing and dilution processes, and modify the physicochemical behavior of aquifer systems [75,76]. These findings indicate that technological innovation does not remove system constraints but instead transforms them into new forms of uncertainty.

The diversity of DLE technologies further reinforces this conclusion. Ion-exchange systems, membrane-based approaches, and solvent extraction technologies each exhibit distinct profiles in terms of water demand, input requirements, recovery efficiency, and operational costs [74]. Rather than converging toward a single optimal solution, technological development has produced multiple configurations characterized by different strengths and limitations.

Institutional and governance factors also influence technological performance. The way brines are conceptualized and regulated within water management frameworks can facilitate or constrain integrated management approaches, thereby affecting both operational feasibility and territorial acceptance [65]. Technological outcomes therefore depend not only on engineering considerations but also on broader institutional conditions.

Overall, the evidence confirms that technological performance should not be assessed through a "best technology" paradigm. Instead, it should be understood as an emergent property of specific configurations in which benefits and limitations are distributed across hydrological, energy, environmental, and territorial dimensions. This conclusion aligns with the systemic framework proposed in this study and reinforces the need to evaluate extraction methods in terms of their coherence with contextual conditions rather than through isolated performance indicators.

Finally, Table 1 summarizes the principal quantitative indicators reported in the literature for brine evaporation, hard-rock mining, and DLE technologies. Rather than identifying a superior technology, the comparison highlights the substantial variability of sustainability indicators and their strong contextual dependency. The table therefore reinforces the central argument of this study: environmental and operational performance are not inherent technological attributes but emergent outcomes arising from interactions among technology, hydrogeology, territory, and governance.

Table 1. Quantitative indicators reported in the literature for different lithium extraction methods.

Indicator	Brine Evaporation	Hard-Rock Mining	DLE
Brine consumption	~2200 m^3 brine/t LCE [63]	Not applicable	Reduced relative to evaporation through partial reinjection [61]
Brine loss	Up to 95% of extracted volume [64,65]	Not applicable	Reinjection of 50–60% of processed brine [61]
Freshwater consumption	~51.0 m^3/t LCE [67]	Relevant use in processing and leaching; no consolidated value reported [65]	30–150 m^3/t LCE, with cases exceeding 500 m^3/t LCE and alternative ranges of 100–800 m^3/t LCE [25,66]
Lithium recovery rate	42–49% [28,29]	60–70% [40]	80–95% [62]
Processing time	Dependent on solar evaporation; prolonged processing periods of 12–24 months [8]	6–12 months (including mining, calcination at >1000 °C, and chemical leaching) [77]	Significant reduction relative to evaporation [62]; cases of 6–8 h have been reported [25,69]
Carbon footprint	~4.13 t CO_2-eq/t LCE in Chilean operations [71,72]	~2 t CO_2-eq/t LCE for mining and concentration; 9.6–11.9 t CO_2-eq/t LCE including refining; up to 20.4 t CO_2-eq/t LCE in some cases [70,72], with >80% of life-cycle emissions concentrated in processing and refining [72]	High variability; dependent on energy consumption, reagent use, and chemical refining, ranging from 7.6 to 22 t CO_2-eq/t LCE [25,60]
Hydrogeological uncertainty associated with reinjection	No brine reinjection (up to 95% of extracted volume is evaporated) [64,65]	Not applicable	Reinjection associated with potential mixing, dilution, supersaturation, and hydraulic gradient alterations
Dependence on hydrogeological conditions	High dependence on evaporation rates, solar radiation, and brine characteristics [63–65]	Lower direct hydrogeological dependence; greater energy dependence [65]	High dependence on brine composition, freshwater availability, and sorbent performance [60,74]

The reported ranges correspond to values identified in the reviewed literature and do not represent global averages or universal performance criteria. Observed differences depend on technological, hydrogeological, energy, and territorial factors specific to each extraction configuration.

6. Implications for the Lithium Industry in Chile

6.1. Structural Conditions of the Chilean Production System

In 2014, Chile was the world's leading producer of lithium from brines; however, production has remained virtually stagnant since then. This trend cannot be explained by geological constraints alone but rather by a systemic configuration in which institutional, regulatory, technological, and territorial dimensions interact. Within this context, SQM and Albemarle operate under distinct contractual arrangements amid persistent tensions with the Chilean State [4].

Available evidence indicates that the Chilean lithium industry cannot be understood solely through its geological advantages but rather as the outcome of a coupled system of hydrogeological, operational, and governance factors. The high lithium concentration of the Salar de Atacama (~1400 ppm), substantially exceeding that of salars in Argentina (417 ppm), China (420 ppm), and the United States (245 ppm) [42,78], constitutes a favorable initial condition; however, it is not, by itself, a determining factor in production system performance.

The system is situated within an endorheic basin of approximately 17,000 km^2 [53], where 87.2–89% of water inputs originate from Andean recharge and nearly 95% of outputs correspond to natural evaporation. This delicate equilibrium creates a hydrological system that is highly sensitive to groundwater-level disturbances and characterized by recharge times exceeding 65 years for fossil or relict waters [79].

Although the evaporation-based model has historically enabled low production costs, its systemic efficiency remains limited. Recovery rates in Chile (43–49%) [80] are substantially lower than those reported for hybrid processes implemented in China (~90%) [81]. These differences indicate that high resource quality does not necessarily translate into operational efficiency in the absence of coherence between technological configurations and hydrogeological constraints.

The Salar de Atacama also functions as a coupled hydrogeochemical system in which freshwater and brine interact through a continuous interface characterized by salinity gradients of up to 70-fold. The system incorporates hydrological buffering mechanisms (damping capacity), whereby reductions in groundwater levels decrease natural evaporation, generating partial nonlinear compensatory responses [53].

Overall, the evidence suggests that competitiveness depends not on the resource itself but on the capacity to operate within the critical thresholds that sustain the hydrogeological stability of the salar.

6.2. Water Stress and Basin Dynamics

The principal structural constraint of the Chilean lithium model is hydrological rather than geological. The evaporation-based production system requires the extraction of approximately 2.2 million liters of brine per ton of LCE [63], with water losses approaching 95% of the extracted volume [64], thereby constituting a highly linear system with limited water recirculation capacity.

At the basin scale, impacts are spatially heterogeneous. In the Salar de Atacama, groundwater-level declines of up to 9.8 m in areas operated by SQM and 4 m in areas operated by Albemarle have been documented [79], revealing differentiated responses within the same hydrogeological system.

The basin is not merely a physical system but also a coupled socioecological system. In Peine, a transition from agro-pastoral livelihoods toward forms of proletarianization linked to mining activities has been observed [82]. In San Pedro de Atacama, urban expansion and tourism development depend directly on the ecological integrity of the salar, creating a functional dependence on ecosystem stability [79].

From an ecological perspective, the system supports critical biodiversity, including three flamingo species whose abundance depends on the stability of high-Andean lagoons [79]. In addition, the Pampa Colorada conflict that occurred in 2007 represents a landmark event in Indigenous territorial mobilization for water protection, consolidating coordination mechanisms within the Atacameño Peoples Council.

A key structural characteristic of the basin is the interface between freshwater and brine, which should be understood as a hydrogeological continuum rather than as a set of independent compartments. Evidence indicates that the conceptual separation of these flows within existing regulatory frameworks is technically limited [53], reinforcing the need for integrated basin-scale management approaches.

Within this context, Chile ranks among the countries experiencing the highest levels of global water stress [14], intensifying the systemic consequences of the extraction model, including groundwater-level declines, vegetation loss, and soil thermal alterations [17].

Particularly relevant is the interconnection between brine and continental waters, which gives rise to processes described as “water mining” [5,65,83], whereby indirect impacts on aquifers remain largely unaccounted for in conventional water-consumption metrics.

The transition toward DLE does not eliminate these constraints but rather reconfigures them. Although DLE can reduce pressure on brine resources, it may increase freshwater consumption depending on the technological configuration employed [60,61], thereby shifting hydrological pressures within the system.

Governance gaps further exacerbate these challenges. The classification of brine as a mineral resource rather than a water resource limits the implementation of integrated management approaches [65,84,85], reducing institutional capacity to address the complexity of these interdependencies.

Taken together, water stress should not be viewed as an isolated operational constraint but rather as a structuring factor of Chile's lithium production, environmental, and social systems, defining both their expansion limits and their principal territorial trade-offs.

6.3. Strategic Role of Emerging Technologies

Emerging technologies, particularly DLE, do not represent incremental improvements to the existing production model but rather a reconfiguration of the system's decision space. Their adoption modifies the structure of trade-offs rather than resolving the fundamental constraints that characterize lithium extraction systems.

Technology selection must simultaneously consider freshwater availability at the basin scale, hydrogeological reinjection capacity, and territorial compatibility. In the absence of these conditions, DLE may shift or intensify impacts rather than mitigate them.

From a regulatory perspective, the results indicate that the current institutional framework is not adequately prepared for these emerging configurations because of the conceptual separation between brine and freshwater resources. This limitation reduces the capacity to capture impact redistribution and cumulative effects.

From an economic perspective, the incorporation of DLE introduces additional complexities, including the potential loss of strategic by-products such as potassium, increased energy requirements, and the reconfiguration of value chains. Consequently, competitiveness becomes a property of the entire system rather than of any individual process.

In this context, technological innovation increases system complexity rather than reducing it, expanding both the range of possible configurations and the associated trade-offs.

6.4. Territorial Governance and Knowledge Co-Production in Chile

System sustainability depends not only on technical variables but also on how knowledge is produced, legitimized, and incorporated into decision-making processes. In the Salar de Atacama, communities such as Peine and San Pedro have experienced profound hydrosocial transformations associated with proletarianization processes and increasing dependence on mining and tourism activities [79,82]. Within this setting, lithium governance emerges as a process of knowledge co-production involving both scientific and territorial forms of knowledge.

Local communities have developed their own hydrogeological and environmental monitoring capacities [86,87], demonstrating that disputes are not solely economic but also epistemological, as they involve competing definitions of what constitutes valid knowledge for assessing sustainability. At the same time, the National Lithium Strategy (NLS) has introduced a significant institutional reconfiguration, including the Codelco–SQM agreement (NovaAndino Lithium), which projects majority state participation by 2031 and operations through 2060 [88–90], together with the creation of the National Lithium and Salars Institute (INLiSa).

Despite these developments, tensions in Indigenous governance persist, reflected in the gap between formal participation mechanisms and effective influence, even after 13 CEOL consultation processes, of which 12 had been completed by 2026 [90]. The literature characterizes this framework as a "governance of dispossession," in which dynamics favoring extractive expansion continue to prevail over ecosystem protection [91,92].

The concentration of hydrogeological data among industrial actors reinforces asymmetries in evidence production [93], while communities face material constraints in generating independent knowledge despite ongoing local monitoring efforts [21]. These asymmetries are further intensified by corporate compensation strategies that fail to address the structural causes of conflict [91].

Taken together, technical uncertainties associated with water consumption and reinjection [25,60], combined with divergent territorial perceptions [94], indicate that uncertainty is a structural feature of the system. Consequently, lithium-related conflicts are also epistemological in nature. In response, an "ecology of knowledges" integrating scientific, territorial, and ancestral knowledge has been proposed as a pathway toward more inclusive governance arrangements [91].

In summary, sustainability depends not only on technological performance but also on the institutional and territorial capacity to manage uncertainty and govern knowledge within complex socio-hydrogeological systems.

6.5. DLE Projects in Chile

Recent evidence from Chile indicates that the incorporation of DLE technologies does not merely improve operational indicators but instead represents a structural reconfiguration of the production system, consistent with the trade-offs identified throughout this study. Ongoing projects illustrate how DLE adoption materializes through specific technological configurations constrained by hydrogeological, operational, energy, and regulatory factors, reinforcing the need to evaluate performance from a systemic rather than a technology-centered perspective.

A representative example is the Salares Altoandinos project, developed by ENAMI in partnership with Rio Tinto in the Atacama Region. The project has achieved an average lithium recovery rate of 92%, compared with approximately 42.6% under conventional evaporation-based methods [95]. It also reports substantial reductions in brine consumption, land occupation (approximately 10 ha compared with more than 1000 ha), and processing times (6–8 h cycles). From a conventional perspective, these outcomes could be interpreted as significant sustainability improvements. However, the analysis developed in this study suggests that such outcomes should be understood as manifestations of impact redistribution within the system rather than as net reductions in environmental pressures.

Similarly, Albemarle's TED Project in the Salar de Atacama proposes a transition toward DLE through adsorption processes integrated into the existing evaporation-based operation. This configuration enables the reinjection of approximately 90% of the processed brine into the aquifer, reducing net extraction from 442 L/s to approximately 142 L/s [96,97]. Nevertheless, it introduces new pressures, particularly through industrial freshwater consumption (131 L/s), which will be supplied externally. This case illustrates the central hydrological trade-off identified in this study: reductions in pressure on brine resources are accompanied by increased freshwater demand, thereby shifting hydrological pressures within the system rather than eliminating them. Moreover, the incorporation of supporting infrastructure, including a 220-kV transmission line, reinforces interdependencies among hydrological, energy, and technological systems, extending the scope of potential impacts.

Projects promoted by CODELCO in the Maricunga and Pedernales salars introduce another critical dimension for systemic evaluation: the experimental validation of brine reinjection as a central component of DLE configurations. In Maricunga, testing programs include 15 extraction wells and 19 reinjection wells, whereas in Pedernales a large-scale program involving more than 100 wells and extensive hydrogeological monitoring has been proposed [98,99]. These initiatives demonstrate that the viability of DLE depends not only on technical performance but also on the capacity to understand and manage hydrogeological responses to reinjection, which may generate risks associated with brine mixing, resource dilution, and alterations in hydraulic gradients [18,30].

Recent modeling and experimental studies indicate that variables such as reinjection rate, well location, and brine chemical composition can generate nonlinear system responses, including changes in lithium concentration, mineral dissolution, and groundwater flow patterns [75,76]. This introduces a critical dimension of uncertainty in which operational efficiency may come into direct tension with hydrogeological stability, creating one of the principal trade-offs of the system.

Conversely, initiatives such as SQM's Extraction Reduction Plan in the Salar de Atacama reflect an alternative strategy based on optimizing the existing evaporation model through progressive reductions in extraction rates (up to 822 L/s of brine) without introducing structural technological transformations [100]. This approach demonstrates that transitions toward more sustainable configurations do not depend exclusively on the adoption of new technologies but may also emerge through operational adjustments within existing systems, reinforcing the coexistence of multiple technological pathways within the Chilean production system.

Collectively, these cases indicate that DLE adoption in Chile should not be interpreted as a universal solution but rather as a process of systemic reconfiguration in which improvements in specific indicators—such as recovery rates, processing times, and brine use—coexist with new dependencies related to freshwater consumption, energy requirements, chemical reagents, and hydrogeological control [25,60,65]. This behavior empirically supports the central argument of this study: impacts are redistributed among system components rather than eliminated, challenging assessments based on isolated indicators.

These projects further demonstrate that DLE implementation is strongly conditioned by contextual factors, including freshwater availability, hydrogeological monitoring capacity, salar geochemical characteristics, and the prevailing regulatory framework. Consequently, the viability of these technologies cannot be generalized and must be evaluated on a case-by-case basis according to their coherence with system constraints.

Thus, empirical evidence from Chile directly reinforces the research gap identified in the literature: approaches that evaluate technologies in isolation are insufficient to capture system complexity. Instead, comparisons among extraction methods should be framed as analyses of technological configurations operating under specific constraints, where impacts are redistributed across hydrological, environmental, energy, and territorial dimensions.

6.6. Differentiated Operational Configurations: SQM vs. Albemarl

Operations in the Salar de Atacama represent two distinct production configurations operating within the same basin system.

SQM operates across approximately 394 km^2, extracting 1700 L/s of brine and 240 L/s of freshwater [83]. Its production model integrates lithium extraction with the recovery of by-products such as potassium and boron, creating a multiproduct value-generation strategy. Through its "Salar Futuro" initiative, the company aims to reduce continental water consumption to 80 L/s by 2030 [79,88]. This model is further supported by a contractual structure based on leasing rights from CORFO and a broader diversification strategy.

Albemarle operates across approximately 137 km^2, extracting 442 L/s of brine and 24 L/s of freshwater [83]. Its model focuses on the production of battery-grade lithium, with limited diversification of by-products. Through its "New Era of Lithium" strategy, the company plans to progressively replace continental water with desalinated water beginning in 2027, thereby shifting part of the environmental burden toward energy consumption [79]. Unlike SQM, Albemarle operates under direct ownership of mineral deposits and holds a contract extending until 2043.

These models represent distinct optimization strategies within the same hydrosocial system: industrial integration versus technological specialization. Such structural differences shape divergent trajectories of investment, innovation, and technological transition, as well as different mechanisms for internalizing hydrogeological constraints.

From a systemic perspective, this comparison demonstrates that sustainability depends not exclusively on extraction volumes or technologies but on how each production configuration integrates water resources, energy, infrastructure, governance, and economic objectives within a shared system. Consequently, SQM and Albemarle illustrate how different configurations can manage system trade-offs through distinct mechanisms of impact redistribution while pursuing similar production objectives through alternative technological pathways.

This finding reinforces one of the central conclusions of the study: transitions toward more sustainable lithium mining do not necessarily converge on a single technological solution but instead depend on specific configurations capable of balancing hydrogeological, production, environmental, and territorial constraints within complex systems.

7. Discussion

7.1. Synthesis of the Literature and Existing Gaps

The literature review indicates that sustainability assessments of lithium extraction have been largely dominated by approaches based on isolated indicators. Within this framework, extraction technologies have primarily been evaluated through independent performance metrics, often without adequately capturing the interdependencies among technological, hydrogeological, environmental, and territorial dimensions.

Several studies have highlighted this analytical fragmentation. Technological performance, environmental impacts, and governance dimensions are frequently examined separately, with limited systemic integration among these components [27]. Similarly, research on critical minerals has emphasized the predominance of approaches focused on supply, demand, costs, and technological efficiency, while dimensions such as water scarcity, water quality, and local socio-environmental impacts have historically received less attention [5]. Furthermore, systematic reviews have shown that a substantial proportion of studies fail to adequately integrate the combined effects of growing demand and technological innovation on socio-environmental outcomes [6].

Collectively, this evidence reveals a persistent analytical gap: the absence of integrated frameworks capable of capturing the interdependence among technological systems, hydrogeological processes, and territorial dynamics, as well as the redistributive nature of impacts across these dimensions.

Within this context, Table 2 synthesizes the principal trade-offs identified in the literature.

The trade-offs summarized in Table 2 derive from a qualitative synthesis of scientific literature, technical reports, and empirical case studies. They do not constitute a quantitative assessment or a standardized multicriteria comparison; rather, they represent recurrent patterns of impact redistribution across technological, environmental, economic, territorial, and institutional dimensions.

Table 2. Structural trade-offs in lithium extraction methods under a systemic framework.

Extraction Method	Main Reported Improvement	Water Trade-Off	Environmental Trade-Off	Economic/Operational Trade-Off	Systemic Implication
Brine evaporation	Low operating costs and utilization of natural climatic conditions [52]	Massive brine extraction (~2200 m^3/t LCE) and irreversible losses through evaporation (up to 95%) [63–65]	Alteration of hydrogeological balance and indirect effects on interconnected freshwater systems [5,83]; cumulative impacts on water-dependent ecosystems and territorial dynamics	High dependence on climatic conditions and long production times (10–24 months) [25]	Linear water-system configuration, with impacts concentrated on brine loss and limited resilience to water stress; operational efficiency strongly depends on specific hydrogeological conditions
Hard rock	Greater process control and operational stability [47]	Freshwater use during mineral processing and leaching, without impacts on brines; major pressures shift toward energy consumption and carbon emissions	High carbon footprint (up to ~20.4 t CO_2-eq/t LCE) and generation of solid waste [66,101]; more than 80% of emissions occur during processing and refining	High energy requirements associated with calcination and leaching, resulting in higher operating costs [18]	Redistribution of impacts toward energy consumption and emissions while maintaining significant water requirements and strong dependence on the energy mix
DLE with brine reinjection	High recovery rates (80–95%), reduced processing times, and potential partial preservation of water balance through brine reinjection (50–60%) [18,51,61,62]	Reduced brine extraction but increased freshwater use (30–150 m^3/t LCE, with some cases exceeding 500 m^3), together with uncertainty regarding hydrogeological effects of reinjection [18,25,30,60]	Use of chemical reagents, energy consumption, and generation of new environmental and hydrogeological uncertainties associated with reinjection and aquifer responses [52,53,62]; redistribution of impacts from brine toward freshwater, chemical inputs, and downstream refining stages	Greater operational complexity and dependence on specific geochemical conditions, requiring advanced monitoring and hydrogeological modeling; non-recovery of secondary salts results in loss of by-products and reduced economic value capture compared with evaporation systems [25,29,75,76]	Reconfiguration of the water system, shifting pressure from brine toward freshwater while introducing structural uncertainty; sustainability depends on the capacity to understand, monitor, and manage complex hydrogeological systems and on the compatibility among technology, hydrogeology, and territorial conditions
Cross-method comparison (all methods)	Optimization of specific indicators (recovery, cost, or time)	Redistribution of pressures between brine and freshwater resources [25,61]	Redistribution of impacts among water, energy, and emissions [65]; dependence on contextual variables such as brine composition, water availability, and energy mix	Trade-offs among technical efficiency, costs, and operational stability	Sustainability emerges as a system property rather than a technological attribute; impacts are redistributed rather than eliminated and depend on the coherence among technological configuration, hydrogeological conditions, and territorial context

7.2. Study Findings and Analytical Contribution

The findings of this study indicate that comparisons among lithium extraction methods cannot be based on isolated indicators, as such indicators emerge from interdependent technological, hydrogeological, and territorial configurations. Variables commonly used to evaluate sustainability—including water consumption, carbon footprint, and recovery rates—exhibit substantial variability depending on operational conditions and system boundaries, highlighting the importance of contextual interpretation [60,66].

From a hydrological perspective, the results show that evaporation-based systems concentrate impacts on irreversible brine losses and alterations of hydrogeological balance, whereas DLE technologies shift part of this pressure toward freshwater consumption and uncertainties associated with reinjection processes [25,61]. Consequently, technological change does not eliminate impacts but reconfigures their distribution within the system.

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In particular, improvements frequently associated with DLE, including higher recovery rates and shorter processing times, should be interpreted as manifestations of structural trade-offs rather than as unequivocal sustainability gains. Reduced brine consumption is accompanied by increased freshwater demand and the emergence of new operational and chemical dependencies [25,65]. These findings reinforce the argument that efficiency is not an intrinsic property of a technology but an emergent outcome of the broader system in which it operates.

7.3. Hydrogeological Reconfiguration and Empirical Cases

Within this framework, brine reinjection emerges as a critical component of DLE-based configurations. Although reinjection may contribute to the partial preservation of water balance, the available evidence reveals substantial uncertainties associated with brine mixing, resource dilution, and alterations in hydraulic gradients [18,30].

These issues are particularly evident in emerging Chilean projects. In Maricunga and Pedernales, CODELCO has incorporated extensive extraction, reinjection, and hydrogeological monitoring programs, including 15 extraction wells and 19 reinjection wells in Maricunga, and more than 100 projected wells in Pedernales [98,99]. Similarly, Albemarle's TED Project proposes the reinjection of approximately 90% of the processed brine [96,97]. These initiatives demonstrate that the viability of DLE technologies depends not only on extraction efficiency but also on the response of the hydrogeological system to reinjection.

Accordingly, uncertainty associated with reinjection should not be regarded as a secondary consideration but rather as a central determinant of the sustainability of DLE configurations.

7.4. Economic, Social, and Governance Dimensions

The analysis also reveals an economic trade-off that is frequently overlooked in discussions of lithium sustainability: the non-recovery of secondary salts. While evaporation-based systems allow the valorization of by-products such as potassium, DLE configurations are generally designed for selective lithium extraction, reducing opportunities for additional value generation [25,29].

A further finding concerns the divergence between technical indicators and territorial perceptions. In Chile, local communities report impacts on water availability and livelihoods even when technical assessments indicate improvements in operational performance. This discrepancy reflects differences in the production, validation, and interpretation of knowledge within governance systems, demonstrating that sustainability depends not only on biophysical outcomes but also on the institutional capacity to integrate scientific evidence, local knowledge, and meaningful participation.

In this context, knowledge co-production emerges as a critical element for strengthening the legitimacy of lithium development strategies and improving the governance of complex socio-hydrogeological systems.

7.5. Systemic Synthesis and Validation of the Framework

Overall, the empirical evidence from Chile demonstrates that technological adoption does not reduce impacts in net terms but instead reconfigures their distribution across system components. The analyzed cases show improvements in recovery rates and processing times while simultaneously generating new pressures on freshwater resources, energy systems, and hydrogeological management, thereby validating the trade-offs summarized in Table 2.

At the global scale, the results indicate that the technological transition driven by increasing lithium demand contributes to greater system complexity through the coexistence of multiple technological configurations and the variability of geochemical, hydrogeological,

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and regulatory conditions [60,62]. This complexity limits the transferability of technological solutions across contexts and reinforces the need for place-specific approaches.

Taken together, these findings validate the proposed analytical framework and support a shift from linear comparisons among extraction methods toward the evaluation of systemic configurations operating under specific constraints. This transition is both methodological and conceptual, as it enables sustainability to be understood as an emergent property arising from the redistribution of impacts among interdependent system components rather than as a characteristic attributable to individual technologies.

8. Study Limitations

This study acknowledges several limitations associated with data availability, the developmental stage of emerging technologies, and persistent knowledge gaps across key sustainability dimensions.

First, the analysis does not examine waste and by-product management in depth, particularly the fate of residual salts and the mechanisms available for value recovery. As a result, the study does not provide a fully integrated assessment of material flows throughout the lithium production system.

Second, a major source of uncertainty concerns brine reinjection in DLE technologies. Current knowledge remains limited regarding its long-term hydrogeological effects, including the potential risks of resource dilution, aquifer alteration, and changes in groundwater dynamics within salt-flat systems.

The analysis is also constrained by industrial confidentiality and by the pilot or pre-commercial status of many DLE projects. These conditions restrict the availability of complete, transparent, and independently verifiable operational data on critical variables, including water and energy consumption, reagent use, reinjection rates, operating costs, and long-term hydrogeological performance. Consequently, reported values often vary substantially across studies, generating broad performance ranges and, in some cases, significant discrepancies among sources. This variability complicates direct technological comparisons and reduces the level of certainty associated with specific performance indicators.

Furthermore, a substantial proportion of the available evidence is derived from pilot-scale tests, conceptual assessments, or corporate estimates developed prior to large-scale commercial deployment. As a result, actual performance may differ once these technologies operate under real production conditions and are subjected to long-term monitoring. Therefore, the comparisons presented in this study should be interpreted as an evaluation of trends, interdependencies, and trade-offs identified within the currently available evidence rather than as a definitive assessment of technological superiority or performance.

This limitation is particularly significant in the case of brine reinjection, where the scarcity of long-term empirical evidence hinders a robust evaluation of its effects on the hydrogeological functioning of salt flats. Similarly, the limited transparency surrounding some projects introduces uncertainty regarding the reproducibility and verifiability of reported indicators, especially when discrepancies arise among data reported by operators, independent studies, and observations from local communities and other territorial stakeholders.

These constraints reinforce the need for systemic analytical frameworks capable of integrating uncertainty, multiple sources of evidence, and the interdependent relationships that characterize lithium extraction systems.

Nevertheless, these limitations do not diminish the contribution of this study. On the contrary, they highlight the inadequacy of conventional approaches based on fragmented information and isolated indicators for understanding the complexity of lithium production systems. In this regard, the study further validates the identified research gap by demonstrating the need for systemic frameworks capable of explicitly incorporating uncertainty, interdependencies, and trade-offs into sustainability assessments of lithium extraction technologies.

9. Conclusions

The results of this study demonstrate that lithium extraction cannot be evaluated through linear approaches or isolated performance indicators. Instead, sustainability emerges as a systemic property resulting from interactions among technological processes, hydrogeological dynamics, territorial conditions, and governance structures.

The first finding reveals that extraction methods do not generate universal sustainability gains but rather redistribute impacts across interconnected subsystems. Improvements in specific variables are frequently accompanied by trade-offs in other dimensions, indicating that technological assessment should move beyond isolated performance metrics toward the systemic traceability of impact redistribution. This finding has important regulatory implications, as assessment frameworks based on individual thresholds or disconnected indicators are unable to capture the complexity of system-wide interactions.

The second finding confirms that technological performance is inherently context-dependent. The evidence shows that the viability of DLE technologies is not determined solely by technological characteristics but is strongly conditioned by hydrogeological constraints, water availability, and institutional arrangements. Consequently, assessment approaches should prioritize territorial and hydrogeological compatibility at the basin scale rather than rely on generalized comparisons among technologies. This highlights the need for adaptive regulatory frameworks capable of responding to local environmental and socio-institutional conditions.

The third finding demonstrates that the relationship between brine and freshwater constitutes a critical mechanism of impact reconfiguration. Reductions in brine consumption do not necessarily translate into lower overall water pressures; instead, pressures may be redistributed across other components of the system, including freshwater resources, energy demand, and chemical inputs. This underscores the need for integrated assessment approaches that treat water systems as coupled and interdependent units rather than as separate categories. In practical terms, long-term hydrogeological monitoring should focus on tracking interactions and flows among subsystems rather than solely measuring aggregate consumption indicators.

The fourth finding establishes that governance is not an external factor influencing sustainability but a structural component of it. The observed divergence between technical performance metrics and territorial perceptions demonstrates that sustainability depends not only on biophysical outcomes but also on institutional capacities to manage uncertainty, legitimacy, and socio-environmental conflict. Accordingly, regulatory frameworks should incorporate binding participation mechanisms and knowledge co-production processes as integral elements of decision-making rather than as supplementary consultation stages.

From a theoretical perspective, this study proposes a systemic sustainability model for lithium extraction (Figure 2) that integrates trade-offs, impact redistribution, hydrogeological interdependencies, and governance within a unified analytical structure. In contrast to conventional indicator-based approaches, the model conceptualizes sustainability as an emergent property of specific socio-technical configurations rather than as an intrinsic characteristic of individual technologies.

The proposed model advances existing literature by replacing fragmented assessments with an integrated representation of the interactions among technological systems, water resources, territorial dynamics, and institutional processes.

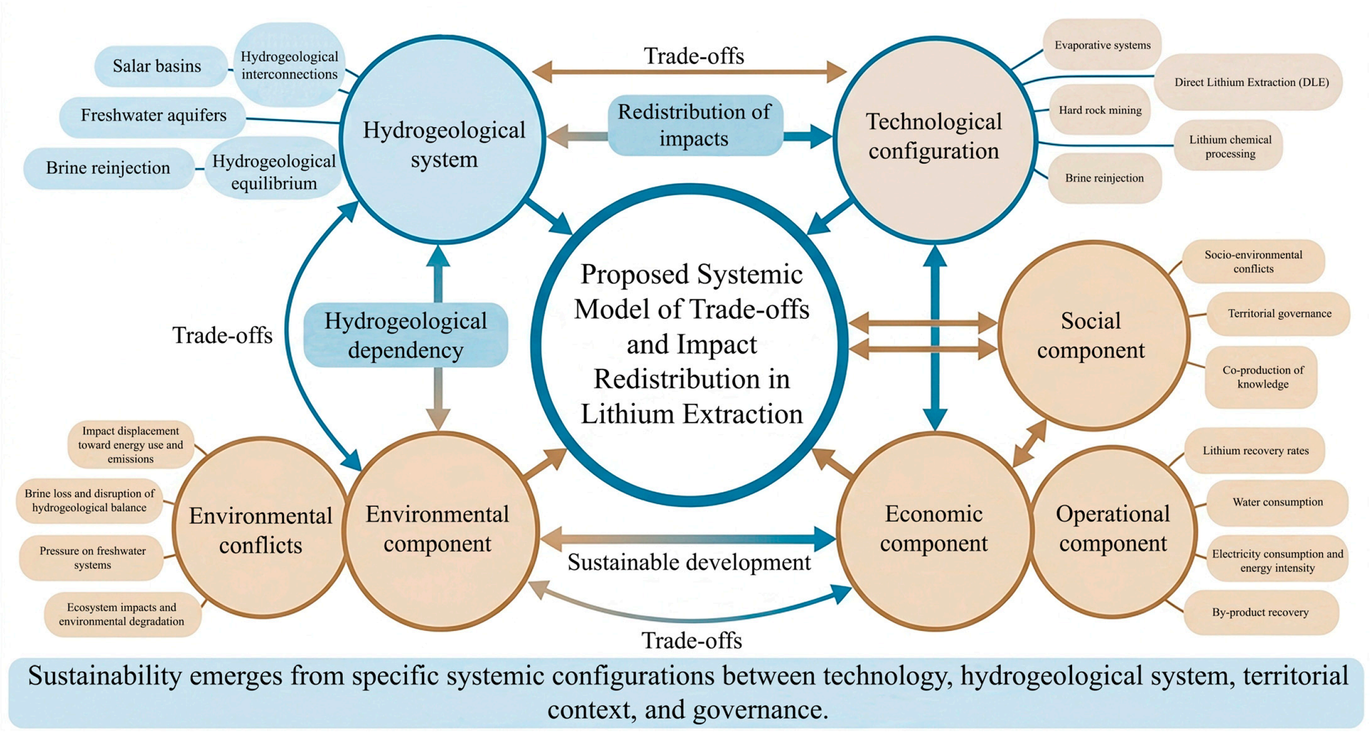

Figure 2. Proposed systemic model of trade-offs and impact redistribution in lithium extraction.

From a public policy perspective, the findings indicate that Chile requires a transition from regulatory approaches centered on operational metrics toward adaptive hydro-territorial governance models capable of capturing interactions among brine systems, freshwater resources, and productive activities. Achieving this transition will require strengthening long-term hydrogeological monitoring, improving interoperability among environmental information systems, and expanding territorial decision-making mechanisms with binding authority. In practical terms, the proposed framework can be operationalized as an ex ante assessment tool that compares alternative technological configurations under specific hydrogeological conditions rather than evaluating technologies in isolation.

For the Lithium Triangle, three strategic priorities emerge: (i) integrated evaluation of extraction technologies using multiscale performance criteria; (ii) explicit incorporation of hydrogeological uncertainty and cumulative effects into regulatory processes; and (iii) consolidation of governance mechanisms for shared basins. Together, these priorities support a shift from sectoral resource management toward the systemic governance of critical mineral systems. Future research should focus on developing quantitative socio-hydrogeological models capable of simulating impact redistribution under alternative technological and territorial scenarios.

Ultimately, this study contributes to redefining sustainability in lithium extraction. Rather than seeking to identify universally superior technologies, it demonstrates that sustainability depends on how socio-hydro-technological configurations manage interactions, constraints, and trade-offs across interconnected systems. The principal contribution is therefore structural rather than comparative: it shifts the analytical focus from technologies to configurations, from isolated indicators to interdependencies, and from static performance assessments to the dynamic processes through which sustainability emerges.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gas
DLE	Direct Lithium Extraction
LCA	Life Cycle Assessment
LCE	Lithium Carbonate Equivalent
ppm	Parts per million

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