

Review

Pathways to Greener Primary Lithium Extraction for a Really Sustainable Energy Transition: Environmental Challenges and Pioneering Innovations

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Abstract: The rapid increase in lithium demand has recently drawn attention to the environmental impacts of conventional mining processes. Pyrometallurgical extraction from hard rock is associated with high energy consumption, greenhouse gas (GHG) emissions, and land degradation. Extraction from brines involves the depletion of water resources and risks to local ecosystems. In response to these environmental challenges, this study explores innovative pathways for more sustainable primary lithium extraction for a truly green energy transition across the entire supply chain. This paper provides a comprehensive examination of novel technologies designed to mitigate these impacts, with particular emphasis on direct lithium extraction (DLE) technologies, which offer promising solutions for water savings, CO₂e emissions reduction, and improved lithium recovery. A comprehensive review of the scientific literature, along with an analysis of data and information from various pilot projects and demonstration plants, have been conducted. The main conclusion is that, despite considerable efforts by mining companies, two primary obstacles remain to the implementation of novel technology: scalability and operational costs. To address these challenges, it is essential to sustain consistent investments in R&D (Research and Development) initiatives and continue testing the implementation of the most sustainable experimental practices on an industrial scale.

Keywords: lithium extraction; direct lithium extraction (DLE); environmental sustainability; hard rock mining; Brine Extraction; renewable energy integration; water consumption reduction; carbon emissions mitigation; green energy transition; sustainable mining practices



Academic Editor: Qingguo Shao

Received: 17 November 2024

Revised: 23 December 2024

Accepted: 26 December 2024

Published: 28 December 2024

Citation: Ruberti, M. Pathways to Greener Primary Lithium Extraction for a Really Sustainable Energy Transition: Environmental Challenges and Pioneering Innovations. *Sustainability* **2025**, *17*, 160. <https://doi.org/10.3390/su17010160>

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1. Introduction

Lithium, the “white gold” or “white oil” of the green energy transition [1], is a critical component for a sustainable low-carbon future. It is the key element in lithium-ion batteries (LIBs), which power electric vehicles (EVs), renewable energy storage systems, and portable electronic devices. As nations strive to achieve ambitious carbon neutrality goals by the mid-century, lithium mining, and supply chains are under significant pressure to meet growing market demands for EVs and to face challenges due to environmental concerns and geopolitical constraints on resource access. In 2023, global lithium production, excluding that of the USA, increased by 23 percent, reaching approximately 180,000 tons, up from 146,000 tons in 2022; this growth was driven by a considerable rise in demand for LIBs, which account for 87 percent of global lithium end-users [2]. The growing demand for lithium, projected to increase 40-fold by 2040 [3], has led to a rapid expansion of primary lithium extraction, raising critical questions and challenges regarding the sustainability of these operations.

The transition to renewable and low-carbon energy sources require access to critical materials such as lithium, but the extraction of these resources must not come at the expense of the environment. While lithium is essential for the green transition to renewable energy, its current extraction methods risk undermining the same sustainability goals that they aim to support. This paradox has increased the demand for methods that enable lithium to be extracted more sustainably. Therefore, the mining industry is at a crossroads, tasked with ensuring an adequate supply of lithium while minimizing its environmental impact; this is both a challenge and an opportunity. For these reasons, promoting and implementing sustainable lithium mining practices is very important.

1.1. Background

The context of this research is closely aligned with global sustainability goals, such as those outlined in the Paris Agreement [4] and the United Nations Sustainable Development Goals (SDGs) [5]. Lithium is primarily extracted from two sources: hard rock (pegmatites) and brines (*salars*). The conventional extraction methods for these two sources—namely pyrometallurgical processes and solar evaporation—have been shown to cause significant environmental impacts. Pyrometallurgical processes are high-temperature methods used to extract metals like lithium from hard rock, involving heating minerals to extremely high temperatures to make lithium chemically reactive. The solar evaporation method is a traditional process where lithium-rich brines are pumped into large ponds and left to evaporate under the sun, leaving lithium salts behind. While cost-effective, it consumes considerable amounts of water.

Current lithium mining techniques are highly invasive and intensive, particularly in terms of land occupation, energy and water consumption, and GHG emissions [6]. Indeed, the extraction of minerals, mainly spodumene, from hard rocks, particularly in Australia, has been associated with considerable carbon emissions, habitat destruction, and extensive land degradation. This method also requires high energy consumption, partly due to drilling, blasting, and calcining processes, and involves the use of a significant amount of chemical reagents [7]. Brine extraction in regions such as the Lithium Triangle (Chile, Argentina, and Bolivia) involves pumping lithium-rich brine into large evaporation ponds. Although this method is less energy-intensive than hard rock mining, it has a significant water footprint, exacerbating water scarcity in arid regions like the Atacama Desert. The depletion of water resources significantly impacts local agriculture, community water access, and fragile local ecosystems [8].

In response to the challenges associated with conventional extraction, innovative solutions have been developed, and more sustainable alternative extraction technologies have been proposed. A substantial body of scientific literature and experimental data has emerged from research and industrial tests conducted in numerous pilot projects and demonstration plants in recent years. Among these, direct lithium extraction (DLE) technologies—based on adsorption, ion exchange, solvent extraction, and membrane separation—have emerged as some of the most promising innovations. DLE is a modern technique for recovering lithium from brines without relying on large evaporation ponds. It mitigates environmental impacts by improving water efficiency, reducing GHG emissions, and increasing lithium recovery rates.

1.2. Aim, Scope and Method

The research examines both conventional and innovative primary lithium extraction techniques that can facilitate a truly sustainable transition. It focuses on unconventional scientific, technological, and operational pathways that aim to achieve better outcomes: minimizing ecological impacts while preserving productivity and efficiency in the mining

process. This study is significant for several reasons. Firstly, it provides a comprehensive analysis of conventional extraction methods and their environmental implications, evaluating their efficiency, carbon emissions, and water use performance. Secondly, it assesses the potential of emerging technologies, examining their advantages, limitations, and production and environmental effectiveness. The objective is to offer a more detailed and accurate representation of the potential for lithium mining to evolve towards more environmentally friendly methods. Furthermore, this work identifies the most preminent initiatives by mining companies adopting the best environmentally sustainable strategies. These company-led initiatives play a crucial role in bridging the gap between laboratory-scale research and large-scale commercial application, serving as a test bed for innovative technologies and more sustainable best practices.

The scope of this study includes an analysis of both conventional and emerging extractive processes. The research examines the current state of pilot technologies and their evolution over the coming years, which are crucial for the energy transition. Geographically, the study focuses on major mining centers worldwide, with particular attention to mining-intensive regions such as Australia for hard rock extraction and South America for brine extraction. However, less explored but growing contexts, such as lithium extraction from geothermal waters and oilfield brines, will also be examined.

In terms of methodology, the research adopts an interdisciplinary approach, combining a systematic review of scientific literature and company reports with real case studies from demonstration and pilot plants. These case studies assess environmental performance metrics, including water consumption, energy consumption, and GHG emissions. This study is distinguished by its comprehensive and systematic examination of key tests and pilot plants used to evaluate the industrial potential of the most promising and sustainable extraction technologies proposed in previous experimental research.

To ensure methodological rigor and relevance, the selection of case studies and pilot projects follows clearly defined criteria. These criteria are designed to maintain consistency, comparability, and depth of analysis while addressing the research objectives, which focus on sustainable lithium extraction methods and their environmental implications. Case studies form the foundation for analyzing real-world applications of lithium extraction technologies, with the selection process prioritizing cases that offer a comprehensive understanding of innovative practices across different geographical and operational contexts.

The specific criteria include: (1) Relevance to research objectives: Case studies must directly pertain to innovative lithium extraction technologies, particularly those aimed at minimizing environmental impacts. (2) Geographical representation: To ensure a global perspective, the selection includes projects across various continents with distinct ecological contexts. Special emphasis is placed on regions with high lithium reserves, such as South America (e.g., the Lithium Triangle) and Australia. (3) Scale of operation: The study incorporates cases from large-scale industrial operations and small-scale pilot projects, ensuring the inclusion of both mature technologies and experimental or developmental methods. (4) Data availability and transparency: Selected case studies must provide accessible and verifiable data on operational methods, resource efficiency, energy consumption, and waste management practices.

The evaluation of pilot projects focuses on assessing the feasibility, scalability, and sustainability of experimental lithium extraction methods, highlighting best practices and identifying areas for improvement. The assessment framework employs standardized quantitative and qualitative metrics, enabling a multidimensional analysis of (1) Water usage: The volume of water extracted, consumed, and/or recycled per metric ton of lithium produced. (2) Carbon emissions: CO₂ equivalent emissions per metric ton of lithium produced. (3) Land use: The area of land disturbance, including measures for rehabilitation

and biodiversity conservation. (4) Waste generation: The quantity and types of waste produced, with a focus on tailings management and hazardous by-products. (5) Scalability: The potential to transition from pilot-scale to industrial-scale operations without significant environmental or economic trade-offs. (6) Operational efficiency: Metrics such as recovery rates, energy consumption, and technological reliability. This structured approach to case study selection and pilot project data evaluation ensures the methodological rigor and relevance needed to achieve the objective of this study.

2. Conventional Extraction and Environmental Implications

The two principal sources of economically important lithium ores are pegmatites (hard rocks containing mainly spodumene) and brines, which are lithium-rich salt lakes. Spodumene is typically mined from pegmatite deposits primarily located in Australia (Greenbushes, Wodgina, Earl Grey, and Pilgangoora), Canada (Tanco and Whabouchi), and Brazil (Grotta do Cirilo) [9]. Australia is the global leader in spodumene extraction, with projects such as Greenbushes producing substantial quantities of lithium concentrate [10]. Lithium-rich brine deposits are mainly found in the Lithium Triangle, which spans Chile (Salar de Atacama and Maricunga), Argentina (Centenario, Hombre de Muerto and Cauchari), and Bolivia (Salar de Uyuni) [11]. It is estimated that this region holds 54 percent of the world's lithium resources, with Chile hosting the largest known brine deposits.

2.1. Extraction from Hard Rocks by Pyrometallurgical Processes

The extraction of lithium from hard rocks, or lithium rock-based technology (LRT), is a typical process for pegmatites, which are lithium-rich intrusive igneous rocks containing spodumene ($\text{LiAlSi}_2\text{O}_6$) and petalite ($\text{LiAlSi}_4\text{O}_{10}$) [12]. This method, primarily conducted in Western Australia, is highly energy-intensive and environmentally impactful, involving multiple steps such as drilling, blasting, crushing, grinding, calcining, and roasting. The calcination of spodumene, the initial stage of pyrometallurgical processes, transforms its crystal structure from the α (inactive) phase to the β (reactive) phase. This transformation is essential to make the ore more reactive to subsequent chemical treatments [13]. However, it is particularly energy-intensive, requiring the heating of α -spodumene to approximately 1000 °C and accounting for a significant proportion of Scope 1 and Scope 2 GHG emissions [14]. Following calcination, the ore is combined with additives such as sulfates and chlorides (e.g., CaCl_2 or Na_2SO_4) and subjected to further heating at temperatures ranging from 800 to 1000 °C. This step facilitates the conversion of lithium into soluble forms, such as lithium sulfate (Li_2SO_4) or lithium chloride (LiCl), thereby enhancing extractability [15,16]. In some methodologies, the roasting step is followed by acid digestion using sulfuric acid (H_2SO_4), which significantly improves lithium recovery, particularly for lithium in complex structures. Acid digestion has been shown to achieve up to 90% extraction from β -spodumene at temperatures of approximately 250 °C [17]. The resulting Li_2SO_4 or LiCl solution is then processed through precipitation reactions to produce lithium carbonate (Li_2CO_3) or lithium hydroxide monohydrate ($\text{LiOH}\cdot\text{H}_2\text{O}$), making it suitable for industrial applications [18].

The total energy consumption for lithium extraction from spodumene, frequently derived from fossil fuels, is estimated at approximately 223 GJ per ton of lithium carbonate equivalent (LCE), making it more energy-intensive than alternative extraction methods, such as brine extraction and DLE. LCE is a standardized way to measure and compare lithium production, regardless of its chemical form, representing the amount of lithium contained in lithium carbonate. The estimated carbon emissions for producing one ton of LCE via LRT are around 20 tons of CO_2e , depending on process efficiency and the specific

energy source. Regardless of these variables, emissions are significantly higher than those associated with lithium extraction from brines [19].

The environmental implications of LRT are multifaceted and significant. They include, but are not limited to, land disturbance, deforestation, and the generation of tailings and waste materials. These implications stem, in part, from the use of chemical reagents in several steps to render lithium extractable, as well as from traditional open-pits or underground mining processes. Additionally, these operations have a considerable carbon footprint, contributing to Scope 1, Scope 2, and Scope 3 GHG emissions [20]. Specifically, Scope 1 emissions arise from direct mechanical extraction processes (drilling, crushing, etc.), Scope 2 emissions are associated with electricity consumption during pyrometallurgical processing, and Scope 3 emissions include those from transportation and downstream processing. Although water consumption in LRT is lower than that in brine extraction, substantial quantities of water are still required for ore processing and dust suppression. Freshwater demand for hard rock mining is approximately 80 cubic meters per ton of LCE produced [19].

Lithium extraction through open pit mining necessitates the removal of vegetation and topsoil, inevitably leading to the destruction of local habitats for numerous plant and animal species, as well as the potential loss of biodiversity. In Australia, for instance, the expansion of spodumene mines has had a deleterious impact on local ecosystems, resulting in habitat fragmentation and threatening vulnerable species. Furthermore, hard rock mining generates considerable quantities of waste, including tailings, which are often stored in large dams. These storage facilities pose potential risks such as acid waste leakage, tailings dam failure, and water contamination [21]. Tailings, which contain heavy metals (e.g., arsenic, cadmium, and lead) and processing chemicals, can contaminate local water systems if not properly managed, with adverse effects on aquatic ecosystems and human health [22]. The collapse of a tailings dam in Brumadinho, Brazil, in 2019 highlighted the severe consequences of inadequate tailings management practices, prompting increased regulatory scrutiny of tailings facilities across the mining industry [23].

Talison Lithium's Mine

The Greenbushes mine is managed by Talison Lithium, a joint venture between Tianqi Lithium Corp (Chengdu, China), which owns 51%, and Albemarle Corporation (Charlotte, NC, USA), which owns the remaining 49%. It is the largest and longest operating hard-rock lithium mine in the world, with high-grade spodumene ore [24]. Greenbushes is one of the oldest operating mines in Australia, with a history dating back to 1888, when it initially served as a mining site for tin and tantalum. Commercial lithium mining began in the 1980s, making it the first facility to produce lithium concentrate from a hard rock source [25]. The mine is a lithium–cesium–tantalum (LCT) family pegmatite deposit, measuring approximately 3 km in length and up to 300 m in width. It is located along the Donnybrook–Bridgetown Shear Zone within the Balingup Metamorphic Belt, which was formed approximately 2.5 billion years ago [26,27].

Mining is conducted via open-pit methods, employing drilling and blasting techniques, followed by ore transportation. The mine currently operates four processing plants. The first is a Technical Grade Plant (TGP), which produces concentrates from tailing retreatments for industrial applications. The second is a Chemical Grade Plant (CGP), designated CGP1, which produces spodumene concentrate suitable for conversion into lithium compounds for batteries. In 2019, an expansion was completed with the construction of the third chemical plant (CGP2), nearly doubling the mine's production capacity to 1.34 million tons per year of lithium concentrate. A fourth chemical plant (CGP3) is currently under construction, with the goal of further increasing production. The planned investment

for this project is approximately US\$ 382 million [25,26]. Greenbushes was the first Australian mining site to undergo an independent audit in accordance with the Initiative for Responsible Mining Assurance (IRMA) Standard. The aim of this initiative is to ensure responsible mining practices, encompassing environmental compliance and community engagement [28].

2.2. Extraction from Salars by Evaporation

Lithium brine-based technology (LBT) is the most common extraction method for various sources, including salars, geothermal, and oilfield brines. The world's main lithium production from liquid sources occurs in the salars of the Lithium Triangle (South America). The process is straightforward: low lithium concentration brines are pumped from underground aquifers into large solar evaporation ponds, where the crystallization and precipitation of less soluble salts occur. These salts include halite (NaCl), sylvite (KCl), potassium lithium sulfate (KLiSO₄), lithium sulfate (Li₂SO₄·H₂O), and others. The remaining higher-lithium concentration brine is then subjected to chemical processing in facilities near the extraction sites. This involves treatment with sodium carbonate (Na₂CO₃) to precipitate lithium as Li₂CO₃ [29–31]. The duration of this process depends on prevailing climatic conditions (e.g., temperature, humidity, solar radiation) and can extend from 12 to 18 months, increasing lithium concentration from 0.2% to 6% [32].

The extraction of lithium from brine is typically less energy-intensive than that from hard rocks, as the solar evaporation process does not require additional energy input. Furthermore, the environmental impacts of LRT are considerably greater than those of LBT, with differences reaching up to 60.4-fold [20]. Nevertheless, the process still requires energy (approximately 40 MJ per ton of Li₂CO₃), particularly for pumping the brine from the aquifer and its subsequent transportation. Emissions are lower, ranging from approximately 2.8 to 7.5 tons of CO_{2e} per ton of LCE [19,33].

The intensive water consumption during this process can significantly impact local water resources. The water footprint of this process is substantially higher, posing significant challenges in arid ecosystems [34]. On average, the extraction of one ton of lithium results in the loss of approximately 500 m³ of water, with serious ecological consequences for local ecosystems. The high water use has been the subject of considerable criticism and conflicts, particularly among local communities striving to safeguard their agricultural and livestock activities [35]. Furthermore, the chemical intensity, slow extraction rate, and substantial waste generation associated with this process present additional significant challenges [34].

The waste generated by brine extraction primarily consists of highly saline residual solutions containing considerable concentrations of magnesium, calcium, potassium, and other salts, along with trace amounts of heavy metals. These elements can cause environmental degradation if not adequately treated [34]. Managing and separating these cations requires integrated desalination processes, such as cation exchange membrane (CEM) electrolysis, to prevent the discharge of contaminants into groundwater or surface water [36]. The reinjection of spent brines into groundwater basins can alter natural salinity, potentially harming local fauna and flora [35,37]. Companies are exploring methods to treat these residual brines or repurpose them as by-products, such as potash (KCl), lithium chloride (LiCl), magnesium, sodium, calcium, and magnesium carbonate, with the goal of reducing waste [35,38,39].

Sociedad Química y Minera de Chile (SQM) and Albemarle's Mines

The largest and most important lithium brine extraction plant is in the Salar de Atacama, Chile. This site, operated primarily by companies such as SQM and Albemarle

Corporation, is a major global source of lithium. Covering an area of approximately 3000 km², the Salar de Atacama is one of the largest lithium deposits in the world, containing nearly 42 percent of global lithium reserves. The high lithium concentrations, which can reach up to 1500 ppm, enable an extremely efficient evaporation process, making the Salar de Atacama one of the most economical and productive lithium extraction sites globally [40]. However, the site raises significant environmental concerns, particularly regarding water consumption, which impacts local water resources and the fragile ecosystems of the Atacama Desert. Water withdrawal for lithium extraction has resulted in considerable effects on groundwater levels, with subsequent consequences for local populations and habitats [41]. For instance, in this region, where evaporation rates are exceptionally high, lithium mining has reduced water availability for local communities. Moreover, pumping activities have led to a decline in wetland areas, which are critical habitats for migratory birds and other wildlife. This has endangered species, such as the Andean flamingo (*Phoenicopterus andinus*), which rely on wetlands for survival and reproduction [42,43]. Conserving the biodiversity of these hypersaline lakes requires the implementation of rigorous, long-term monitoring programs that include key taxa such as *Artemia salina*. In this context, the Chilean government has granted mining companies new extraction quotas until 2030, raising concerns about whether economic demands can be reconciled with biodiversity conservation [44].

From an ecosystem balance perspective, a study [41] has identified lithium mining in the Atacama Desert as the principal stressor contributing to local environmental degradation. The study found that the continued expansion of lithium mining shows a strong negative correlation with the NDVI (Normalized Difference Vegetation Index) and SMI (Soil Moisture Index) and a strong positive correlation with LST (Land Surface Temperature). In response, SQM and Albemarle have integrated novel technologies to enhance process efficiency and minimizing environmental impact. Both companies have established carbon neutrality objectives, with SQM aiming to achieve neutrality for its lithium operations by 2030 [45]. Albemarle has implemented an advanced hydrogeological model to enable real-time monitoring of water conditions, while SQM has reduced its reliance on continental water resources by 50 percent and has set a target to achieve a 65 percent reduction by 2040 [46]. SQM was recently certified as IRMA 75, a recognized standard for sustainability practices in mining operations [47]. The IRMA 75 designation indicates that a mining operation has undergone an impartial third-party evaluation and achieved at least 75% compliance with the Initiative for Responsible Mining Assurance (IRMA) Standard [48]. Both SQM and Albemarle are actively investigating the potential implementation of DLE technologies, not necessitating evaporation ponds [49].

3. DLE Methods: Advantages and Challenges

Due to the considerable impacts of conventional processes, new technologies are being developed to improve resource-use efficiency and minimize adverse environmental effects. DLE, in particular, is rapidly gaining interest among major mining players. It overcomes the two main limitations of the solar evaporation method: long processing times and high water consumption. DLE technologies, completing a lithium concentration cycle in less than 24 h, are significantly more efficient and less dependent on environmental conditions than solar evaporation, which requires 12 to 18 months [50–52]. This significant time reduction enables a faster response to market demand, helping to prevent overproduction and stabilize prices and the overall supply chain. Moreover, DLE results in a substantial reduction in water consumption compared to conventional processes.

A flowchart provides a clear visual representation of the primary lithium extraction methods, outlining their respective steps and processes and emphasizing the differences in

complexity, resource use, and environmental impact between conventional and innovative technologies (Figure 1).

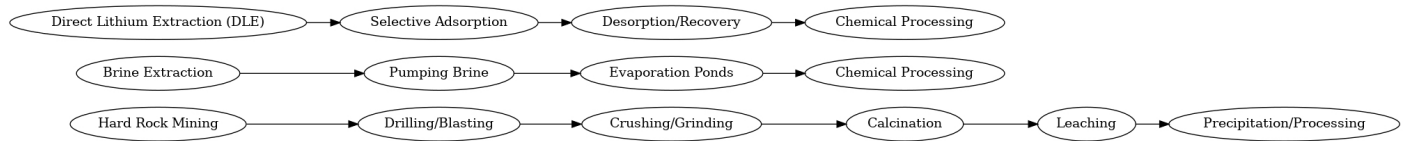


Figure 1. Flowchart of the three extraction processes [12–18,29–31,34–37,50–53].

For hard rock mining, the sequence begins with mechanical operations like drilling and blasting, followed by crushing, calcination, and chemical leaching, which are energy-intensive and environmentally impactful. Brine extraction highlights the traditional approach of pumping lithium-rich brine into evaporation ponds, where natural processes concentrate lithium over extended periods before chemical processing. DLE offers a more advanced and sustainable method, focusing on selective adsorption and desorption to extract lithium directly from brines, bypassing evaporation ponds and significantly reducing water and land use.

DLE methods achieve high lithium recovery rates, reaching up to 98–99% compared to the 30–50% recovery rate of evaporation methods [37,53]. The lithium recovery rates vary significantly across extraction technologies, reflecting their efficiency and suitability for different geological and operational contexts (Figure 2).

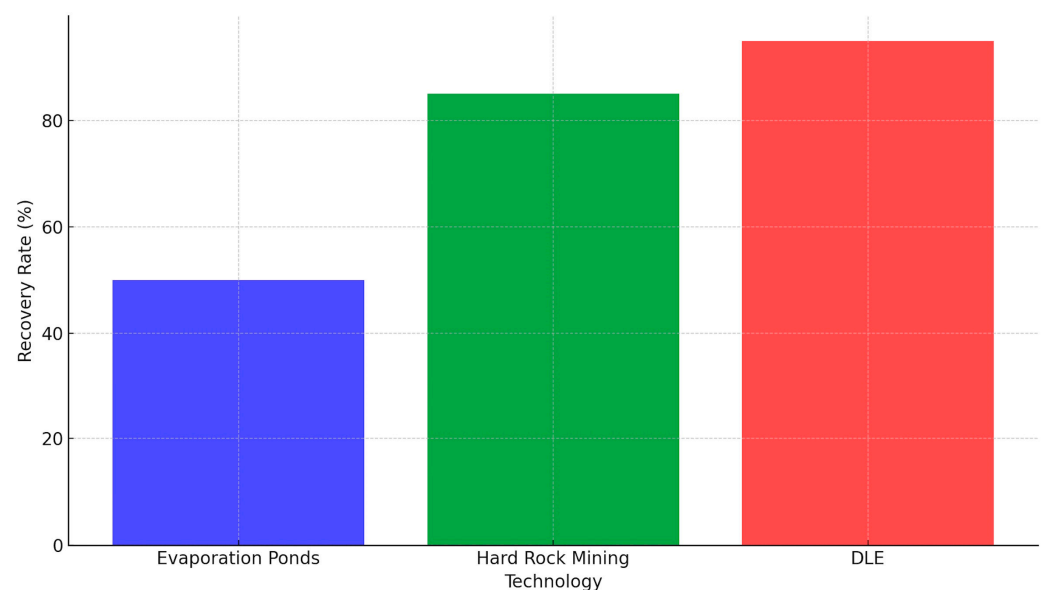


Figure 2. Lithium recovery rates by technology [13–18,29–31,37,53].

Evaporation ponds, while widely used, achieve a modest recovery rate of approximately 50%, highlighting inefficiencies inherent in the prolonged evaporation process. Hard rock mining methods show higher efficiency, with an 85% recovery rate, benefiting from advanced processing techniques despite their environmental and energy-intensive drawbacks. Direct Lithium Extraction (DLE) stands out with a remarkable recovery rate of 95%, showcasing its potential as a highly efficient and sustainable alternative. However, the scalability and economic feasibility of DLE remain critical challenges for widespread adoption. This enhanced efficiency not only increases productivity but also reduces the operational carbon footprint by minimizing the materials required to produce the same amount of final product. Moreover, DLE enables the extraction of lithium from marginal

resources that are unsuitable for evaporation methods, including low-concentration and geothermal brine [54,55].

Nevertheless, there are several technical and operational challenges to the scalability of DLE technologies. These include significant capital investment, high operating costs, expensive adsorbents, the need for responsible waste management, and greater energy requirements for the process. Collectively, these factors may limit the economic feasibility of DLE compared to traditional evaporation ponds [56]. Although DLE has shown promising results in pilot studies, its scalability for large-scale and complex operational contexts remains a work in progress. Further research and development are necessary to overcome these challenges and establish the commercial viability of DLE as a feasible alternative across different geological settings [37,57,58].

Another adverse environmental consequence is the generation of waste materials from the adsorbents. The periodic replacement of adsorbent materials, such as ionic sieves or zeolites, can result in waste that is difficult to dispose of properly. In particular, some inorganic compounds used as adsorbents require special disposal procedures to prevent environmental contamination [59]. Additionally, the regeneration of adsorbents using agents, such as acids or solvents, can generate hazardous chemical waste. This necessitates the implementation of rigorous management strategies to prevent soil and water resource contamination. It is essential that regeneration operations are conducted sustainably to minimize environmental impacts [60].

Some adsorption methods require considerable energy to regenerate the adsorbents. The environmental impact, in terms of CO₂ emissions, can be significant if the energy required for the regeneration process is derived from non-renewable sources [61]. The higher energy consumption of DLE compared to solar evaporation techniques—due to the active extraction and separation processes—can be mitigated through the use of renewable energy sources [62,63]. The comparison of water and energy consumption across lithium extraction technologies highlights significant variations in resource efficiency (Figure 3).

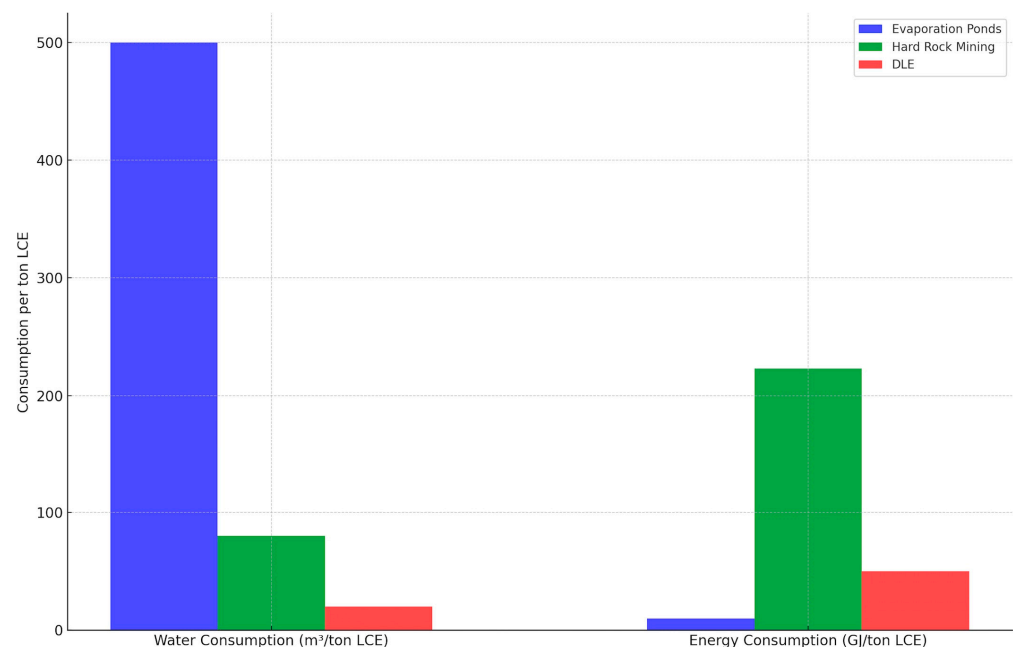


Figure 3. Water and energy consumption by technology [14,19,33–35,37,53,56,62,63].

Evaporation ponds are the most water-intensive, consuming approximately 500 m³ of water per ton of lithium carbonate equivalent (LCE), with relatively low energy requirements of 10 MJ/ton LCE due to reliance on natural evaporation. Hard rock mining

consumes far less water, at around 80 m³/ton LCE, but is the most energy-intensive, requiring 223 GJ/ton LCE due to high-temperature processes like calcination. Direct Lithium Extraction (DLE) emerges as the most resource-efficient option, using only 20 m³ of water per ton of LCE while consuming 50 GJ/ton LCE, a reflection of its advanced chemical and adsorption technologies.

The complexity of brine compositions and parameters (e.g., pH, temperature, organic carbon, solid suspended solids, ion concentrations, and Na/Li and Mg/Li ratios), which vary significantly between extraction sites, requires adaptation of DLE techniques to specific brine conditions, and research and testing to ensure process efficacy [52,64,65].

Another considerable challenge is the scalability of DLE (Table 1).

Table 1. Scalability insights on lithium extraction technologies.

Technology	Scalability Challenge	Key Barriers	Scalability Potential
Evaporation Ponds	Low	High land and water usage; long processing times	Easily scalable but unsustainable long-term
Hard Rock Mining	Moderate	Energy-intensive processes; high capital investment; environmental impact	Moderately scalable with established infrastructure
DLE	High	High costs for adsorbents and energy; site-specific brine customization	High potential but requires significant R&D and investments

Sources: [12–19,29–31,34–37,50–56,64,65].

In Table 1, there is a comparison of lithium extraction technologies, highlighting their scalability challenges, barriers, and potential and emphasizing the need for innovation to balance scalability with sustainability. Indeed, evaporation ponds are easily scalable but unsustainable due to high land and water usage. Hard rock mining has moderate scalability, limited by energy intensity and environmental impact. DLE shows high potential but requires significant R&D to address costs and customization to site-specific brine.

To date, various DLE techniques are being tested and implemented in several pilot projects and mining sites worldwide, particularly in regions where traditional extraction through solar evaporation would be less effective, too slow, or overly impactful. DLE enables the extraction of lithium from brines and other liquid sources using selective adsorbent materials, membrane separation, ion exchange resins, and solvents. Each of these methods involves distinct technologies with specific advantages and challenges regarding efficiency, scalability, and environmental impact.

3.1. Adsorption-Based DLE (A-DLE)

Specific adsorbent materials with a porous structure and high affinity for lithium (such as zeolites and clays) enable the selective and efficient adsorption of lithium from brines, even in the presence of interfering ions (e.g., Na⁺ and Mg²⁺), followed by its release during the desorption phase [37,51,66]. A-DLE does not require additional chemicals, thereby reducing its overall environmental impact and achieves high lithium recovery rates (up to 90%). Furthermore, A-DLE technologies reduce water consumption compared to solar evaporation [51], minimize surface and land use degradation [35], and significantly reduce the generation of saline waste [67]. However, these technologies require elevated operating temperatures and involve considerable initial costs, which can be a barrier to their implementation [68]. A-DLE encompasses various innovative methods and technologies that utilize specific ionic sieves, oxide materials, and functionalized nanomaterials. The

characteristics of each material vary, presenting both advantages and challenges related to adsorption capacity, selectivity, and the durability of regeneration cycles.

3.1.1. Research Studies

In this section, the research on materials offering more sustainable lithium capture methods with lower environmental impact and improved efficiency is briefly summarized.

- (a) Manganese Ionic Sieves (LMO-type LISs). Lithium ionic sieves (LISs) are categorized based on their chemical composition into lithium manganese oxides (LMO-type) and lithium titanium oxides (LTO-type). LMO-type LISs, such as LiMn_2O_4 , in the form of nanorods or nanocrystals, exhibit high lithium adsorption capacity (up to 37.5 mg/g) and excellent selectivity for Li^+ over competing cations (Mg^{2+} , Na^+ , and Ca^{2+}), thanks to their crystalline structure [69]. Often combined with inorganic supports, these sieves also demonstrate strong structural stability and easy regeneration [70–72].
- (b) Lithium Titanium Oxide Sieves (LTO-type LISs). $\text{H}_4\text{Ti}_5\text{O}_{12}$ nanorods show a high lithium adsorption capacity (23.2 mg/g in LiCl solutions), selectivity, and structural stability, retaining 91 percent of their capacity after five cycles. Lithium is adsorbed through an ion exchange process and released during acid treatment. Their porous structure and stability enable selective extraction even in brines with high Mg^{2+} concentrations, making them suitable for industrial applications [73].
- (c) Manganese–Titanium Ionic Sieves (M–T-type LISs). M–T nanocomposites selectively adsorb lithium from high-salinity brines. They feature high adsorption capacity (up to 25.85 mg/g) and resistance to desorption, enabling sustainable lithium recovery over multiple use cycles [74]. These materials are chemically and structurally stable, even in highly concentrated brines, and avoid interference from cations such as Mg^{2+} and Ca^{2+} [75]. They represent a promising alternative to solar evaporation and other DLE technologies [52].
- (d) Layered Double Hydroxides (LDHs). LDH adsorbents, such as Li/Al-LDH, selectively recover lithium from brines with high Mg/Li ratios, like those of the Qarhan Salt Lake. Their two-dimensional structure enables the selective binding of Li^+ ions. With adsorption capacities up to 7.27 mg/g and ease of regeneration, magnetic LDHs present a viable solution for lithium extraction [76,77].
- (e) Electrochemical Hybrid Materials. Combining A–DLE with electrochemical processes, such as iron-modified manganese oxides, enhances adsorption efficiency, improves selectivity in saline environments, and optimizes regeneration. Used in capacitive deionization (CDI) configurations, these materials achieve high lithium selectivity (up to 76%) over Na^+ and K^+ ions [78].
- (f) Macroporous Microspheres. Functionalized with specific chemical groups, like aminoethyl benzo-12-crown-4, these microspheres enhance lithium capture in highly saline solutions. They are synthesized via multiple emulsions and have a multi-chamber structure that enhances their lithium-binding capacity and enables repeated adsorption–desorption cycles. They present high selectivity and stability, retaining approximately 91.1% of the initial capacity after multiple regeneration cycles [79,80].
- (g) Zeolites. Zeolite 13X exhibits effective adsorption capacity (up to 20.3 mg/g), but improvements in selectivity and regenerability are needed. Zeolites are robust and stable, with recovery rates of 94–100% when using desorption solutions such as NaCl and CH_3COONa . However, acids used in desorption may cause dealumination, reducing durability [51,81]. Nanofibers incorporating zeolites and crown ethers (CEs) have shown improved lithium-specific adsorption mechanisms, offering high selectivity and adsorption capacity (~8.6 mg/g) with excellent stability after multiple cycles [82].

- (h) Carbon-based Materials. Ionically imprinted carbon nanoparticles, such as Fe_3O_4 (Li^+ -IIP- Fe_3O_4 @C), represent a significant advancement for selective lithium extraction. Magnetic nanoparticles, such as Fe_3O_4 support, modified with carbon materials and selective agents like 2-hydroxy-12-crown-4 achieve high adsorption capacity (up to 22.26 mg/g) and excellent regenerability, with only an 8.8% decline in efficiency after six cycles [83–85].

The following prospect (Table 2) provides a concise summary of key A-DLE methods for lithium extraction, highlighting their unique characteristics, recovery properties, and relevant references.

Table 2. Summary table of A-DLE methods.

Material Type	Key Characteristics	Retention Capacity	References
Manganese Ionic Sieves (LMO-type LISs)	High selectivity for Li^+ over Mg^{2+} , Na^+ , and Ca^{2+} ; strong structural stability; easy regeneration	37.5 mg/g	[69–72]
Lithium Titanium Oxide Sieves (LTO-type LISs)	Retains 91% capacity after 5 cycles; effective in high Mg^{2+} brines; stable porous structure	23.2 mg/g	[73]
Manganese-Titanium Ionic Sieves (M-T-type LISs)	Stable in high-salinity brines; resistant to desorption; chemically and structurally robust	25.85 mg/g	[74,75]
Layered Double Hydroxides (LDHs)	Effective in high Mg/Li ratio brines; easy regeneration; two-dimensional structure	7.27 mg/g	[76,78]
Electrochemical Hybrid Materials	Combines adsorption and electrochemical processes; achieves high selectivity in saline environments	Up to 76% selectivity	[78]
Macroporous Microspheres	Enhanced lithium binding with multi-chamber structure; retains 91.1% capacity after multiple cycles	91.1% retention	[79,80]
Zeolites	Robust and stable; requires improvement in selectivity and regenerability; effective desorption capacity.	20.3 mg/g	[51,81,82]
Carbon-based Materials	Magnetic nanoparticles with carbon support; excellent regenerability; minimal efficiency decline	22.26 mg/g	[83–85]

3.1.2. Demonstration Plants

This section reviews advanced technologies for sustainable lithium extraction, focusing on Summit Nanotech's DenaLi™, Qarhan Salt Lake, and Vulcan Energy Resources' Zero Carbon Lithium™ projects. These initiatives represent significant advancements toward more sustainable and efficient lithium production.

- (a) DenaLi™ Technology Demonstration Plant. Summit Nanotech Co.'s (Calgary, AB, Canada) DLE project utilizes its DenaLi™ technology to enhance lithium extraction from brines. In Chile's Salar de La Isla, Cobax Mining Ltd. (Santiago, Chile) and Summit Nanotech are collaborating to test this process. DenaLi™ technology employs selective nanomaterials to capture lithium from brines, using a reaction between LiCl and CaCO_3 . This approach reduces the need for chemicals, improves purity, conserves water resources, and shortens extraction time from 18 months to just 24 h. It optimizes water use by recycling it within the system [86–89]. To scale up its DenaLi™ technology, Summit Nanotech inaugurated a facility in Santiago in 2023, partnering

with local lithium producers. The facility is designed to expand in response to market demand and local policies, as highlighted during the recent Canada–Chile trade mission [88,90,91].

- (b) Qarhan Salt Lake A–DLE Plant. The Qarhan Salt Lake plant in China’s Qinghai Province is one of the most technologically advanced lithium extraction sites. It employs cutting-edge A–DLE techniques that minimize dependence on solar evaporation and mitigate impacts on local water supplies. The plant can produce up to 20,000 tons of battery–grade LCE (99.5%+) and 30,000 tons of general–grade LCE (95–98%). Trial operations were completed, and large–scale production began in 2021 with an initial capacity of 10,000 tons per year of LCE [92,93]. The Qarhan project employs Li/Al–LDHs and other materials to separate lithium from brines with high Mg/Li ratios. The adsorbents are regenerable, enhancing efficiency and reducing operating costs. Even after 12 cycles, the lithium adsorption process remains stable. Neutral water is used for regeneration, minimizing chemical reagent consumption. The adsorbents achieve a notable sorption capacity, with a separation coefficient between Li^+ and Mg^{2+} of 125. Additionally, the pilot plant is testing magnetic Li–Al layered double hydroxides (MLDHs). Fe_3O_4 nanoparticles enable the recovery of MLDHs via magnetic fields, further improving efficiency [76,77,94,95].
- (c) Zero Carbon Lithium™ Project. Vulcan Energy Resources Ltd.’s (Perth, Australia) Zero Carbon Lithium™ project integrates A–DLE with renewable energy to extract lithium from geothermal brines in Germany’s Upper Rhine Valley. Vulcan established the Lithium Extraction Optimization Plant (LEOP) in Landau, which began producing LiCl in 2023. This precommercial-scale facility is designed to refine the production process ahead of commercial production, planned for 2025. The technology has achieved up to 95 percent lithium recovery using Vulcan’s patented adsorbent, VULSORB® [96,97]. Vulcan aims to produce 24,000 tons/year of LiOH, sufficient to supply lithium for 500,000 electric vehicles. The geothermal energy integrated with lithium extraction results in a significantly smaller carbon footprint compared to traditional methods [98].

Below is a summarized prospect (Table 3) of the above projects, including the specific A–DLE technology employed.

Table 3. Summary table of A–DLE projects.

Project Name	Key Features	Production Capacity	A–DLE Technology	References
DenaLi™ Technology Demonstration Plant	Selective nanomaterials: LiCl reacts with CaCO_3 ; reduces chemical use, shortens extraction time to 24 h	Scalable facility in Santiago; aims to meet local demand	DenaLi™ technology with selective nanomaterials	[86–91]
Qarhan Salt Lake A–DLE Plant	Cutting-edge A–DLE techniques; regenerable adsorbents; high Mg/Li separation; stable over 12 cycles	20,000 tons battery-grade LCE; 30,000 tons general-grade LCE annually	Li/Al–LDHs and magnetic MLDHs with Fe_3O_4 nanoparticles	[76,77,92–95]
Zero Carbon Lithium™ Project	Integrates A–DLE with renewable energy; VULSORB® adsorbent; geothermal brine extraction; low carbon footprint	24,000 tons/year of LiOH; targets supply for 500,000 EVs	VULSORB® adsorbent integrated with geothermal energy	[96–98]

3.2. Membrane-Based DLE (M-DLE)

Highly selective semi-permeable polymeric membranes filter brines, separating lithium from other cations (such as Na^+ and Mg^{2+}) based on the size and chemical characteristics of ions. This method is one of the most promising and versatile technologies for lithium recovery, as it is highly selective and can be adaptable to different chemical compositions of brines. These membranes can also be integrated with other processes [54]. M-DLE does not require chemicals, offering advantages in terms of cost and environmental impact [54,55]. However, it is water-intensive, which could pose challenges in arid regions. Additionally, the effectiveness and versatility of the separation process are limited by several factors, including (1) membrane fouling, which necessitates frequent flushing or replacement [99]; (2) high-salt concentration brines, which can reduce separation efficiency. Moreover, this method is costly to implement, with high installation and operational expenses [68].

3.2.1. Research Studies

This section reviews advanced M-DLE technologies, including nanofiltration, metal-organic framework membranes (MOFs), electrodialysis with selective membranes (ED-ISMs), and methods based on innovative materials such as ion-imprinted polymers and oxidized graphene. These technologies offer notable advantages in selectivity and minimized use of chemical reagents. The implementation of advanced methodologies, such as capacitive deionization and thermally regenerative electrochemical cycles, demonstrates the potential to enhance energy efficiency and reduce environmental impact.

- (a) Nanofiltration (NF) and Reverse Osmosis. NF and reverse osmosis processes are advanced purification methods that remove Mg^{2+} and Na^+ ions, thereby improving the purity of extracted lithium. NF membranes have been optimized to enhance selectivity and resist slag deposit formation, increasing the efficiency of lithium separation from complex salt solutions [100].
- (b) Metal-Organic Frameworks (MOFs) Membranes. MOFs, due to their porous structure, efficiently separate lithium ions through a “host-guest” chemical process. These materials are particularly effective for brines with high Mg/Li ratios and can be incorporated into MOF-based membranes for selective lithium separation with minimal operational costs [101].
- (c) Electrodialysis (ED) with Ion Selective Membranes (ED-ISMs). ED applies an electric field to direct ion migration through ISMs, facilitating lithium separation. This method is well-suited for low lithium-content solutions, offering high energy efficiency and reduced reliance on chemical reagents [102]. Monovalent membranes enhance lithium separation in brines with high Mg content [103], reducing the Mg/Li ratio from 100 to 2 [52]. ED-ISMs significantly lower water consumption during separation [62], consume minimal energy (up to 16 Wh/g of Li) [104], and achieve lithium recovery rates of up to 96% without toxic reagents [52].
- (d) Ion-Imprinted Polymer-Based Membranes (IIMs). IIMs, designed by imprinted selective sites for lithium ions, exhibit high lithium selectivity and adsorption capacity. These membranes maintain efficiency even after regeneration, making them particularly suitable for recovering lithium from seawater. Esterified membranes demonstrate remarkable stability and energy efficiency in lithium recovery processes [105].
- (e) Capacitive Deionisation (CDI) with Anion Exchange Membranes (AEMs). The CDI-AEMs use carbon-based electrodes for lithium-ion removal, enabling energy-efficient desalination. The integration of anion-exchange membranes in hybrid CDI systems enhances selectivity, improving flux and extraction stability. This method is

- promising for recovering lithium from dilute solutions, offering precise control over energy input [106].
- (f) Thermo–Osmosis–Coupled Thermally Regenerative Electrochemical Cycle (TO–TREC). TO–TREC employs low-temperature solutions to extract lithium ions through electrochemical cycles, reducing electricity. This approach leverages industrial heat by-products and solar facilities to improve energy efficiency, making it a promising innovative technology [107].
 - (g) Ion–Specific Membranes for Electrolysis. Electrolysis membranes for DLE utilize a three-compartment reaction to selectively migrate ions and crystallize lithium into high-grade LCE. This process consumes fewer resources and results in less water evaporation compared to traditional methods [108].
 - (h) Polymer Inclusion Membranes (PIMs). PIMs use extractants, such as tributylphosphate (TBP)/FeCl₃ combined with polyvinyl chloride (PVC), to isolate lithium. This method is efficient and environmentally friendly, improving membrane stability and selectivity [109]. A combination of TBP/FeCl₃ in methyl isobutyl ketone (MIBK) enabled a 10–stage counter–current system achieving over 98% lithium recovery while reducing the Mg/Li ratio, making high Mg/Li brines viable lithium sources [110].
 - (i) Graphene Oxide (GO) Membranes. GO membranes for pervaporation effectively concentrate lithium (from 0.3 to 1.27 g/L) in brines with high salt concentrations. These membranes resist crystallization and maintain high flux rates, enabling concentration on a smaller surface area with a reduced environmental impact. However, this technique is economically unviable when the sole objective is lithium recovery [111].

The following prospect (Table 4) provides a concise summary of key M–DLE methods for lithium extraction, highlighting their unique characteristics, recovery properties, and relevant references.

Table 4. Summary table of M–DLE methods.

Material Type	Key Characteristics	Retention Capacity	References
Nanofiltration (NF) and Reverse Osmosis	Removes Mg ²⁺ and Na ⁺ ions; improves lithium purity	Enhanced efficiency; resists slag formation	[100]
Metal–Organic Frameworks (MOFs) Membranes	Effective for high Mg/Li ratios; minimal operational costs	Selective lithium separation	[101]
Electrodialysis (ED) with Ion Selective Membranes (ED–ISMs)	High energy efficiency; reduces Mg/Li ratio	Lithium recovery up to 96%; energy-efficient (16 Wh/g Li)	[52,62,102–104]
Ion–Imprinted Polymer–Based Membranes (IIMs)	High lithium selectivity; suitable for seawater recovery	Energy-efficient; maintains efficiency after regeneration	[105]
Capacitive Deionisation (CDI) with Anion Exchange Membranes (AEMs)	Energy-efficient desalination; improves flux and stability	Precise control over energy input	[106]
Thermo–Osmosis–Coupled Thermally Regenerative Electrochemical Cycle (TO–TREC)	Low-temperature extraction; utilizes industrial heat and solar energy	Improves energy efficiency; reduces electricity demand	[107]
Ion–Specific Membranes for Electrolysis	Selective ion migration; crystallizes high-grade LCE	Fewer resource requirements; high-grade LCE production	[108]
Polymer Inclusion Membranes (PIMs)	Environmentally friendly; high lithium recovery	98% lithium recovery; reduces Mg/Li ratio	[109,110]

Table 4. Cont.

Material Type	Key Characteristics	Retention Capacity	References
Graphene Oxide (GO) Membranes	Concentrates lithium in high-salt brines; reduced environmental impact	Up to 1.27 g/L concentration	[111]
Manganese Ionic Sieves (LMO-type LISs)	High lithium adsorption capacity (37.5 mg/g); strong structural stability	37.5 mg/g	[69–72]
Lithium Titanium Oxide Sieves (LTO-type LISs)	Retains 91% capacity after 5 cycles; effective in high Mg ²⁺ brines	23.2 mg/g	[73]
Manganese-Titanium Ionic Sieves (M-T-type LISs)	Stable in high-salinity brines; resistant to desorption	25.85 mg/g	[74,75]
Layered Double Hydroxides (LDHs)	Effective in high Mg/Li ratio brines; easy regeneration	7.27 mg/g	[76,78]
Carbon-based Materials	High adsorption capacity; excellent regenerability	22.26 mg/g	[83–85]

3.2.2. Demonstration Plants

Currently, several companies are engaged in testing and developing pilot- and industrial-scale M-DLE technologies. This section examines innovative solutions such as LiTASTM, ElectraLithTM, Northern Lithium's M-DLE, Li-ProTM, and AcQUATM.

- (a) LiTASTM (Lithium-Ion Transport and Separation) Technology. EnergyX Inc.'s (Austin, TX, USA) LiTASTM technology combines multiple DLE techniques. In collaboration with the Bolivian government, EnergyX has initiated the construction of pilot plants in the Salar de Uyuni with plans for large-scale deployment in the USA and Argentina. This method utilizes MOF membranes that selectively transport lithium ions, filtering lithium while blocking other ions (e.g., Na⁺ and Mg²⁺). MOF sub-nanometer pores ensure high selectivity even in high-salinity brines [112–115]. LiTASTM is a modular system offering scalability and adaptability. Multiple units can be connected to meet production demands, reduce costs, and minimize the use of chemical reagents [116]. With a lithium recovery of 90%, LiTASTM reduces extraction time from several months to a few days while using less water and renewable energy and emitting lower CO₂ compared to traditional methods [114,115,117].
- (b) ElectraLithTM Technology. ElectraLithTM, a spin-off from Monash University in Australia, has developed proprietary ED-ISM technology for recovering lithium efficiently and sustainably from geothermal and oilfield brines while conserving water. Pilot testing facilities have been established in Rincon, Argentina, with plans for further development over the next two years. The technology employs an ED process with ion-selective membranes made from polymer and ceramic materials designed to operate with minimal energy input. ElectraLith's "Reverse ED" system regenerates membranes without harsh chemicals, extending their lifespan and reducing costs. By eliminating evaporation ponds and utilizing renewable energy, ElectraLithTM significantly reduces water consumption and the CF of lithium mining [118,119].
- (c) Northern Lithium and Evove's Project. Northern Lithium Ltd. (Bishop Auckland, Durham, UK) and Evove Ltd. (Warrington, Cheshire, UK) are developing an M-DLE plant in north-east England. This approach will minimize energy and water consumption, aiming to provide a sustainable source of LCE in the UK [120]. The process utilizes polymeric or ceramic materials for selective lithium ion transport while blocking other ions [121–123]. Tests with UK brine have confirmed the efficiency and sustainability of this method [124,125]. The M-DLE project is modular,

allowing scalable expansion to increase production capacity. Initial operations aim for demonstration-level production at a facility in County Durham facility by autumn 2024, with full commercial production targeted for 2027 [126].

- (d) Li-Pro™ Technology. Koch Technology Solutions (KTS) Ltd. (London, UK) has developed the Li-Pro™ DLE project, which integrates advanced membranes with selective adsorption techniques for lithium extraction. Li-Pro™ employs PURON® MP ultrafiltration membranes made of PVDF (polyvinylidene fluoride) to remove particles and impurities, ensuring system efficacy and resistance to high-brine hardness [127,128]. The process relies on the Lithium Selective Sorption (LSS) system, which retains Li⁺ ions with up to 95% recovery efficiency. Treated water is recycled to reduce overall water consumption, and salt by-products are reused to enhance sustainability [129,130].
- (e) AcQUA™ Technology. LiTHOS Group Ltd.'s (Toronto, ON, Canada) AcQUA™ technology improves sustainability through patented pretreatment and a novel lithium concentration process. By eliminating evaporation ponds, freshwater consumption, and harsh reagents, AcQUA™ ensures environmental sustainability [131,132]. AcQUA™'s lithium concentration process uses a hybrid electro-pressor membrane. This process employs pressure gradients and electric fields to concentrate lithium in brines with a recovery efficiency of at least 89%, without chemicals or freshwater. It is faster and less energy-intensive than conventional methods [133,134]. Tested in a pilot plant in Bessemer, Alabama, AcQUA™ has shown promising results [132,133].

Below is a summarized prospect (Table 5) of the above projects, including the specific M-DLE technology utilized.

Table 5. Summary table of M-DLE projects.

Project Name	Key Features	Production Capacity	M-DLE Technology	References
LiTAS™ Technology	MOF membranes with sub-nanometer pores; scalable modular system; reduces extraction time to days	Pilot plants in Salar de Uyuni; scalable for large deployments in USA and Argentina	MOF-based modular system for selective lithium extraction	[112–117]
ElectraLith™ Technology	ED process with ion-selective membranes; reverse ED system regenerates membranes; renewable energy integration	Pilot facility in Rincon, Argentina; further development in the next two years	Polymeric and ceramic ion-selective materials	[120–126]
Northern Lithium and Evove's Project	Polymeric/ceramic materials for selective Li ⁺ transport; modular design for scalable expansion	Demonstration facility in County Durham by 2024; full commercial production by 2027	Polymeric and ceramic ion-selective materials	[120–126]
Li-Pro™ Technology	PURON® MP membranes for ultrafiltration; Lithium Selective Sorption system; 95% recovery efficiency	Advanced filtration system with recycled water; pilot-scale testing underway	PVDF ultrafiltration and LSS adsorption techniques	[127–130]
AcQUA™ Technology	Patented hybrid electro-pressor membrane; eliminates evaporation ponds and harsh reagents; 89% recovery efficiency	Pilot plant in Bessemer, Alabama; scalable for sustainable large-scale production	Hybrid electro-pressor membrane with patented concentration process	[131–134]

3.3. Ion Exchange–Based DLE (IX–DLE)

IX technology, which relies on specific materials that selectively exchange lithium ions with others in brines, is among the most promising and innovative DLE methods. It provides high lithium selectivity and separation efficiency, significantly reducing impurities in LCE. This technology is particularly well-suited for low-lithium concentration brines, making it highly versatile across a variety of geological settings. Furthermore, IX technology requires less water and energy, enhancing operational cost-effectiveness and resource efficiency. However, it necessitates the use of harsh chemicals, such as acids or bases, which may pose environmental and operational challenges. Furthermore, this method is associated with high initial costs and potential material degradation over time due to chemical exposure [68].

3.3.1. Research Studies

In this section, cutting-edge technologies for lithium extraction, including IX resins, electrochemical IX systems, and ionically imprinted polymers (IIPs), are examined. These advanced technologies enhance recovery efficiency and reduce environmental impact compared to conventional methods.

- (a) **IX Resins.** Cation exchange resins, such as those containing tin-antimony (SnSbA), exhibit a high degree of selectivity for lithium over other alkali ions, making them effective for separating lithium from seawater. Lithium is then eluted, and the resin is regenerated. This technology enables efficient separation even at low lithium concentrations due to the high affinity of the materials for this cation [135].
- (b) **Electrochemical Switched IX (ES–IX) Systems.** This technology utilizes electrodes coated with materials capable of selectively exchanging lithium during electrolysis. Through electrochemical intercalation with materials such as LiMn_2O_4 , a high IX capacity is achieved. The system demonstrates low energy demand and high separation capacity for lithium from other species in solution [136]. For instance, an ES–IX approach achieved a lithium recovery rate of 95% (10.88 mg/g) with minimal energy consumption (1.007 Wh per mole of LiCl) by recycling energy during ion separation [137].
- (c) **IX Membranes with Electrodialysis (ED) Processes.** In ED systems, cationic membranes operate within a three-compartment electrodialysis configuration to separate lithium and cobalt from LiCoO_2 in brines [138]. This setup allows selective lithium permeation, which is subsequently concentrated in a purified solution [139]. The process can reduce the overall water requirements by up to 90–95 percent by retaining treated water within the separation cycle [52], achieving lithium recovery rates of 94–100% [51].
- (d) **Multi-Phase IX Resins.** This technology integrates a multi-stage system combining cation exchange resins based on $\lambda\text{-MnO}_2$ to remove divalent metals and $\beta\text{-diketon}$ impregnated resins to remove Na^+ and K^+ , resulting in high-purity LCE. The process achieves 56% recovery of Li_2CO_3 with purity exceeding 99.9%, demonstrating its efficacy for purifying complex solutions. The resins employed are regenerable, enhancing the economic and environmental sustainability of the process [140].
- (e) **Inorganic Materials for Lithium–Specific IX.** Titanium antimonate (TiSbA) demonstrates exceptional selectivity for lithium, even in solutions with high concentrations of other cations, such as magnesium (Mg^{2+}) and calcium (Ca^{2+}). TiSbA is highly effective and versatile, especially for unconventional lithium sources like seawater and geothermal brines. The material can be regenerated with HNO_3 , reducing the need for additional exchange materials, improving process sustainability, and lowering long-term costs [141].

- (f) **FePO₄-Based ‘Rocking–Chair’ Batteries.** This LIB-based technique utilizes electrode materials, such as LiFePO₄, to selectively absorb Li⁺ from brines, significantly reducing the Mg/Li ratio in treated solutions. The “Rocking–Chair” system relies on a selective membrane with a dual-chamber configuration, enabling lithium recovery with high purity and reduced operating costs [142].
- (g) **Ionically Imprinted Polymers (IIPs).** IIPs, such as phthalocyanine-based polymers, selectively adsorb lithium from brines. Chemical modification creates active sites with strong lithium affinity, enabling highly selective separation even in brines with high levels of Na⁺ and Ca⁺. These polymers remain efficient even after multiple adsorption/desorption cycles. Regeneration is achieved through a desorption process utilizing low acid concentration solutions, reducing operating costs compared to other IX methods and minimizing environmental impact by reducing chemical waste [59].

The following prospect (Table 6) provides a concise summary of key IX–DLE methods for lithium extraction, highlighting their unique characteristics, recovery properties, and relevant references.

Table 6. Summary table of IX–DLE methods.

Material Type	Key Characteristics	Retention Capacity	References
IX Resins	High selectivity for lithium over alkali ions; effective at low lithium concentrations	Efficient separation; resin regeneration; effective for seawater	[135]
Electrochemical Switched IX (ES–IX) Systems	Electrodes coated with lithium-selective materials; low energy demand	Lithium recovery rate of 95% (10.88 mg/g); energy-efficient (1.007 Wh/mol LiCl)	[136,137]
IX Membranes with Electrodialysis (ED) Processes	Three-compartment ED configuration; selective lithium permeation	Water requirements reduced by 90–95%; lithium recovery rates of 94–100%	[51,52,138,139]
Multi-Phase IX Resins	Multi-stage system; removes divalent metals; high-purity LCE	56% recovery of Li ₂ CO ₃ ; purity exceeding 99.9%	[41]
Inorganic Materials for Lithium-Specific IX	Exceptional selectivity in high-cation environments; regenerable with HNO ₃	Effective for seawater and geothermal brines; improved process sustainability	[141]
FePO ₄ -Based ‘Rocking–Chair’ Batteries	Selective lithium absorption; dual-chamber configuration	Significant Mg/Li reduction; high-purity recovery	[142]
Ionically Imprinted Polymers (IIPs)	Strong lithium affinity; efficient after multiple cycles	Highly selective separation; low acid concentration for regeneration	[59]

3.3.2. Demonstration Plants

In this section, advanced lithium extraction technologies based on IX–DLE systems are analyzed. These innovations enhance the efficiency and sustainability of lithium extraction. The following demonstration plants have been identified as among the most promising for large-scale deployment.

- (a) **Geo40 Ltd.’s Technology.** Geo40 Ltd.’s (Taupo, Waikato, New Zealand) IX–DLE technology extracts lithium directly from geothermal fluids with low lithium content [143,144]. It utilizes an IX process in which lithium is selectively retained by optimized adsorbents, ensuring high selectivity and reducing energy requirements. Residual fluids are treated and reinjected into the geothermal layers, minimizing water consumption [145]. Field tests at the Ohaaki geothermal site in New Zealand

have demonstrated a separation efficiency of up to 90 percent, enabled by membranes with a nanostructured channel architecture [145]. Geo40's closed-loop system purifies and reintegrates geothermal fluids into the groundwater, ensuring minimal impact on local water resources [145,146].

- (b) **Lilac Solutions Ltd.'s Project.** Lilac Solutions Ltd.'s (Berkeley, CA, USA) IX-DLE process, part of the Standard Lithium Project, uses less water and has a smaller environmental footprint compared to conventional methods. It is also more cost-effective when using lower lithium concentration brines [147]. This technology uses ceramic spheres loaded with IX materials to absorb lithium from brine. Once saturated, lithium is extracted by acid washing, producing a LiCl concentrate refined to battery-grade LCE. The Lilac method uses 10 times less water than traditional technologies, with neutralized reagents to prevent hazardous waste [148]. In the Kachi Demonstration Plant project in Argentina, Lilac's IX technology achieved 80% lithium recovery at 99.9% purity, processing 5.2 million liters of brine under challenging conditions, demonstrating stability and scalability [149].
- (c) **E3 Lithium Ltd.'s Project.** E3 Lithium Ltd. (Calgary, AB, Canada), supported by Emissions Reductions Alberta (Edmonton, AB, Canada) and the Canadian government, is developing lithium mining infrastructure in Alberta. Using IX-DLE technology, E3 reduces water consumption and has demonstrated promising results in pilot tests [150–153]. The Clearwater project utilizes oilfield brines to produce battery-grade LCE, reducing production time from months to hours [151,152]. The project aims for an annual production of 20,000 tons of LiOH over 20+ years, with an estimated post-tax net present value of ~\$820M and a 27% internal rate of return [152]. It received a \$5 million grant from Emissions Reduction Alberta, with collaboration from the local government, petroleum, and mineral sectors [151,152].
- (d) **Conductive Energy's Process.** Conductive Energy Inc. (Calgary, AB, Canada) employs IX-DLE to extract lithium from brines and refine it into high-quality LCE. Its IX resins are compatible with various brine compositions, aiming to create a cost-effective and environmentally sustainable process with AquaMin Ltd. (Maidenhead, UK) at Berkshire Hathaway Energy Renewables' geothermal brine resource in the Salton Sea (CA, USA). Proprietary IX materials exhibit a strong affinity for Li⁺ ions. Once saturated, an elution process produces a concentrated LiCl solution, which is electrolytically refined into battery-grade Li₂CO₃ [154,155]. The system achieves up to 95 percent lithium recovery, maintaining a high impurity removal efficiency. Rapid IX material regeneration and minimal chemical usage contribute to reduced environmental impact and operating costs [155].
- (e) **SunResin's Project.** The Zangge Lithium Co. Ltd.'s (Golmud, China) project in Qinghai, China, utilizes IX-DLE technology to efficiently recover lithium with low environmental impact. With an estimated production capacity of 20,000 tons/year of LCE, it is poised to become a major DLE facility in the region [95,156,157]. SunResin's process employs columns filled with specialized resins to retain lithium. After saturation, lithium is recovered and converted into LCE [158,159]. The Simulated Moving Bed (SMB) technology reduces maintenance requirements and enhances efficiency through continuous resin regeneration. This approach lowers resin consumption, improves sustainability, and reduces operating costs [160]. Using water for resin purification instead of aggressive chemicals further limits environmental impact and minimizes waste, making the process cost-effective for long-term projects [95,157,159,161].

Below is a summarized prospect (Table 7) of the above projects, including the specific IX-DLE technology utilized.

Table 7. Summary table of IX–DLE projects.

Project Name	Key Features	Production Capacity	IX–DLE Technology	References
Geo40's Technology	Selective IX process with nano-structured membranes; closed-loop system reintegrates geothermal fluids	Field tests at Ohaaki site; demonstrated 90% separation efficiency	Nano-structured IX membranes with optimized adsorbents	[143–146]
Lilac Solutions Ltd.'s Project	Ceramic spheres with IX materials; acid washing for LiCl concentrate; uses 10× less water than traditional methods	Processes 5.2M liters of brine; achieves 80% recovery at 99.9% purity	Ceramic IX spheres with scalable acid washing process	[147–149]
E3 Lithium Ltd.'s Project	Uses oilfield brines; reduces production time from months to hours; significant government support	20,000 tons/year of LiOH over 20+ years; \$820M NPV and 27% IRR	IX with oilfield brines; advanced pilot testing underway	[150–153]
Conductive Energy's Process	Proprietary IX materials with high Li ⁺ affinity; electrolytic refining into battery-grade Li ₂ CO ₃	95% lithium recovery with high impurity removal efficiency	Rapid-regeneration IX materials; electrolytic lithium refinement	[154,155]
SunResin's Project	Specialized resin columns with SMB technology; continuous resin regeneration lowers costs and waste	20,000 tons/year of LCE; cost-effective for long-term projects	SMB-based resin columns; water-based resin purification	[156–161]

3.4. Solvent–Based DLE (S–DLE)

The S–DLE method utilizes a range of techniques that employ organic solvents to separate and recover lithium ions from brines or other complex solutions. This approach is highly effective in achieving high separation efficiency and is particularly well-suited for brines containing multiple salt ions. Its ability to process complex brines offers significant advantages across diverse locations and extraction scenarios. However, despite its benefits, the method is costly to implement and relies on organic solvents, which pose environmental risks and potential fire hazards [68].

3.4.1. Research Studies

The following S–DLE approaches, focusing on organophosphoric acids, ionic liquids, and complexing agents, aim to enhance DLE efficiency and sustainability, as supported by recent studies.

- (a) **Organophosphoric Acids (OPAs).** A widely used method employs organic phase agents (OPAs), such as di-2-ethylhexylphosphoric acid (D2EHPA), to recover lithium from geothermal sources. These extraction agents form stable complexes with Li⁺ ions, transferring them from the aqueous phase to the organic phase. The use of D2EHPA achieved a lithium recovery rate of 75% within approximately six hours, with an optimal pH of 1.5 [162].
- (b) **Ionic Liquids (ILs).** Ionic liquids combined with organic complexants, such as tri-*n*-butylphosphate (TBP), have proved effective for lithium extraction in high Mg/Li ratio brines, a common challenge. For example, the application of 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide demonstrated a lithium extraction efficiency of 92.37%. UV–vis and FT–IR analyses confirmed the formation of a 1:1 configuration of metal complex [163].

- (c) **Mixtures of Complexing Agents.** Systems utilizing combinations of extractive agents, such as D2EHPA and phosphates (e.g., Cyanex 923), dissolved in solvents like Shellsol D70, have been investigated for lithium recovery from treated brines. This method achieved 74% LCE with 97% purity. Its feasibility was demonstrated on a mini-pilot scale in countercurrent mode, highlighting its potential for industrial applications [164].
- (d) **Functionalized IL Microsystems.** Functionalized ILs, such as 1-hydroxyethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([OHEMIM][NTf₂]), paired with trialkylphosphine oxide (Cyanex 923), exhibited lithium extraction efficiencies exceeding 93% in a single operation. This success is attributed to an IX mechanism facilitated by the IL structure, making this approach highly effective in separating lithium from alkaline brine [39].
- (e) **Neutralizing Agents for Lithium Isotopes.** For specific applications, solvent extraction is used to separate lithium isotopes (such as ⁶Li and ⁷Li). Systems employing ILs, such as C8mim+PF₆⁻, combined with agents, such as 2,2'-binaphthyl-diyl-17-crown-5 (BN-17-5), allow for the enrichment of ⁶Li in the organic phase. This method achieves a separation factor of 1.046 ± 0.002 , demonstrating its high efficiency in isotope extraction [165].

The following prospect (Table 8) provides a concise summary of key S-DLE methods for lithium extraction, highlighting their unique characteristics, recovery properties, and relevant references.

Table 8. Summary table of S-DLE methods.

Material Type	Key Characteristics	Retention Capacity	References
Organophosphoric Acids (OPAs)	Uses organic agents (e.g., D2EHPA) to form stable Li ⁺ complexes; suitable for geothermal sources	75% lithium recovery within ~6 h at pH 1.5	[162]
Ionic Liquids (ILs)	Combines ILs with organic complexants (e.g., TBP); effective for high Mg/Li ratio brines	92.37% extraction efficiency; 1:1 metal complex configuration confirmed by UV-vis, and FT-IR	[163]
Mixtures of Complexing Agents	Utilizes combined extractive agents (e.g., D2EHPA and Cyanex 923) in solvents; demonstrated on mini-pilot scale	74% LCE recovery with 97% purity; scalable for industrial applications	[164]
Functionalized IL Microsystems	Functionalized ILs paired with trialkylphosphine oxide (Cyanex 923); IX mechanism facilitates separation	Lithium extraction efficiencies > 93% in a single operation	[39]
Neutralizing Agents for Lithium Isotopes	Solvent systems with ILs (e.g., C8mim+PF ₆ ⁻) and crown ethers; targets lithium isotope separation	Separation factor of 1.046 ± 0.002 for isotope enrichment	[165]

3.4.2. Demonstration Plants

This section reviews innovative S-DLE pilot plants designed to reduce environmental impact during lithium extraction, with a focus on the NeoLith Energy project as a significant advancement.

- (a) **NeoLith Energy Project.** Schlumberger Ltd. (Houston, TX, USA), in collaboration with Pure Energy Minerals Ltd. (Vancouver, BC, Canada), is advancing the Clayton Valley project. Pure Energy Minerals holds mineral rights to a 9450-hectare property in Clayton Valley. This partnership consolidates access to lithium resources and demonstrates the scalability of DLE technology. Following the test phase, the project may proceed

to further development stages. The NeoLith Energy pilot project in Clayton Valley, NV, USA, represents a breakthrough in sustainable DLE technology. By significantly reducing water consumption (over 85%) and minimizing environmental impact, this approach efficiently produces battery-grade LCE with shorter extraction times [166]. Schlumberger’s technology combines solvents, membranes, and electrochemical systems to concentrate and purify lithium directly from underground brines, ensuring a sustainable and efficient process [153,167].

- (b) Syensqo’s Technology. Syensqo’s (Bruxelles, Belgium) S-DLE technology employs the CYANEX® 936P extractor to efficiently separate lithium from brines. This solvent-based S-DLE process surpasses conventional evaporation methods in efficiency and sustainability. Cyanex® 936P selectively binds to lithium ions (Li⁺) in brines, transferring them from the aqueous to the organic phase and thereby yielding a concentrated lithium solution ready for purification. The process achieves a lithium recovery rate exceeding 99%, resulting in high-purity LCE within a few hours [168,169]. Unaffected by environmental conditions, this technology is adaptable to various brines and geothermal resources [168]. Furthermore, Syensqo’s closed liquid-liquid system minimizes water use, as the lithium-free brine is returned to the environment without altering its composition, ensuring sustainability [168–171].
- (c) Flionex® Technology. Adionics (Les Ulis, France) has developed Flionex®, a solvent-based liquid-liquid extraction system that produces high-purity LiCl while adapting to brines with high Mg²⁺ and Ca²⁺ concentrations, which typically hinder separation efficiency. Flionex® operates without conventional chemical reagents, conserving water and minimizing energy consumption [172]. The system uses a proprietary organic fluid that selectively extracts Li⁺ ions from other cations, following a “lock and key” model. This high-selectivity formulation achieves 99.8% recovery efficiency, producing high-purity LiCl. It efficiently handles lithium concentrations ranging from 50 to 80 mg/L without altering pH or generating toxic waste [172–174]. With a water consumption of less than 10 m³/ton of LCE and energy usage below 700 kWh and 1500 kWh per ton, Flionex® stands out as one of the most sustainable DLE systems in terms of water and energy savings [173,174].

Below is a summarized prospect (Table 9) of the above projects, including the specific S-DLE technology employed.

Table 9. Summary table of S-DLE projects.

Project Name	Key Features	Production Capacity	S-DLE Technology	References
NeoLith Energy Project	Combines solvents, membranes, and electrochemical systems; reduces water consumption by 85%; minimizes environmental impact	Pilot project in Clayton Valley producing battery-grade LCE with shorter extraction times	Integrated solvent, membrane, and electrochemical system for sustainable extraction	[153,166,167]
Syensqo’s Technology	CYANEX® 936P selectively binds lithium ions; adaptable to various brines; closed liquid-liquid system minimizes water use	High-purity LCE with 99% lithium recovery rate within hours	Solvent-based liquid-liquid extraction using CYANEX® 936P	[168–171]
Flionex® Technology	Proprietary organic fluid selectively extracts lithium; handles high Mg ²⁺ and Ca ²⁺ brines; conserves water and energy	99.8% recovery efficiency producing high-purity LiCl; processes brines with 50–80 mg/L lithium concentrations	Liquid-liquid extraction with proprietary organic fluid and ‘lock and key’ selectivity	[172–174]

4. Novel Approaches

In addition to the DLE process, other innovative methods for lithium extraction from both brine and hard rocks are being tested or implemented as more sustainable alternatives to conventional techniques. These technologies have the potential to significantly reduce environmental impact, particularly regarding water use, energy consumption, and GHG emissions, compared to conventional methods. Several pioneering companies worldwide, from the USA to Australia, are actively engaged in constructing large-scale demonstration plants and pilot projects to implement these novel techniques. It is worth noting that the majority of these methods are still in the experimental pilot stages or under commercial development. Each process offers specific advantages and challenges, with the selection of the most suitable approach often depending on the characteristics of the lithium reservoir and the availability of technological and financial resources.

The following sections provide an overview of the principal innovative technologies and industries for novel lithium extraction, including geothermal and oilfield brines, clay extraction, novel hard-rock methods, and bio extraction. This field of research is evolving dynamically, with promising new solutions emerging regularly. Continued investment in R&D is crucial to ensuring a more sustainable lithium supply in the future. The commercial success and large-scale deployment of these technologies will depend not only on the aforementioned factors but also on their efficiency, cost-effectiveness, and environmental sustainability.

4.1. Extraction from Geothermal Brines

Lithium extraction from geothermal brines, similar to DLE technology, utilizes a renewable source—geothermal hot water—for the co-production of electric or thermal energy. While this approach adds complexity to the process, it also enhances sustainability. The geothermal brine undergoes filtration and selective adsorption, after which the remaining water can be reused to power the extraction process or a cogeneration system. Geothermal brines, with lithium concentrations of up to 480 mg/L, represent a promising alternative source of lithium, which could be efficiently extracted using A-DLE processes [51]. However, despite its technical feasibility, significant challenges remain in developing an economically and environmentally sustainable process at a large scale [37].

The extraction of water from groundwater inevitably results in resource depletion. To mitigate potential negative effects, such as land subsidence, it is essential to replenish the extracted water. Additionally, geothermal energy production may generate GHG emissions, although at significantly lower levels compared to fossil fuel-based energy sources. The extraction process can also affect local ecosystems, particularly in environmentally sensitive areas. Furthermore, the implementation of this technology is geographically limited to regions with substantial geothermal reserves, and large-scale extraction remains in the experimental phase.

4.1.1. Research Studies

DLE from geothermal brines employs specific inorganic adsorbents and has been successfully tested in the Salton Sea geothermal field in California, demonstrating high recovery efficiency compared to conventional methods [37]. The use of highly selective materials with good chemical stability facilitates the retention of lithium ions from geothermal salt solutions [66]. For instance, Reich et al. [51] evaluated the potential of 13X zeolite as an adsorbent, demonstrating its capacity to adsorb up to 20.3 mg/g of lithium with high selectivity. However, the study also highlighted limitations for large-scale applications. Similarly, Paranthaman et al. [175] developed a three-step system using LDHs for the selec-

tive extraction of lithium from geothermal brines, achieving a lithium recovery efficiency of up to 91%.

Kalmykov et al. [176] identified membrane fouling and dirt accumulation as significant factors reducing system efficiency during lithium extraction from geothermal brines. They emphasized the need for low-cost membranes to alleviate the financial burden associated with frequent replacements.

Despite certain limitations, these techniques offer significant advantages over traditional methods, including reduced land impact, lower energy consumption, decreased carbon emissions, improved waste management, and more efficient water resource use. Unlike evaporative methods, geothermal extraction requires a minimal land footprint, as it eliminates the need for extensive evaporation ponds. Moreover, the use of geothermal energy reduces reliance on fossil fuels for brine heating and GHG emissions. Additionally, these processes generate less chemical waste and enable the recovery of valuable by-products, such as $\text{Mg}(\text{OH})_2$ [37,177].

4.1.2. Demonstration Plants

This section highlights more sustainable approaches adopted by CTR, EnergySource Minerals, and Geo Dipa Energi to improve sustainability in lithium mining.

- (a) **Controlled Thermal Resources' (CTR) Project.** CTR (Imperial, CA, USA) is a leading company in lithium extraction from geothermal brines, currently developing the Hell's Kitchen project at the Salton Sea Geothermal Field (SSGF), one of the largest geothermal deposits in the world. This initiative integrates geothermal power generation with DLE and forms a key part of the Lithium Valley development in the USA, gaining recognition for its commitment to a "zero emissions" approach [178]. The process employs DLE technology for lithium concentration, eliminating the need for evaporation ponds and reducing chemical usage, water consumption, extraction time, and environmental impact [179,180]. In its first phase, the project aims to produce 49.9 MW of geothermal energy and 25,000 tons/year of LiOH, with a potential output of up to 300,000 tons of lithium carbonate equivalent (LCE) and 1100 MW of electricity at full capacity [181]. Despite its promise, the Hell's Kitchen project faces two main technical challenges: the management of geothermal brines and membrane fouling [182].
- (b) **EnergySource Minerals' (ES Minerals) Project.** ES Minerals LLC (San Diego, CA, USA) is advancing lithium extraction from geothermal brines using proprietary technology in collaboration with the SSGF. Its ATLiS project integrates geothermal energy with sustainable lithium extraction, utilizing heat and geothermal fluids from the John L. Featherstone Power Plant. The ATLiS project employs ES Minerals' ILiAD™ platform, which achieves lithium recovery with 99% purity and 90% efficiency. ILiAD™ technology incorporates lithium-selective adsorbents, and its desorption system uses water instead of chemicals, reducing costs and water consumption by up to nine times compared to traditional methods. The modular "plug and play" unit is adaptable to different locations and brine compositions [183–185]. Furthermore, ILiAD™ technology significantly reduces land use and GHG emissions [186]. However, challenges remain in scaling up the technology and addressing membrane fouling, a common issue in DLE systems that could impact industrial efficiency [183,187].
- (c) **Geo Dipa Energi's Project.** Geo Dipa Energi (Jakarta Selatan, Indonesia) is focused on recovering lithium from geothermal brines at the Dieng Geothermal Plant in Indonesia. These brines, containing lithium and other minerals, are a by-product of geothermal power generation. Lithium concentrations in the Dieng area range from 36 to 86 mg/L, with the potential to produce 1500–2400 tons/year of LCE.

Geo Dipa is exploring A–DLE technologies utilizing lithium–specific adsorbents that evaporation ponds [188], thereby reducing water usage and land use. The technology will be selected based on site-specific conditions to optimize recovery efficiency [189,190]. This A–DLE process is environmentally sustainable, producing minimal CO₂ emissions, requiring only 3 m³ of water per ton of lithium extracted, and maintaining a land footprint of 1 m²/ton of lithium extracted [188].

Below is a summarized prospect (Table 10) of the above projects, including the specific extraction technology employed.

Table 10. Summary table of geothermal brine projects.

Project Name	Key Features	Production Capacity	Extraction Technology	References
Controlled Thermal Resources' (CTR) Project	Integrates geothermal power with DLE; eliminates evaporation ponds; reduces environmental impact and extraction time	25,000 tons/year of LiOH; 49.9 MW geothermal energy; potential up to 300,000 tons LCE and 1100 MW electricity	DLE with zero emissions approach	[178–182]
EnergySource Minerals' (ES Minerals) Project	ILiAD™ platform with lithium-selective adsorbents; uses water for desorption; modular 'plug and play' units	99% purity and 90% efficiency; adaptable to various brine compositions	ILiAD™ platform with lithium-selective adsorbents	[183–187]
Geo Dipa Energi's Project	Focuses on recovering lithium from geothermal brines; reduces water and land usage; minimal CO ₂ emissions	1500–2400 tons/year of LCE; Dieng brine lithium concentrations of 36–86 mg/L	A–DLE using lithium-specific adsorbents	[188–190]

4.2. Extraction from Oilfield Brines

The recovery of lithium from oilfield brines is an emerging area of study, targeting the extraction of unconventional and potentially significant resources, specifically brines derived from oil and gas extraction operations. Although further advancements in separation technologies are required to address the inherent complexity of oilfield brines, progress in A–DLE, IX–DLE, and M–DLE technologies has the potential to render these resources both economically and environmentally viable [37]. Oilfield brines contain a variety of metals, including lithium, at varying concentrations. Lithium levels are positively correlated with potassium concentrations and inversely correlated with pH. For instance, brines from the Montney Formation in the Western Canada Sedimentary Basin have been found to contain lithium concentrations up to 79 mg/L, while brines from other formations, such as the Smackover Formation in the United States, exhibit average concentrations ranging from 100 to 500 mg/L [191].

4.2.1. Research Studies

Recent studies have investigated the potential for extracting lithium from wastewater generated by North Sea oilfields (Montrose, Brisling, Nelson, Ekofisk, etc.) using lithium-specific IX membranes of LiMnO₂. These membranes enable the selective separation of lithium in concentrated solutions, achieving an efficiency of 9.94 mg/g. However, further development is necessary to optimize their application in complex industrial settings characterized by high salt concentrations [192]. In some cases, such as lithium-containing waters from the Smackover oil fields (Arkansas, USA), chemical precipitation techniques have been employed to isolate lithium directly from brines. This involves the use of precipitating agents, such as diketone (e.g., dipivaloylmethane), which act as chelating agents that form insoluble lithium compounds [193]. While the S–DLE methodology is less

selective, it can be effectively combined with other innovative technologies to enhance the purity of lithium compounds. The integration of lithium extraction processes with existing oil and gas production infrastructure offers advantages in terms of reducing implementation costs and improving logistical efficiency. However, the chemical complexity of oilfield brines, which often contain high concentrations of other ions (e.g., magnesium, calcium, and sodium), poses significant challenges to the lithium extraction process. Research efforts are therefore focused on developing advanced IX materials and specialized membranes to improve the selectivity and purity of LCE [194].

4.2.2. Demonstration Plants

This section reviews innovative lithium extraction projects from oilfield brines in Alberta, Canada, focusing on advanced technological developments of the Rainbow Lake project of Volt Lithium (VLT) Corp. and the partnership between POSCO Holdings and Invest Alberta Corporation.

- (a) Volt Lithium (VLT) Corp's Project. The Rainbow Lake Project extracts lithium from oilfield brines in northwestern Alberta. VLT (Calgary, AB, Canada) aims to become North America's first producer of battery-grade LCE, with an initial production capacity of 20,000 tons/year. VLT has secured rights to over 430,000 acres of land at Rainbow Lake, where brine contains lithium concentrations of up to 121 mg/L. The brines are sourced from three major aquifers being utilized as a by-product of oil operations [195–197]. VLT employs the IX–DLE technology, IES–300, in two primary stages: (1) Brine treatment: Purification of brines to remove impurities, including heavy metals and other cations. (2) Lithium extraction: Concentration of lithium into a LiCl solution, subsequently converted into battery-grade LCE [196,198]. In its 2023 pilot program, VLT achieved lithium recovery rates of up to 98%, producing Li_2CO_3 with a purity of 99.5%. The pilot program demonstrated operating costs below CA\$4000 per ton, making the project highly competitive within the lithium industry [196].
- (b) The partnership between POSCO Holdings Inc. and Invest Alberta Corporation (IAC). POSCO Holdings Inc. (Seoul, Republic of Korea) and IAC (Edmonton, Alberta, Canada) have partnered to develop lithium extraction projects from oilfield brines in Alberta, Canada. The collaboration was formalized through a Memorandum of Understanding (MOU) signed in November 2023 [199], aimed at assessing and optimizing commercial extraction processes [199,200]. The initiative leverages Alberta's established resource infrastructure, accessing North American markets and facilitating project implementation [201]. POSCO plans to deploy advanced DLE technologies, enabling selective lithium extraction without the need for evaporation ponds. This approach minimizes environmental impact, significantly reduces water consumption, and is compatible with existing oilfield infrastructure [202,203].

Below, there is a summarized prospect (Table 11) of the above projects, including the specific extraction technology employed.

4.3. Extraction from Clays

The extraction of lithium from clays through closed-loop processes represents an innovative approach designed to recover lithium in a sustainable and cost-effective manner. Although the study of lithium extraction from clays has spanned decades, recent advances in extraction chemistry have rendered the process economically viable. Clay resources are abundant in specific regions, and the extraction process generates less waste and requires less water compared to traditional brine evaporation methods. Additionally, the reagents and water utilized in the process can be recycled, and the extraction process can be

integrated with other mining operations. However, the method requires the use of chemical reagents (e.g., acids or bases) as solvents, necessitating careful management of chemical waste [6,204]. For example, a process for lithium extraction from borax-containing clays has demonstrated that leveraging by-products and low-cost resources can significantly lower operating costs. A robust design, as illustrated by the borax clay industry in Turkey, can enhance productivity by reducing variability in LCE purity and minimizing overall expenses [205].

Table 11. Summary table of oilfield brine projects.

Project Name	Key Features	Production Capacity	Extraction Technology	References
Volt Lithium (VLT) Corp's Project	Extracts lithium from oilfield brines; employs IES-300 IX-DLE technology; two-stage brine treatment and lithium extraction process	20,000 tons/year of battery-grade LCE; lithium recovery rate of 98%; purity of 99.5%	IES-300 IX-DLE technology	[195–198]
POSCO Holdings and Invest Alberta Corporation (IAC) Partnership	Develops lithium extraction projects leveraging Alberta's infrastructure; uses advanced DLE technologies compatible with oilfield operations	Focuses on optimizing commercial extraction processes; production targets yet to be defined	Advanced DLE technologies (specific details not disclosed)	[199–203]

4.3.1. Research Studies

A recent study [206] has developed a closed-loop process for lithium recovery from aluminum-rich clay ores, combining solvent extraction with selective precipitation. This process employs organic H_3PO_4 to separate lithium from other clay components. The recycling of the reagent significantly reduces chemical resource consumption, achieving an extraction efficiency of 92%. In a closed-loop system, this approach minimizes hazardous waste production by reintegrating by-products into the process or recovering them for alternative applications. For instance, a method utilizing a Na_2SO_4 solution facilitates efficient lithium extraction from spodumene clays in a closed-loop configuration, thereby reducing H_2SO_4 consumption and limiting waste generation [207].

4.3.2. Demonstration Plants

This section examines innovative projects to extract lithium from lithium-rich clays, focusing on Lithium Americas' Thacker Pass and Ioneer Ltd.'s Rhyolite Ridge. These projects reflect advancements toward sustainable technologies, improving extraction efficiency while minimizing environmental impacts in the context of the energy transition.

Lithium Americas' Project. Lithium-rich clays, such as hectorite from the Thacker Pass deposit in the USA, represent an unconventional lithium source. The clays are mined and treated using alkaline or acid solutions in a closed-loop process. Lithium Americas Corp.'s (Vancouver, BC, Canada) Thacker Pass project is one of the most significant global initiatives, employing advanced clay leaching techniques to extract lithium from hectorite ore in the McDermitt Caldera (Nevada, USA), an area of substantial lithium-rich clay deposits. The process incorporated a closed-loop Zero Liquid Discharge (ZLD) system, allowing for the recycling of water up to seven times during production, achieving a reuse rate of over 80% [208]. The facility produces 40,000 tons of LCE annually, with a potential for 80,000 tons. Lithium Americas received \$2.26B in DOE funding to establish a sustainable critical minerals supply chain and facilitate the energy transition, with GM investing \$650 million in the project to secure lithium for its Ultium batteries [209–212]. The Thacker Pass project represents a significant step toward US lithium self-sufficiency. The facility employs

Dry-Stacked Tailings (DST) technology, which extracts water from mining tailings for reuse and stores compacted material to limit environmental contamination, reducing the need for large liquid waste storage facilities. Additionally, the project includes an onsite H_2SO_4 plant, generating 45 MW of energy through a cogeneration (CHP) system to minimize CO_2 emissions [213,214].

Ioneer Ltd.'s Project. Ioneer Ltd.'s (Sydney, Australia) Rhyolite Ridge Project, located in Esmeralda County, Nevada, is a major lithium and boron mining initiative. It is the only known deposit in North America with clay rich in both lithium and boron, making it a critical future source of essential minerals for battery production and industrial applications in the USA. The leaching technology employed in this project has been optimized to reduce environmental impact and enhance recovery efficiency. Rhyolite Ridge is projected to produce 20,600 tons of Li_2CO_3 and 174,400 tons of boric acid annually, supporting a 26-year production cycle. The strategy leverages revenue from boric acid production to offset lithium extraction costs [215,216]. Environmental impacts are minimized by avoiding the use of evaporation ponds and tailings dams. The process utilizes excess steam from its onsite sulfuric acid plant to generate electricity, reducing reliance on the grid. Production is slated to begin in 2025, with strategic partnerships established with Ford Motor Company and Sibanye-Stillwater to support its operations [215–219].

Below, there is a summarized prospect (Table 12) of the above projects, including the specific extraction technology utilized.

Table 12. Summary table of the lithium extraction projects from clays.

Project Name	Key Features	Production Capacity	Extraction Technology	References
Lithium Americas' Thacker Pass Project	Employs advanced clay leaching; closed-loop Zero Liquid Discharge system; Dry-Stacked Tailings technology; onsite H_2SO_4 plant with cogeneration system	40,000 tons of LCE annually, expandable to 80,000 tons; \$2.26B DOE funding; GM investment of \$650M	Closed-loop alkaline/acid leaching with ZLD and DST systems	[208–214]
Ioneer Ltd.'s Rhyolite Ridge Project	Lithium and boron extraction; optimized leaching technology; avoids evaporation ponds and tailings dams; onsite sulfuric acid plant for electricity generation	20,600 tons of Li_2CO_3 and 174,400 tons of boric acid annually; 26-year production cycle	Optimized leaching for lithium and boron; integrated energy recovery from sulfuric acid plant	[215–219]

4.4. Novel Hard-Rock Mining Processes

The extraction of lithium from hard rocks, such as spodumene, has traditionally been a highly energy-intensive process. However, recent advancements are improving the efficiency of this methodology. Innovative hydrometallurgical techniques are emerging as less environmentally damaging alternatives to pyrometallurgical processes, each characterized by reduced energy consumption and lower pollutant emissions. The adoption of advanced leaching methods that utilize less corrosive acids has significantly mitigated the environmental impact of chemical processing.

4.4.1. Research Studies

A recent study [220] demonstrated that hydrometallurgical extraction using organic acids, such as citric ($\text{C}_6\text{H}_8\text{O}_7$), oxalic ($\text{C}_2\text{H}_2\text{O}_4$), and formic (HCOOH) acids, in aqueous solutions, could potentially reduce environmental impact compared to traditional methods reliant on strong acids. These biodegradable organic acids enable efficient lithium extraction from sources such as treated spodumene. For example, the combination of citric acid with hydrogen peroxide (H_2O_2) has shown high recovery efficiency and reduced gener-

ation of toxic byproducts. The hydrothermal alkaline leaching method employs sodium hydroxide (NaOH) or other alkaline reagents under hydrothermal conditions to extract lithium from minerals like spodumene, avoiding the high temperatures typically required in pyrometallurgical processes. Using NaOH in a closed-loop system facilitates the direct decomposition of the alpha-spodumene crystal structure under moderate pressure and temperature conditions, thereby reducing energy consumption [221].

Combining vacuum pyrolysis with hydrometallurgy—utilizing moderate temperatures in oxygen-free environments followed by hydrometallurgical leaching—provides a more environmentally sustainable approach to processing complex lithium sources [222]. This process achieved a leaching efficiency of approximately 90% under alkaline conditions [221]. Another alternative involves the use of sodium sulfate (Na_2SO_4) and NaOH as additives during spodumene roasting, enabling more effective and less impactful lithium extraction compared to H_2SO_4 , with an efficiency of about 90.7% [14,207,223].

In summary, while these initiatives support the use of extensively studied resources and enable direct lithium extraction from high-concentration sources, they remain energy-intensive and generate waste. Despite potential advancements that could lower their environmental impact and energy demands, these processes are not yet considered environmentally sustainable.

4.4.2. Demonstration Plants

This section examines advanced lithium extraction technologies employed by Pilbara Minerals and Lepidico Ltd. at their Pilgangoora projects.

Pilbara Minerals' Project. Pilgangoora, operated by Pilbara Minerals Ltd. (West Perth, Australia), is among the world's largest hard rock lithium mines. Initially developed by Altura Mining and acquired by Pilbara Minerals in 2020, the ore is processed using a High-Pressure Grinding Roll (HPGR) system and a Dense Media Separation (DMS) circuit to produce spodumene concentrate and tantalite. The plant currently produces 540,000 to 580,000 tons of spodumene concentrate annually. Planned expansion, including the P680 and P1000 projects, aims to increase production by 100,000 and 320,000 tons/year, respectively, reaching a total annual capacity of 1 million tons by 2025 [224,225]. Pilbara Minerals, in collaboration with Calix Ltd. (Pimble, NSW, Australia), is developing a demonstration plant to produce high-quality LCE directly on-site. This innovation reduces reliance on off-site refineries and improves overall process efficiency. The project incorporates sustainable technologies, including a Gas-fired Power (GFP) plant supported by solar and battery storage [225], targeting a 30% reduction in CO_2 emissions by 2030. This aligns with Pilbara Minerals' commitment to becoming a low-emission producer [226]. The demonstration plant utilizes Calix's electric calcination technology to process spodumene concentrate with reduced CO_2 e emissions [227]. Its primary output is lithium phosphate (Li_3PO_4), an 18% lithium salt suitable for lithium iron phosphate (LFP) and nickel cathode batteries. On-site production of Li_3PO_4 minimizes waste volumes and reduces logistics costs [228], aiming for near-zero waste production. Supported by the Australian Government, the project has an estimated cost of A\$105 million. The first production phase is expected to commence in 2025, reaching full capacity by 2026 [229,230].

Lepidico Ltd.'s Project. Lepidico Ltd.'s (West Perth, Australia) innovative Lepidolite Lithium Project uses L-Max[®] and LOH-Max[®] to recover lithium sustainably from lithium mica resources, such as lepidolite. L-Max[®] technology extracts lithium without requiring high-temperature calcination [231], employing H_2SO_4 leaching at moderate temperatures (approximately 120 °C). This significantly reduces energy consumption and CO_2 emissions compared to conventional spodumene extraction methods [232]. L-Max[®] also recovers valuable by-products, including amorphous silica, gypsum, and various salts, optimizing

resource use and minimizing hazardous solid waste [233,234]. Vieceli et al. (2017) [235] demonstrated that mechanical activation enhances lepidolite reactivity, enabling low-temperature acid digestion and improving lithium recovery. This process aligns closely with L–Max[®] technology, further reducing energy consumption. LOH–Max[®] groundbreaking solutions for the lithium hydroxide industry by eliminating sodium sulfate (Na₂SO₄) as a by-product, a common and costly waste material. Lepidico Ltd.’s incorporates water-efficient processes, achieving over 90% extraction efficiency while reducing CO₂ emissions by 25% compared to conventional methods [235,236]. Currently, Lepidico is extracting lithium from lepidolite and other minerals in Namibia. It is constructing two lithium hydroxide plants: one nearing completion in Abu Dhabi and another in Karabib, expected to begin full production by 2025 [237].

Below, there is a summarized prospect (Table 13) of the above projects, including the specific extraction technology utilized.

Table 13. Summary table of the novel hard-rock extraction projects.

Project Name	Key Features	Production Capacity	Extraction Technology	References
Pilbara Minerals’ Pilgangoora Project	Produces spodumene concentrate; incorporates HPGR and DMS technologies; demonstration plant for on-site LCE production with Calix’s electric calcination	540,000–580,000 tons of spodumene concentrate annually; expansion to reach 1 million tons/year by 2025	HPGR, DMS, and electric calcination; lithium phosphate production on-site	[224–230]
Lepidico Ltd.’s Lepidolite Lithium Project	Utilizes L–Max [®] and LOH–Max [®] technologies; extracts lithium from lepidolite; recovers by-products; reduces energy use and CO ₂ emissions	Over 90% extraction efficiency; two lithium hydroxide plants (Abu Dhabi and Karabib) set to begin full production by 2025	H ₂ SO ₄ leaching at 120 °C; L–Max [®] and LOH–Max [®] for sustainable lithium extraction	[231–237]

4.5. Bioleaching

Bioleaching, or bioextraction, is a biological process that employs microorganisms to facilitate the extraction of metals, such as lithium, from rocks and ores. This technology, already widely used for the extraction of copper and other metals, is now being adapted for the recovery of lithium from low-grade ores (e.g., spodumene or lepidolite) and waste materials.

4.5.1. Research Studies

Microorganisms, including bacteria and fungi, can oxidize ores through the production of acid metabolites, thereby releasing lithium into solution. This lithium-enriched solution can subsequently be recovered using separation processes [238]. This method is potentially environmentally friendly, as it reduces the reliance on harsh chemical reagents. However, its efficiency and scalability remain subjects of ongoing research [239]. For example, Rezza et al. [240] demonstrated that microorganisms, such as *Penicillium purpurogenum*, *Aspergillus niger*, and *Rhodotorula rubra*, are capable of extracting lithium from spodumene. These organisms, by producing organic acids such as gluconic and citric acid, increase the solubility of lithium in the leaching fluid, achieving concentrations as high as 1.53 ppm of lithium in solution. Bioleaching has also been applied to lithium extraction from lepidolite using various microorganisms. An autotrophic bacterial consortium of *Acidithiobacillus ferrooxidans* and *A. thiooxidans* has shown some effectiveness, albeit with extended timescales (up to 336 days). Other microorganisms, including the fungus *Aspergillus niger* and the

yeast *Rhodotorula mucilaginosa*, achieved a faster extraction rate (40 days) but with lower efficiency [241].

These studies suggest that, while bioleaching for lithium extraction remains experimental, it holds promise as a low-impact alternative when implemented with appropriate microbiological support and optimal conditions. This process is considerably less invasive than traditional methods and avoids the use of harsh chemicals. However, the longer extraction times and the challenges associated with controlling microbiological conditions present significant hurdles [241].

4.5.2. Cemvita Factory's Project

The Cemvita Factory's project, in collaboration with Arizona Lithium (AZL), employs bioleaching to extract lithium from unconventional sources, aiming to reduce the environmental impact of lithium mining. The partnership operates at AZL's Lithium Research Center in Tempe, AZ, USA, where Cemvita is installing a pilot plant to test bioleaching techniques on lithium ores. The primary objective is to evaluate mineral bioprocessing and lithium bioextraction methods on a pre-commercial scale [242]. Cemvita seeks to replace conventional mining processes with biotechnological approaches. Bioleaching leverages bacteria and fungi to produce organic acids that dissolve lithium in minerals. This method significantly reduces the use of toxic chemicals, energy, and water compared to traditional mining techniques, thereby minimizing its environmental footprint [243,244]. Cemvita's strategy also incorporates in-situ mining techniques, which mitigate ground disturbance. Sedimentary lithium resources further reduce the carbon footprint compared to spodumene extraction, as bioleaching processes operate at lower moisture levels, requiring less water than brine-based methods [242]. At the Lithium Research Center, Cemvita and AZL are conducting bioleaching trials using tank and heap leaching techniques. These methods are adaptable to diverse mining contexts and can be scaled for commercial applications [243].

5. Conclusions

This study provides an in-depth analysis of the potential benefits and challenges associated with adopting innovative technologies for a more sustainable lithium extraction process, with the ultimate goal of supporting a really sustainable energy transition. The reviewed projects and studies present a range of hypotheses regarding the optimal pathways to achieve sustainable extraction. In some instances, the integration of renewable energy sources into the power grid is identified as a crucial factor for reducing emissions. Conversely, in other cases, the adoption of novel extraction technologies, such as DLE, emerges as the only viable solution to address critical issues like water scarcity and biodiversity loss. This variability highlights the complex challenges of establishing a genuinely sustainable and tailored lithium supply chain. A multifaceted approach—encompassing technological innovation, regulatory frameworks, and scientific research—is essential to overcome these challenges.

Traditional lithium extraction methods, including pyrometallurgical processes and solar evaporation from brines and hard rocks, have considerable ecological drawbacks. These include high fossil fuels and water consumption, significant CO₂e emissions, and the destruction of natural habitats. Addressing these environmental challenges requires a combination of technological innovation, regulatory oversight, and industry collaboration. Key pathways for reducing environmental impacts include transitioning to renewable energy-powered operations, adopting advanced mining technologies, and implementing rigorous water resource management strategies. Emerging technologies, such as DLE and alternative extraction methods (e.g., from geothermal and oilfield brines), offer promising opportunities to mitigate environmental impacts while enhancing extraction efficiency. In

particular, the use of lithium-specific adsorbents and selective membranes has shown the potential to improve recovery rates in brines with high concentrations of competing cations, reducing water usage and minimizing soil disturbance.

The sustainability initiatives and technological advancements discussed in this study represent significant progress toward more responsible lithium production. These approaches not only improve mining efficiency but also align with emerging international regulations and natural resource conservation goals. Nonetheless, considerable operational challenges remain. For instance, the variability in brine compositions, such as fluctuating Mg/Li ratios and other ionic parameters, significantly affect the performance of adsorbents and membranes, necessitating site-specific adaptations for each extraction site. In particular, in high-salinity environments, extraction techniques require highly selective and durable materials capable of maintaining effectiveness under challenging conditions.

Additional concerns include the management of saline and chemical wastes generated by adsorbent materials and the frequent regeneration of membranes, which increases energy consumption. Without adequate treatment and disposal, these waste materials risk contaminating soil and local water resources. Moreover, complex salt mixtures in brines with elevated magnesium and sodium levels necessitate specific strategies to prevent the accumulation of undesired elements. Scaling up emerging technologies to ensure cost-effectiveness in industrial and commercial settings poses another challenge. High energy consumption, especially in electrodialysis systems, constrains the scalability of DLE technologies and necessitates integrating renewable energy sources. Furthermore, the increased complexity of these processes raises operational and maintenance costs, requiring continuous efforts to sustain efficiency.

Future research and field trials are crucial to optimizing the large-scale applicability of these methods. Research should focus on developing new adsorbent materials and membranes with enhanced regeneration capabilities and lower production costs. Existing materials, such as manganese-based ionic sieves and bilayer hydroxides, show considerable potential in extraction capacity but require improvements in regeneration efficiency to reduce operational costs and extend plant lifespan. Additionally, integrating renewable energy sources, such as geothermal and photovoltaic systems, into mining operations offers a promising pathway for further reducing carbon emissions. It is clear that identifying optimal sustainable pathways must remain the primary objective of the lithium mining industry. By embracing lithium mining innovations, integrating renewable energy, and adopting low-impact technologies, the sector can substantially reduce its environmental footprint.

Lithium extraction technologies must be adapted to regional variations in geology and environmental contexts. This adaptation is essential for ensuring efficient and sustainable extraction processes. Indeed, the geology of lithium deposits differs significantly across regions, requiring tailored technological approaches. For example, South America's Lithium Triangle is characterized by salt flat brines rich in lithium chloride. These deposits necessitate DLE technologies optimized for high salinity and complex ion competition, such as LMO-type LISs or LDHs. In contrast, Australia's abundant spodumene deposits depend on energy-intensive hard rock mining techniques. Here, efforts should prioritize optimizing pyrometallurgical and hydrometallurgical processes to reduce carbon emissions and energy consumption, including the use of renewable energy for calcination and roasting. Meanwhile, North America's clay-based deposits, such as those in Nevada, demand adaptations of acid leaching or closed-loop processes to minimize water usage and hazardous waste generation.

Furthermore, environmental conditions also vary drastically between lithium-rich regions, presenting additional challenges. For instance, the arid environments of Chile and Argentina face severe water scarcity, necessitating water-efficient technologies such as

low-water DLE processes. Conversely, Australia's tropical mining zones face challenges related to deforestation and biodiversity loss, making habitat restoration and tailings management crucial. In regions with sensitive ecosystems, such as Bolivia's Salar de Uyuni, stricter adherence to environmental preservation frameworks is imperative: processes that minimize salt crust disruption and groundwater depletion are essential to protect these fragile landscapes.

Specifically, solar- and wind-powered DLE facilities in regions with abundant renewable resources, such as the lithium triangle in South America, could significantly reduce the carbon footprint of extraction operations. Intensive pilot studies are recommended to model these hybrid systems and evaluate their scalability. Additionally, advancing data-driven decision-making through sophisticated modeling and machine learning will be essential. Geospatial analytics, integrated with real-time monitoring systems, can enable more accurate resource targeting and environmental impact forecasting. This approach would lower exploratory drilling costs and optimize resource allocation. To ensure equitable development, research efforts should also investigate public-private partnerships and policy mechanisms that incentivize innovation. Collaborative funding models—bringing together academic institutions, industry stakeholders, and government agencies to co-invest in pilot projects—could markedly accelerate technology transfer and commercialization. Moreover, a comprehensive lifecycle assessment (LCA) framework should underpin all research activities. By systematically quantifying the trade-offs among environmental, social, and economic factors, researchers can identify the most sustainable pathways for lithium extraction.

To address the dual priorities of resource efficiency and environmental preservation, future research must adopt a focused and interdisciplinary approach. The extensive body of scientific research and numerous case studies provided by mining companies demonstrate that meaningful progress is achievable and that there are significant opportunities for further improvement.

Funding: This research received no external funding.

Institutional Review Board Statement: The study does not require ethical approval because not involving human or animal rights.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: I sincerely thank the reviewers for accepting to review this manuscript and for their valuable contributions to its improvement.

Conflicts of Interest: The author declares no conflicts of interest.

Glossary

Bioleaching	A biological process where microorganisms, such as bacteria or fungi, break down minerals to release metals like lithium. It is an eco-friendly alternative to traditional methods.
Calcination	The process of heating a mineral, such as spodumene, to high temperatures, changing its chemical structure, making lithium easier to extract.
Carbon Sequestration	The process of capturing and storing carbon dioxide to mitigate its release into the atmosphere. It is sometimes integrated into mining operations to reduce their carbon impact.

CDI	CDI is a water treatment technology that uses electrical charges to attract and remove ions like lithium from brine, similar to a magnetic separation process.
Circular Economy	An economic system aimed at eliminating waste and continuously reusing resources. In lithium extraction, this could include recycling water and reprocessing waste materials.
Closed-Loop Systems	Systems where all resources, such as water and chemicals, are continuously recycled and reused, minimizing waste and environmental impact.
Desorption	The process of removing lithium ions from adsorbent materials or membranes allows these materials to be reused in subsequent cycles.
DLE	Modern technique for recovering lithium from brines without large evaporation ponds
Geothermal Brines	Hot, mineral-rich water from underground geothermal reservoirs that contains lithium. It can be used both for lithium extraction and renewable energy generation.
Geothermal Lithium Extraction	A method of extracting lithium from geothermal brines, which also generates renewable geothermal energy as a by-product.
Hard Rock Mining	A method of extracting lithium from mineral-rich igneous rocks, such as spodumene and petalite. It involves processes like drilling, blasting, crushing, and chemical treatment.
Hydrometallurgy	A chemical process is used to extract metals like lithium from minerals using aqueous solutions, often involving leaching and precipitation.
Ion Exchange	A chemical process in which specific ions, such as lithium, are selectively replaced or exchanged from a solution by a material like a resin or adsorbent.
LCE	A standardized way to measure and compare lithium production, regardless of its chemical form. It represents the amount of lithium contained in lithium carbonate.
LDHs	These are materials with a layered structure that can selectively bind lithium ions while rejecting other salts like magnesium or sodium.
Life Cycle Assessment (LCA)	A comprehensive analysis of the environmental impact of a product or process throughout its entire life cycle, from raw material extraction to disposal or recycling.
Magnesium-to-Lithium (Mg/Li) Ratio	A measure used to describe the concentration of magnesium relative to lithium in brines. Higher ratios make lithium extraction more challenging.
Nanomaterials	Extremely small materials engineered at the nanometer scale are often used in lithium extraction technologies for their high surface area and reactivity
Oilfield Brines	These are salty waters extracted during oil and gas drilling operations. They often contain small amounts of lithium, which can be recovered using specialized techniques.
Organic Acids	Naturally occurring acids, such as citric or oxalic acid, are used to dissolve lithium from minerals during processes like bioleaching.
Pilot Project	A small-scale, experimental implementation of a lithium extraction process used to test feasibility, efficiency, and scalability before full-scale deployment.
Precipitation Reactions	Chemical processes are used to convert lithium-rich solutions into solid compounds, such as lithium carbonate or lithium hydroxide, suitable for industrial use.

Renewable Energy Integration	The use of renewable energy sources, like solar or wind, to power lithium extraction processes reduces the overall carbon footprint.
Saline Brines	Saltwater solutions are found underground or in salt flats, which are rich in dissolved minerals, including lithium.
Scope 1 Emissions	Direct emissions from company-owned facilities or vehicles.
Scope 2 Emissions	Indirect emissions from purchased electricity, heat, or steam.
Scope 3 Emissions	All other indirect emissions, such as those from the supply chain or product use.
Selective Adsorbents	Specialized materials designed to capture lithium ions selectively from brines or other solutions while rejecting competing ions like sodium or magnesium
Spodumene	A lithium-rich mineral commonly used in hard rock mining. It undergoes heating and chemical processes to extract lithium in a usable form.
Sustainability Metrics	Quantitative measures are used to assess the environmental, economic, and social impacts of lithium extraction projects, such as water usage, emissions, and community benefits.
Tailings	The leftover materials or waste produced after lithium or other metals are extracted from ore. They often require careful management to prevent environmental harm.
Tailings Dam	A storage facility for tailings, typically constructed to contain mining waste. Poorly managed dams can pose risks of leakage or catastrophic failure.

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