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Review

Review of Direct Lithium Extraction Methods: Recent Advances and Outlook

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Abstract

Lithium-ion batteries (LIBs) have become the prominent energy storage technology because of their high specific energy, longer lifespan, and excellent efficiency. Traditional lithium extraction processes are energy intensive and time-consuming. Direct lithium extraction (DLE) methods provide a more sustainable and efficient alternative. This review offers a comprehensive overview of lithium-ion battery resources and direct lithium extraction methods. The detailed discussion of the DLE methods, which include adsorption, ion exchange, solvent extraction, membranes separation, and electro-chemical systems is presented. A comprehensive analysis of the recent technological advances of the direct lithium extraction processes in terms of technology readiness levels, and commercial potential is reported. The advantages and the technical challenges of the DLE methods are also reported. Finally, the review outlines the artificial intelligence outlook of the DLE processes. The review aims to provide deeper insights into the limitations and the opportunities of DLE methods towards crucial future research efforts for lithium-ion batteries advancements.

Keywords: lithium-ion; batteries; brine; direct-lithium extraction; energy storage

1. Introduction

Lithium (Li) is a critical element that has emerged as a crucial mineral in modern grid-scale energy storage and electronic applications. Lithium, a critical mineral is light, fast, and dependable, which offers crucial benefits such as high energy density, stable intercalation, small ionic radius, and electrochemical stability. The global transition from fossil-fuel dependent industries toward low-carbon technologies has increased the demand for this energy-critical element. Li deposits are unevenly distributed and mostly geographically concentrated in South America and Australia with production primarily dominated by Australia, China, Chile, and Argentina, which collectively account for over 90% of the global supply. With lithium-ion batteries (LIB) now constituting over 85% of global lithium consumption, demand is estimated at ~0.205 Mt in 2025 and is projected to reach 1.16 Mt by 2050 [1]. This rapid demand trajectory has exposed constraints in conventional extraction methods such as production costs, production times, and environmental effects [2,3]. Furthermore, the regional concentration poses significant supply chain risks and geographical political tensions, which have necessitated the need to diversify resource

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type and extraction technologies [4]. The Li supply chain mainly starts with two main geological deposit resources, which include hard rock and brines. In terms of global Li production supply by deposit type, hard rock mining and brine contribute 60% and 35%, respectively, and the remaining comes from other smaller sources. Whereas in terms of global Li resources, brine accounts for the largest deposit type (60%) followed by clay (25%) and hard rock (15%). Even though hard rock mining is the most used for Li production, it has shortcomings such as moderate Li yield, higher operating expenses, and bigger environmental impact. Brine evaporation is a very slow process with very long production times such as 12–24 months, lower yield, and highly utilized land and water usage [1–4].

Figure 1 illustrates the process mapping for Li extraction. Direct lithium extraction (DLE) is an emerging innovative approach that selectively extracts lithium ions from Li-rich brine and returns the depleted brine to its source aquifer. For pegmatites (Hard Rock), Li is found in hard rock deposits in the form of solid minerals. Initially the solid mineral deposits are extracted by mining and beneficiation (crushed and processed to concentrate Li minerals) and then they go through intense high thermal roasting to liberate Li-bearing minerals and convert into a reactive form which can be utilized to chemically extract Li into a solution. For Salar brines, the Li is dissolved in brine found in salt flats using the brine pumping and solar evaporation. Furthermore, modern DLE methods can also be utilized to supplement or replace the evaporation process to improve cost effectiveness. For the unconventional brines, Li is extracted from the non-traditional sources such as seawater/reverse osmosis, geothermal brines, and sedimentary basins. Further DLE methods such as adsorption, ion exchange, solvent extraction, membranes, and electrochemical systems can be used to extract Li. All three Li extraction routes presented in Figure 1 eventually lead to lithium carbonate (Li_2CO_3) or lithium hydroxide (LiOH) through concentration and refining. DLE combines the speed of hard rock with the low operating expenditure and abundant reserves of brine, unlocking the largest Li resources in competitive timelines. In direct lithium extraction methods, lithium ions are selectively extracted or separated at the ionic level from the sources, whereas the indirect methods mainly rely on bulk concentration and multi-step processing. Direct methods offer a transformative alternative to conventional extraction routes. Direct methods are fast (hours/days), use very low water usage, have a high recovery rate (80–95%), emit less carbon emission (~1.5 tons/t LCE), are weather independent, and have a small environmental footprint. Whereas on the other side, indirect methods are slow (months to years), have extremely high-water usage, a low recovery rate (20–40%), a high carbon footprint (~11 tons/t LCE), are weather dependent, and leave a large environmental footprint. The key advantages offered by DLE processes compared to conventional Li extraction processes include selective extraction processes, less time to market (days to weeks), less usage of land and water compared to traditional brine evaporation, high Li recovery efficiency, lower carbon footprint, and scalability.

This review offers an overview of Li resources and explores all types of lithium resources and extraction pathways, such as conventional Li resources, unconventional Li resources, and DLE methods. In this review, a comprehensive overview of various DLE technologies such as adsorption, ion exchange, solvent extraction, membrane separation, and electrochemical extraction have been presented. Moreover, a comparative analysis in terms of separation mechanism, representative materials/systems, performance metrics, mechanistic strengths, and structural constraints is reported. The review also outlines the industrial DLE technology field deployment advances projects in terms of brine type, DLE method, technology readiness level (TRL), stage, and performance. The advantages and challenges of each DLE method are presented with an emphasis on technical and economic constraints in DLE deployment. Finally, an outlook on the impact of artificial intelligence

on the DLE advancement in accelerating material discovery, predictive modeling, resource evaluation, system-level optimization, and digital integration is discussed.

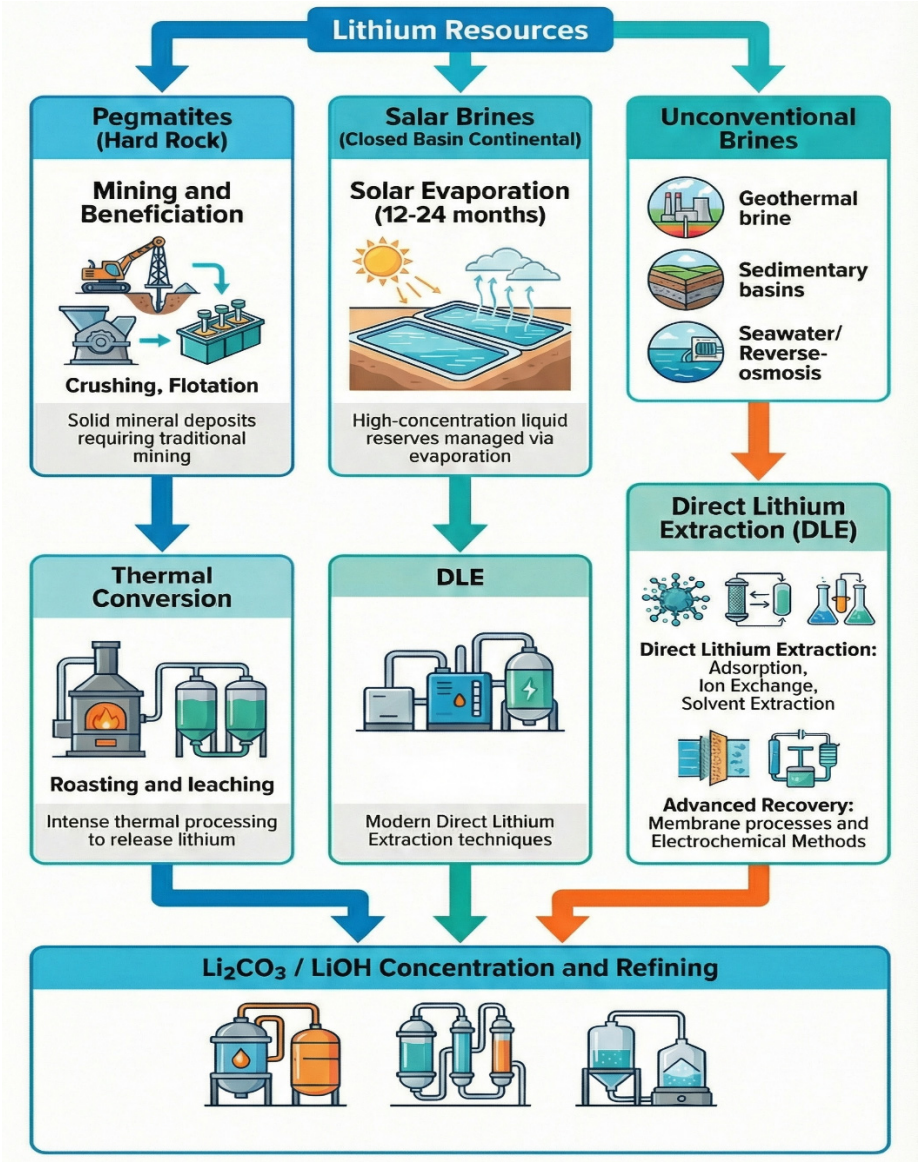


Figure 1. Process mapping for Li extraction.

2. Conventional Lithium Resources

There are three deposit types of lithium, which include hard rock (pegmatite), brine deposit, and sedimentary-hosted deposits.

2.1. Hard Rock Deposits (Pegmatites)

Hard-rock lithium resources consist of solid igneous pegmatite ores such as spodumene, lepidolite, and petalite. They generally contain 1–2% Li_2O, and they are extracted using a conventional open pit followed by crushing, grinding, flotation, and thermal conversion. These deposits represent a mature, high-grade conventional resource type.

Primarily from spodumene ($LiAlSi_2O_6$), it accounts for the largest portion of global lithium production [5,6]. This source has played a defining role in lithium extraction for many years. Other occurrences of lithium in minerals are lepidolite, petalite, and amblygonite and are found in various geographical locations across the world [7]. Lithium found in pegmatites are coarse-grained igneous rocks, which have significantly higher

concentrations of about 1–4 wt% than lithium bearing brines and achieve high recovery rates of about 60–70% [8]. Australia hosts the largest global deposits in spodumene concentrates with over 6 Mt Li spodumene reserves and ore grades between 1 and 2.5% Li. Notable deposits also exists in Canada (James Bau, Quebec), Europe (Cinovec), Africa (Aracdia, Goulamina, Bikita), and China (Jiajika) [5,7,9]. This Lithium resource type requires energy-intensive mining, crushing, and thermal conversion, which increases cost and environmental footprint. Recent studies have shown circular recovery approaches from hard-rock waste streams to improve environmental burdens [9–11].

2.2. Lithium Brines Deposit

Brine lithium resources consist of lithium-rich hypersaline waters in subsurface aquifers. In these brines, Li occurs as dissolved Li^+ ions, with concentrations varying from 200 to 1500 mg/L in salar brines (conventional) to 30–500 mg/L in oilfield brines, 10–200 mg/L in geothermal brines, and trace levels in seawater and industrial brines, which are known as unconventional brines. These brines are extracted by pumping and are processed using evaporation ponds or DLE technologies. Brine resources are the primary liquid feedstocks for DLE due to their fluid characteristics and dissolved lithium content.

Lithium-bearing brines are found in three main geological settings: closed-basin salars (CB), geothermal brines, and deep sedimentary or oilfield formations where prolonged evaporation, rock–water interaction, and geothermal circulation [12–14] leads to the concentration of dissolved lithium concentrations ranging from 200 to 4000 mg/L Li^+ [5,15]. These values can vary widely depending on basin geology due to the heterogenous nature of hydrogeology. The most significant deposits are in Argentina, Bolivia, and Chile (South American Lithium Triangle), and together account for close to 60% of the world's known brine resources [7]. Major brine fields are also present in China's Qinghai region, the United States (Clayton Valley) [16,17], and emerging basins like the Siberian Platform in Russia [18].

In recent decades, the conventional method of brine extraction relied on solar evaporation ponds, where deposits of lithium rich water (brine) are pumped into and concentrated over extended periods of months to years [19–21]. During these periods, several pretreatment processes and steps are carried out to remove unwanted impurities such as Ca^+ and Mg^{2+} [22,23], and as the brine becomes sufficiently concentrated, sequential evaporation takes place and it is further refined to meet the specific quality and purity standards required for the end users [12,24]. While this method is cost effective and widely used in South America and China, it is slow, depends on climatic conditions and requires a large land area and water resources [14,25,26]. Figure 2 gives an overview of conventional and unconventional lithium resources; representative of commercial and emerging project developers associated with each resources type.

Sedimentary clay-hosted lithium deposits are formed in lacustrine environments as a result of geological processes, such as the weathering of volcanic ash, which releases lithium that becomes incorporated into clay minerals like (e.g., hectorite), kaolinite, and illite. These deposits contain 0.1–0.4 wt% Li (1000–4000 ppm), which are lower than pegmatites but higher than those found in brines [27,28]. While conventional recovery methods such as acid leaching, hydrothermal treatment, and alkaline digestion are often effective, they often involve high reagent consumption, high energy input and significant waste generation. Major sites include McDermitt Caldera (USA), Sonora (Mexico), and Yunnan (China) [27–29]. The known reserves for lithium bearing clay deposits account for 7% of the global Li resources [21]. While advancement in lithium recovery from these sources can contribute to global demand, ongoing research to solve challenges such as impurity management,

energy-intensity due to thermal steps, solid waste handling, and high reagent consumption are still in progress before making them commercially viable [23,27,30].

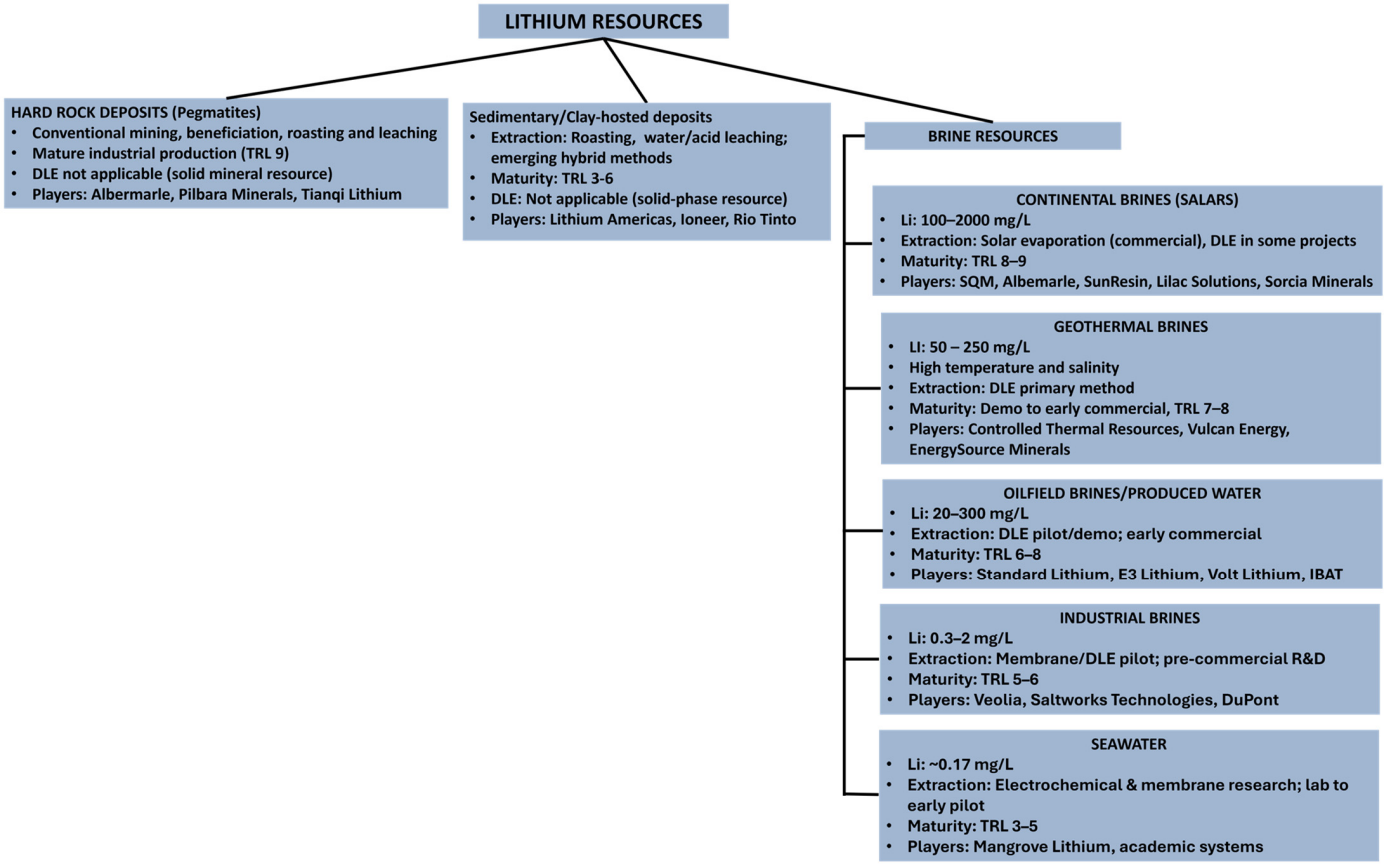


Figure 2. Lithium resources classification and players.

3. Unconventional Lithium Resources

These resources include sedimentary/oilfield brines, geothermal brine, and seawater/desalination concentrates, which are distinct in processing via traditional ponds due to their complex chemistry, temperature, or dilution. These resources are inherently suited with Direct Lithium Extraction (DLE) technologies that allow for selective recovery from complex or low-grade fluids. Geothermal Brines are characterized by high-temperature, and high-salinity with lithium concentrations ranging from 10 to 480 mg/L, where they are influenced by mineralogy and fluid–rock interactions. They are found in locations like the Salton Sea and Upper Rhine Valley (Germany), and these brines are chemically challenging, as they contain high levels of boron, divalent cations, and silica which causes challenges to precipitation-based extraction [26,31–33]. Multiple pilot DLE modular systems have demonstrated their effectiveness, such as ion-exchange sorbents, electro-intercalation, and electrochemical-membrane processes with the added benefit of closed-loop reinjection of spent brine, which enhances sustainability by minimizing surface impacts and enabling renewable power generation.

Oilfield Brines (Produced Water) are by-products generated during hydrocarbon extraction from deep sedimentary formations [32,34] and contain lithium concentrations of 30–500 mg/L, as seen in locations such as Smackover formation (USA), Williston Basin, and Qianjiang Depression (China) [35–37]. Due to their complex chemistries such as containing hydrocarbons, dissolving organics, and scaling ions (Fe, Ba, Sr), they require extensive pretreatment prior to lithium recovery. Despite these challenges, these brines represent a high-volume, infrastructure-ready resource, and daily global production of

produced water exceeding tens of millions of barrels [34,38]. Several scalable field projects by companies have demonstrated over 90% extraction efficiency, reduced capital intensity, and low water usage using DLE technologies [26,34]. Seawater contains vast amount of lithium at approximately 230 billion tons of lithium but at very low concentrations ~0.17 mg/L making direct extraction challenging due to competing ions from (Ca^+, Na^+, Mg^{2+}) [20,39]. Several ongoing studies have been exploring electrochemical membranes, adsorptive DLE systems that are capable of selectively capturing lithium from seawater or enriched reverse-osmosis (RO) brines from desalination plants [34,40–43]. Research into DLE systems targeting these sources is ongoing; however, commercial viability remains constrained by challenges in selectivity, energy intensity, and economic scalability.

Collectively, these unconventional resources highlight a wide range of chemical environments in which Li is found. Despite their differences in concentration and ionic composition, operational constraints, all these resources utilize DLE technologies for selective lithium recovery. The following section outlines how DLE can be applied across diverse resource types, their principal mechanisms, operating principles, and optimal conditions for effective applications.

4. Direct Lithium Extraction (DLE)

Direct Lithium Extraction (DLE) has emerged as one of the significant technological shifts in lithium production, particularly for brine-based resources. This has resulted in the move away from unconventional evaporation-pond systems, which require large land footprints, and timelines ranging from months to years for solar concentrations. According to Flexer et al., [17] the distinction between the evaporation-based recovery and selective approaches lies in the ability of DLE systems to target Li at the ionic level rather than relying on massive concentration via water removal. These technologies facilitate the selective separation of Li ions from complex brines, within considerably shorter times, often hours, while returning most of the brine back to the reservoir or aquifer [15,26]. Numerous brine resources contain high concentrations of magnesium, calcium, boron, or silica, which complicate Li recovery. Through these DLE methodologies, these limitations can be circumvented [17,20,40] and can achieve Li recoveries exceeding 80–95% while minimizing reagent consumption and reducing waste generation compared with multi-stage chemical precipitation. Figure 3 illustrates the detailed comprehensive step-by-step flow diagram on how the final Li product is extracted from brine sources. Figure 4 illustrates the various DLE methods. DLE methods are generally classified mainly by the fundamental separation mechanism used to selectively separate or extract Li^+ ions from the brine sources. In this research, various separation mechanisms included adsorption, ion-exchange, solvent extraction, membrane separation, and electrochemical. The adsorption, ion exchange, and solvent extraction are chemical affinity driven methods. The membrane separation method is physical transport-driven, and the electrochemical methods are energy driven.

4.1. Adsorption DLE Method

These technologies are known as one of the earliest and most widely piloted DLE methods. It involves the selective capture of Li ions from brine onto a solid phase via ion exchange, surface adsorption into a host lattice, and elution into a solution for refining. The materials used for these technologies are organic and inorganic and recent times can be a hybrid (organic–inorganic), serving as a combination of the mechanical strength of polymers with the lithium selectivity of inorganic phases [25].

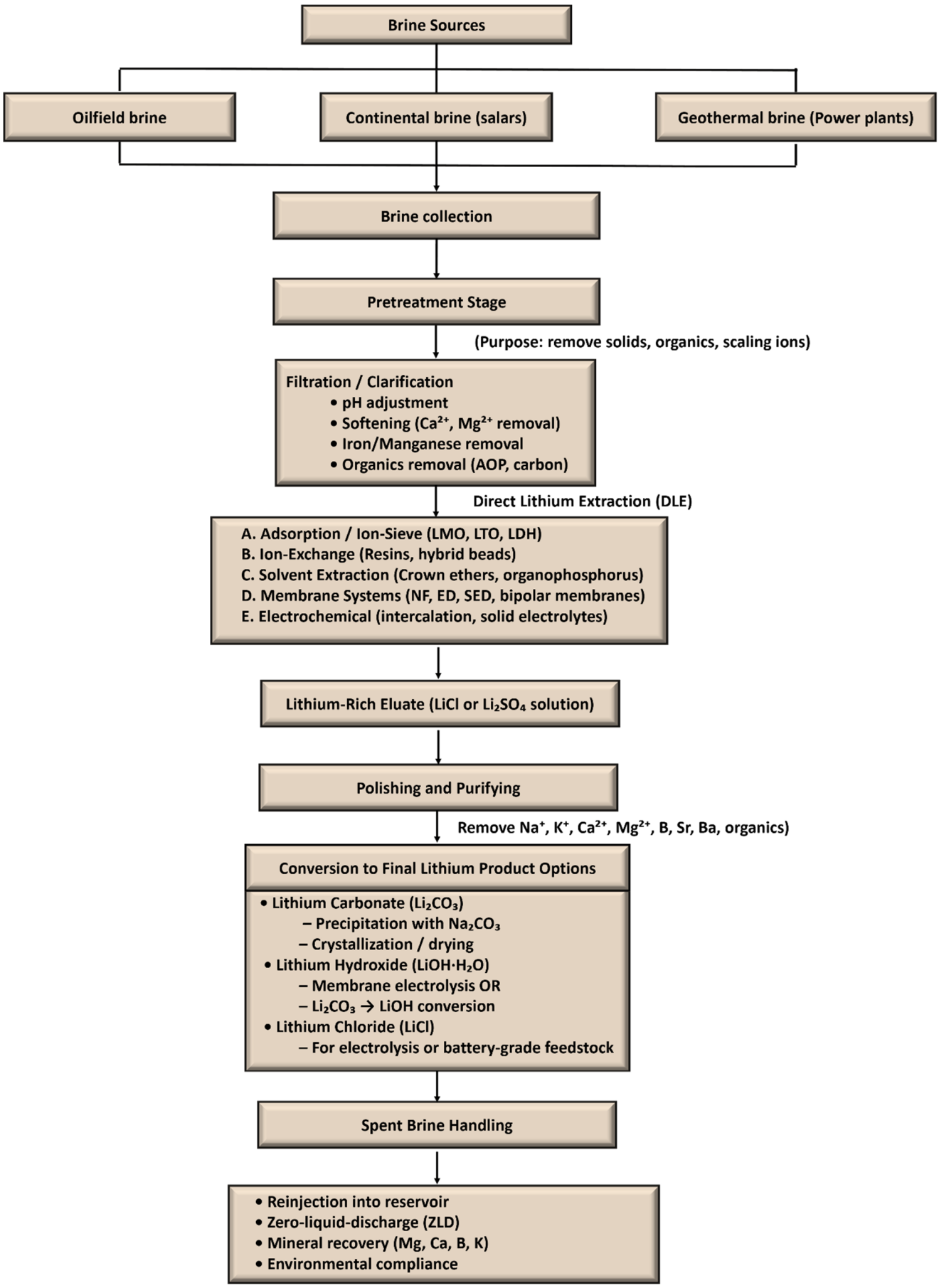


Figure 3. Flow diagram of brine to final lithium product.

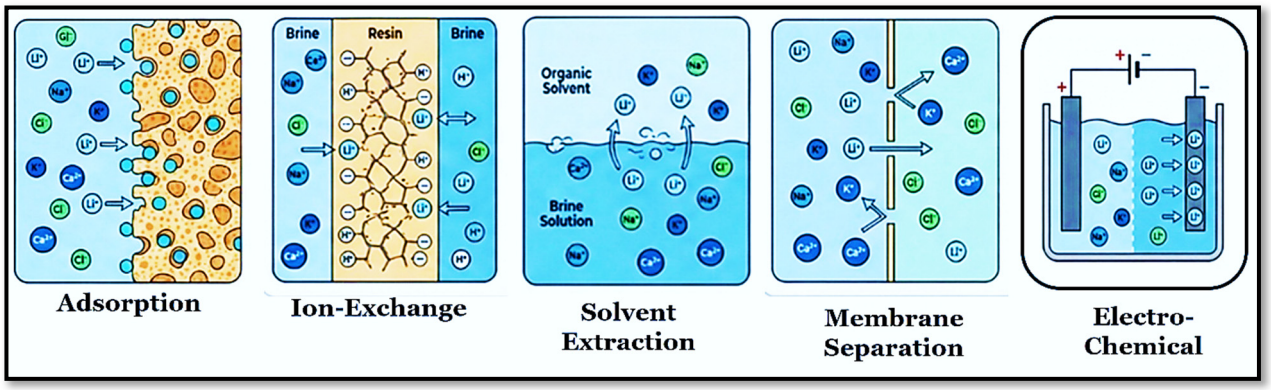


Figure 4. Direct lithium extraction methods.

Early research on organic sorbents focused on sulfonated polystyrene/divinylbenzene and other strong-acid cation exchange resin for lithium recovery. These materials were experimentally investigated, applied in seawater and geothermal brines, and they demonstrated their ability in stripping lithium from diluted solutions [26,44]. However, they exhibited poor selectivity because of Li properties (high hydration energy, small ionic radius, weak affinity) for sulfonic acid groups in comparison to Mg^{2+} and Ca^{2+}. Hence, these resins were deemed not feasible in capturing Li from brine. To enhance selectivity, researchers began to explore crown ethers and cryptand chemistry [26,45,46]. It was observed that crown ether homologues improved the separation of Li/Na or Li/Mg in low saline solutions [46–48]. However, their capacities remained limited at <10 mg Li g^{-1} [20] and were sensitive to factors such as temperature and pH, and they had competing divalent cations. These results further reinforced the struggle pure organic recognition sites had in displacing Li ion and the performance deteriorated in high-total dissolved solid brines [46–48]. Years after, there was a transition towards hybrid sorbents (polymer-supported inorganic sorbents) such as λ MnO_2, Li_2TiO_3, or Al $(OH)_3$ [25,49,50] that served as the selected lithium inorganic phases, and this hybridization addressed several challenges such as enhanced attrition resistance, processability, and column compatibility [51,52]. Wang et al., reported improved attrition resistance, mechanical strength, Li adsorption capacity of 49.0 mg g^{-1} at an initial Li^+ concentration of 200 mgL^{-1} when porous polyacrylonitrile (PAN) beads were infused with lattice-expanded λ MnO_2 in a simulated brine [53]. Furthermore, Ding et al. utilized novel PAN/ion-imprinted polymer (IIP) nanofibers to improve Li/Mg separation selectivity in harsher brines [54], while Li et al. further extended the concept using a substrate doped with nitrogen and integrated with capacitive deionization for acidic solutions showing more improved multi-ion selectivity, higher capacity retention (>91%), and improved electrochemical crown ether sites [55]. In recent years, several innovative methods [56] and materials have emerged in organic sorbents, such as covalent organic framework membranes [57–60], for precise tunable pore sizes thereby allowing size-sieving of lithium with huge chemical and thermal stability. Crown ether-modified organic frameworks, which serve as functionalized porous organic frameworks [61] to enhance Li selectivity through size or coordination chemistry [62–66]; biopolymers, which include chitosan, alignate, lignin-derived materials for specific ion capture [64,67–69]; functionalized polymers that are specific to binding groups such as amines; sulfonates for targeted sorption [70–72]; and hybrid adsorbents, which are the infusing polymers and organic ligands with inorganic cores for better stability and selectivity [73–75].

4.2. Ion-Exchange DLE Method

In recent decades, inorganic molecular sieve ion-exchange sorbents such as Li ion sieves, based on manganese, titanium, and aluminum hydroxides, have been widely

researched and tested for direct Li extraction from complex brines on laboratory and industrial pilot commercial scales. In earlier years [76,77], the appeal of these types of sorbents stemmed from their capacity to offer high Li selectivity and adsorption capacity from high-salinity brines, while rejecting multivalent cations such as Mg^{2+} and Ca^{2+}, but they had drawbacks due to structural degradation, dissolution of Manganese during acidic deposition, and slow kinetics [78]. Gradually, research tilted towards the stabilization and processability of lithium-ion sieves. As decades went by, there was a consistent progression from laboratory synthesis of idealized ion sieves resulting in mechanically robust and chemically stable composites [79]. Coating Li Manganese oxide (LMO) particles [80,81] with inert oxides mitigated manganese dissolution [82], while embedding Li ion sieves in inorganic matrices increased particle strength and improved granular supports [80]. Furthermore, aluminum gel systems, hybridization with granular support using silica sand, and polymer beads reduced clogging and enabled fixed-bed operation. These advancements resulted in pilot demonstrations for geothermal and salar brines and extending adsorption–desorption cycles [83,84]. In recent years, hybridization of systems and notable innovative inorganic sorbents have emerged [85]. Spinel-type manganese variants [86–89] have proven their superior selectivity, rapid kinetics, and enhanced lithium adsorption in brine systems [83,90,91], with a high magnesium and Li ratio due to their spiny nanotube morphological hollow structure. Toprak et al. utilized a one-step hydrothermal method using a spinel-type LMO ion sieve from a γ-MnO_2 polymorph to produce $H_{1.33}Mn_{1.67}O_4$, which has aided in achieving fast kinetic, addressed economic cost concerns, and exhibited a high adsorption capacity, achieving up to 95% Li recovery and minimal manganese dissolution over multiple cycles [92].

Titanium-based oxides (TiOx), containing Li (Li_2TiO_3; monoclinic layered or spinel-like) and hydrogen (H_2TiO_3) in their crystal structure, were part of the early research explored as LIS due to their superior acid stability and tunable lattice channels when compared to MnO_2 [93–95]. Studies demonstrated that these oxide variants exhibited high selectivity (up to 141.81 mg/g), using innovative multilayer LIS structures [95–97] for Li extraction over sodium (Na^+) potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) in brines [98,99]. This allowed intercalation, deintercalation, and made regeneration possible with low structural collapse. As researchers continued to explore hydrothermal and solid-state synthesis methods to regulate particle dimensions and crystalline structures, there was a gradual shift towards infusing TiOx ion sieves into granular supports to optimize column functionality and eliminate loss of pressure [100,101]. Nanorods and nanosheets augmented surface area and reduced diffusion paths of Li ion [102], while surface coatings such as SiO_2, Al_2O_3 reduced Ti leaching during the regeneration process [103]. In progression, for improved mechanical strength in fixed-bed systems, hybrids were formed by embedding TiOx into polymer beads or ceramic matrices for improved mechanical strength [104]. Furthermore, custom-made TiOx sorbents were engineered for brine-specific adaptation and were mostly applied on a pilot commercial scale in China [99,105]. Recent advancements have researched the use of modification strategies in the use of ion-doping and hybrid ion-doping (Mg, Al, Fe, Cr, Zn, Sb, Mo) [106–109] to enhance selectivity, increase the density of active sites, improve lattice stability [110,111], reduce grain size, and create oxygen vacancies [112,113].

Applications of layered double hydroxides of aluminum and its gel systems have also been demonstrated for their Li selectivity and reduction in clogging, enabling fixed-bed operation when hybridized with granular supports. Furthermore, they have faster adsorption kinetics' compared to titanium-based ion sieves making them more reliable for industrial applications as TiOx rely on the use of the ion exchange process working principle, and a change in the pH above 7 [93,114] can result in unwanted hydroxides (Ca,

Mg) interfering with the adsorption and recovery [105] and polluting the environment due to the use of ammonia buffer solutions to maintain the pH level [115]. Aluminum hydroxide (AlOH) sorbents [116,117] are known to be suitable for geothermal brine that have quantifiable compositions of chlorine and sulfur with high Mg/Li ratios [78]. Several institutions [118,119], organizations including Simbol Inc. which participated in a U.S. Department of Energy-funded project, are known to have filed a plethora of patents related to direct lithium extraction from brines [120,121]. They are known for their neutral-pH compatibility, water-only desorption, lack of association with dissolution losses as seen in manganese variants, and ammonia buffer in TiOx systems. Despite these advantages, their significant volume of freshwater consumption during the desorption process, and challenges of severe powdering are major drawbacks [122]. To tackle these challenges, engineering solutions such as embedding in polymer matrices, precipitation onto inert substances, and hybridization are notably explored to prolong the cycle life in continuous flow systems. While the MnOx, TiOx, and AlOH have garnered significant attention, further research has also delved into modified sorbents (antimonates, zeolites, tin-oxides, arsenates) and engineered ion exchange media.

Advanced ion exchange media (Gen 4IX beads) systems from Lilac Solutions are part of novel engineered inorganic sorbents that have been specifically designed to remove contaminants such as Na^+, K^+, Ca^+, and Mg^{2+} with remarkable accuracy [123]. The system achieved lithium recovery rate of 80–98% across a wider range of brine chemistries containing 50–2000 mg/L Li^+, with high impurity rejection rate of up to 99.99% and freshwater reduction by up to tenfold compared to conventional alumina adsorbents [124]. These beads are known for their mechanical durability, ability to withstand adsorption–desorption cycles, and being environmentally friendly (do not need ammonia buffers or acid regeneration), and they are currently used in commercial DLE projects across the USA, Argentina, and Europe [125]. While other emerging inorganic sorbents such as zeolite, titanium (IV) antimonate, spinel-type lithium antimony manganese oxide, thorium arsenate, and tin oxide that have been researched are being proposed to expand the material palette, they are either still in laboratory scale, pilot stages, or not economically viable [126–130]. Ongoing progress in hybridization, shaping technologies, dopant engineering, and surface modification are part of the advances that aid with overcoming existing challenges and facilitate large sustainable lithium recovery [37].

4.3. Solvent Extraction (Sx) DLE Method

The Sx method is well known for the separation of metals from aqueous solutions due to their operational simplicity, efficiency, and scalability even though the cost of reagents is also significant. The effectiveness of Sx depends on the optimization of temperature, choice of extractant, pH, and concentration of competing ions. A variety of solvent separation techniques, including functionalized membranes, liquid–liquid-based extraction, and other solvent-assisted sorption processes have been developed, and they presented unique benefits in terms of selectivity, efficiency and environmental impact [131]. Crown ethers like 18-crown-6, 15-crown-5, 12-crown-4, and 14-crown-4 have increasingly been amongst the most selective extractants for Li [132–134] due to the size of their cavity and binding properties and their affinity to form stable complexes with Li ions, which has resulted in higher rejection of divalent ions (Mg^{2+}) [135–137]. Several studies, such as the development of crown ether-ionic liquid composites [138–140], have demonstrated their improved selectivity in complex brines [141–143]. Specific crown ethers combined with supercritical carbon dioxide ($ScCO_2$) [143,144], crown ethers embedded in MOF or COF [62,141,145,146], and advances in membrane technology [147–150] have shown their

moderate solubility, better stability, environmental friendliness, and enhanced selectivity in achieving high Li enrichment from natural brines [62,146,151,152].

As research progresses, solvent extraction continues to be a versatile and adaptable method for Li recovery, with its extractants presenting distinct advantages and drawbacks. Crown ethers set the standard for selectivity but have high synthesis cost. Organophosphorus systems are cost-effective, although solvent degradation, co-extraction of divalent cations, and acid consumption during stripping are still challenges. Carboxylic and ionic acids offer alternative chemical approaches, with ionic liquids appealing for green chemistries applications despite cost challenges. Other technologies such as supercritical CO2 extraction, supported liquid membranes, and polymer inclusion membranes (PIMs) highlight the trend towards more environmentally friendly, more stable, and continuous processes. Future progress advancement will depend on hybrid systems that have high selectivity, are cost-effective, and are scalable.

4.4. Membrane-Based DLE Method

This method is a combination of various pressure-driven and electric field-driven processes such as nanofiltration, bipolar membranes, electrodialysis, and electrochemical membranes stacks [34,153,154]. It offers lower chemical consumption, modularity, and huge possibilities for renewable energy integration. In contrast to sorbent-based methods or solvent extractions, it relies on factors such as size exclusion, charge selectivity, or electrochemical driving forces to isolate lithium from other ions present in complex brine matrices [148,154–156].

4.4.1. Nanofiltration (NF)

Nanofiltration membranes (NF) through numerous studies [154,155,157–160] have demonstrated their ability to reject divalent cations like Mg^{2+} and Ca^{2+} while Li^{+} passes through the membrane enabling Mg/LI separation factors under optimized conditions [161,162]. A study by Yang et al. highlights the performance of NF, exhibiting a high rejection of up to 98.5% to $MgCl_2$ and a low rejection of up to 46.2% to LiCl, reflecting the synergistic effect of electrostatic exclusion and molecular sieving [158]. Stringfellow et al. [25] highlighted that in geothermal brines, NF is most effective as a brine conditioning step rather than as a standalone DLE technology, due to high temperatures and complex chemistry of geothermal fluids. Hollow-fiber NF configurations have also been explored, offering lower energy consumption and higher packing density with rejection order of ions being $MgCl_2 > MgSO_4 > NaCl \approx LiCl$. Recent studies have shifted towards mechanism-guided membrane design. In a comprehensive review of NF membranes for Mg^{2+}/Li^{+} separation, Xu et al. [163] examined the basic transport mechanism and mathematical models that control ion selectivity in NF systems. They highlighted how membrane surface charge, pore size, mass transfer dynamics, and Donnan exclusion, enhance Li^{+} permeability relative to Mg^{2+}. Das et al. [164] discussed new NF materials, such as MOF-based thin-film nanocomposites and 2D-material membranes, which aim to exceed traditional permeability-selectivity limits. Tang et al. [165] applied explainable machine learning to identify key membrane and operating parameters that control Li^{+}/Mg^{2+} selectivity and Li^{+} recovery in brine separation. Other studies have discussed the positively and negatively charged nanofiltration membranes and its effectiveness, with efficiency in Mg^{2+}/Li^{+} separation from high Mg^{2+}/Li^{+} ratio brine [154,166,167]. As NF continues to advance, brine composition, fouling, and scaling (silica, $CaSO_4$) pose as ongoing challenges [168–170].

4.4.2. Electrodialysis (ED) and Bipolar Membrane Electrodialysis (BMED)

These are electro-driven separation techniques that use ion-exchange membranes to facilitate the selective transportation of ions under an electric field. ED is effective for

lithium extraction because it can enrich Li^+ while rejecting Mg^{2+}, particularly when the current density and membrane charge density are optimized. Neyrizi et al. [171] developed an optimization method to determine the variations in brine composition, and findings estimated USD 2600 to USD 28,000 per ton for the cost of lithium carbonate, depending on brine grade and membrane cost, while energy demands ranged between 5000 and 70,000 kWh/ton [171]. Despite these progresses, high membrane costs, fouling and scaling in real brine, and high energy intensity if Li/Mg selectivity is low are challenges that persist. Meanwhile, BMED has also gained interest for its ability to directly produce LIOH through pH-splitting, thereby reducing chemical consumption and eliminating the need for caustic addition. Research has shown that it can attain high purity levels of LIOH while sustaining stable membrane performance in high-ionic-strength conditions [172,173].

4.4.3. Ion-Conductive and Solid-State Li Membranes

Studies have highlighted that the Li superionic conductor (NASICON)-type solid electrolytes, such as $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ (LATP), have a distinct approach to lithium separation [174,175]. They selectively conduct Li^+ while effectively blocking competing ions such as Mg^{2+}, Ca^{2+}, and Na^+ due to their narrow conduction channels and rigid crystal lattices. Zhou et al., [175] used LATP pellets as a selective membrane for lithium extraction from natural brine, and they demonstrated that the Li extraction device can achieve a superior current efficiency of 97.4% while maintaining a stable ionic conductivity of about 3.9×10^{-4} S cm^{-1}. Li et al. [175] further enhanced LATP-based electrodialysis by introducing an aided charge balance (ACB) system, and results showed a Li/Mg separation coefficient of 5924 and a low energy consumption of 0.80 $kWh.kg^{-1}$ Li in simulated pristine brine. Furthermore, Seo et al. [176] developed an LATP incorporated into a cellulose acetate matrix (LATP/CA) that exhibited ionic conductivity and showed a remarkable selectivity ratio of up to 467.3 in a simulated salt-lake brine under optimized electrically driven conditions. In addition, a two-step extraction process effectively removed competing ions of Na^+, K^+, Mg^{2+}, and Ca^{2+} with values of 6430, 1084, 619, and 45 ppm to 0.3, 15.2, 0.2, and 0.4 ppm in the permeate, respectively, hence contributing to more sustainable Li extraction processes. Garnet-type Li lanthanum zirconate (LLZO) solid electrolytes have been investigated as Li ion selective membranes in both simulated and natural waters [177,178]. Furthermore, their integration into electrochemical extraction configurations resulting in the direct generation of high-purity metallic lithium from low-grade LiCl feed solutions has also been explored [179].

Industries in collaboration with academic groups are also accelerating the transition of these materials. Notably, in 2022, EnergyX's LITAS TM platform incorporated membrane separation with ion-transport materials and electrochemical modules, thereby reducing water consumption and lithium loss [180–182]. This technology was deployed on a pilot commercial scale at Uyuni, the world's largest lithium reserve. In comparison to conventional methods that can take up to 18 months, LITAS TM can achieve extraction of lithium in just 1–2 days. Additionally, in 2024, Boston-based Pure Lithium patented a membrane technology that can directly generate lithium metal anodes from brine, which can reduce the cost of LiB by 80% [183,184]. LITHOS Group commercialized its ACQUATM hybrid-electro pressure membrane technology, which eliminates evaporation ponds and recycles 98% of water [185,185]. Its efficacy was confirmed in trials with the world's biggest lithium producer, Sociedad Quimica y Minera (SQM), using Atacama brines [185,186]. Furthermore, Stanford University, led by Dr. Yi Cui, developed a new membrane technology achieving 99% selectivity and a 40% cost reduction in comparison to conventional methods, while requiring only 1.1 kWh/kg Li (a tenth of conventional DLE methods) [183,187]. LihyTech, in collaboration with Aramco, demonstrated the scalability and Li recovery from oilfield water

at KAUST'S pilot facility utilizing a ceramic membrane, which costs less than USD 10/m^2 (over 100 times cheaper than traditional lithium selective membrane) [183,188]. Collectively, these advancements signify a transition towards modular, resource-efficient lithium recovery systems that can adapt to diverse chemistries and concentration brines [154,189,190].

4.5. Electrochemical Lithium Capture Systems

Electrodialysis variants, ion-pumping reactors, electro-adsorption, electrochemical reactors, and solid-state electrolyte/membrane stacks with Li-selective solid electrolytes are gaining prominence in Li extraction as viable alternatives [191–194]. Following years of ongoing research, studies have demonstrated that ion-pumping and electrodes like $LiMn_2O_4$, can effectively recover lithium from idealized or simplified brine [192,195]. According to Wang et al., the application of coatings (polypyyrole or Al_2O_3) enhanced stability while retaining about 85% capacity over 100 cycles in simulated brines [196]. Concurrent research into electrodialysis (ED) and hybrid ED-membrane highlighted gained attention. Ying et al. discussed rapid advancements in integrated ED and emerging strategies to improve membrane permselectivity in high Mg/Li brines, emphasizing the need for Li-recognition membranes to enhance separation efficiency [197]. Recently, the field has shifted towards more advanced systems. Decoupled, membrane-free electrochemical cells have been successfully demonstrated at the pilot scale: Li et al. used iron phosphate/Li iron phosphate ($FePO_4/LiFePO_4$) electrodes in conjunction with silver/silver-halide (Ag/AgCl) redox couples to separate brine and recovery chambers, achieving up to 84% recovery from Dead Sea brine, with a Li carbonate purity exceeding 99.95% and energy savings of around 21% [198]. Furthermore, flow-by-ion-pumping reactors have also undergone refinement [199,200]; Roggerone et al. reported about an 84% recovery rate and energy use of 3.9–9.5 Wh mol^{-1} Li with a $LiMn_2O_4$/λ-MnO2 electrode in sodium-rich brines [200]. As material innovation continues to enhance performance metrics [201], Luo et al. utilized $LiMn_2O_4$ electrodes modified with tin oxide (SnO_2) nanoparticles "island", which improved diffusion and alleviated stress, resulting in an increased adsorption capacity (19.8 mg g^{-1}) within 1 h, which is 1.7 times higher than unmodified electrodes [202]. Furthermore, solid-electrolyte devices are also emerging; Lei et al. demonstrated LATP ($Li_1 + xAl_xTi_2 - x(PO_4)_3$)-based cells electrolyzing mixed chlorides to yield 98.9% purity of (Li_2CO_3) [203]. In addition to these advancements, Wang et al. developed a redox-driven $FePO_4$ system that effectively adsorbs Li^+ (Li/Na selectivity of about 350) without external energy input, although it is best optimized for geothermal or moderately saline brines [204].

In summary, advances in membrane-free configurations, solid electrolytes, and electrode modification to the field of electrochemical Li extraction have improved recovery, energy efficiency, and selectivity. While many proof-of-concept electrodes and ED membranes to integrated, pilot-scale systems capable of functioning on real brines have been developed, ensuring long-term stability in harsh brine conditions, membrane fouling, and achieving cost competitiveness with alternative DLE methods are persisting challenges [191,205,206]. Finally, developing and integrating advanced manufacturing systems, such as the use of artificial intelligence and machine learning, have been emphasized to serve as a breakthrough in helping researchers address the bottleneck of material synthesis and optimize process parameters and technological design [191,207–211].

Table 1 demonstrates a performance comparison of the major DLE methods discussed in the previous section in terms of separation mechanism, materials, performance metrics, mechanistic strengths, and structural constraints.

Table 1. Performance comparison of major DLE methods [4,12,26,34,37,42,43,58,73,79,88,96,163,168,212–214].

DLE Method	Separation Mechanism	Representative Materials/ Systems	Performance Metrics (Reported Ranges)	Mechanistic Strengths	Structural Constraints
Adsorption (Inorganic Ion Sieves)	Lithium-selective ion exchange within crystalline lattice (H^+/Li^+ exchange in spinel or layered oxides)	$H_{1.6}Mn_{1.6}O_4$ (λ-MnO_2), TiO_2-based sieves, Al-doped oxides, SnO_2-modified composites	Capacity: 20–40 mg g^{-1}; Li/Mg selectivity > 100; Recovery 70–90%	High intrinsic Li^+ selectivity from lattice size matching; relatively low energy demand; modular column integration	Capacity fade during cyclic acid regeneration; dissolution of Mn; often requires post-concentration step; sensitivity to real brine impurities
Ion Exchange (Hybrid Organic–Inorganic Resins)	Functional ligands selectively bind Li^+ via chelation or ion exchange; regeneration via acid/base stripping	Functionalized polymer beads, crown-ether resins, MOF-based sorbents, silica-supported ligands	Recovery 80–95%; moderate–high Li/Na selectivity; eluate LiCl up to 2–5 g L^{-1}	High purity eluate; scalable packed-bed operation; adaptable to variable brine chemistries	Chemical-intensive regeneration (acid/base); resin degradation; OPEX linked to reagent recycling; fouling in high TDS brines
Solvent Extraction (SX)	Transfer of Li^+ into organic phase via selective extractants; stripping into aqueous phase	Organophosphorus reagents (D2EHPA, TBP), Cyanex 272, crown ethers, ionic liquids, synergistic extractant systems	Recovery 90–97% (optimized systems); Li/Na selectivity > 1000 (controlled systems)	Continuous high-throughput operation; high Li concentration in strip solution; mature hydrometallurgical platform	Organic solvent losses; co-extraction of Mg^{2+}/Ca^{2+}; solvent degradation; corrosion and safety concerns
Membrane Separation (NF/ED/BPM/Solid Electrolytes)	Size exclusion and charge-based rejection (NF); electro-migration under applied potential (ED/BPM); solid Li^+-conducting ceramics	Nanofiltration (NF), Electrodialysis (ED), Bipolar membranes (BPM), LATP solid electrolytes	Mg^{2+} rejection > 99.8% (NF); Li/Mg separation factors > 600; Recovery 70–95%; energy 2–10 kWh m^{-3} (ED systems)	Low chemical input; potential direct LiOH production (BPM-ED); modular scalability; continuous processing	Fouling/scaling in high salinity brines; membrane cost; durability under high TDS and temperature; energy sensitivity
Electrochemical Extraction (EIPS/CDI/ Intercalation Systems)	Electro-driven Li^+ intercalation into selective electrode materials under applied potential	$LiMn_2O_4$, $LiFePO_4/FePO_4$, Prussian blue analogs, redox-couple systems	Recovery 80–90%; Li_2CO_3 purity > 99%; energy use 3.9–9.5 Wh mol^{-1} Li	Low chemical footprint; high theoretical selectivity; potential closed-loop operation; compact footprint	Electrode degradation; electrolyte management; scaling of electrode manufacturing; long-term cycling stability not fully validated

4.6. Commercial Technology Advances of DLE Methods

Field deployment of DLE methods marks a remarkable transformation from proof of concept to commercial industry implementation. Table 2 illustrates the top commercial DLE field deployment projects such as Lilac Solutions (Oakland, CA, USA), Standard Lithium Ltd. (Vancouver, BC, Canada), ATLiS (Mesa, Arizona), SLB (Houston, TX, USA), Prairie Lithium (Saskatchewan, Canada), CleanTech Lithium (Jersey, UK), YPF (Buenos Aires, Argentina), XtraLit (Rehovot, Israel), Vulcan Energy Resources (Perth, Australia), EnergyX (San Juan, Puerto Rico), and Volt Lithium Corp. (Calgary, AB, Canada). Each of these projects are outlined in terms of their technology readiness levels (TRL), type of DLE method, stage, and the Li recovery performance. DLE systems are currently being tested and successfully deployed across various brine sources such as continental lake brines, oilfield brines, geothermal brines, subsurface brine, and Salar deposits. Most of these DLE projects have progressed to TRL of 7–9, demonstrating the pilot-scale validation through pre-commercial stages. The performance of these DLE projects had Li recovery efficiencies in the range of 87% to 96%, Even though most of the DLE field deployment projects are in the pilot or pre-commercial stages, the full-scale commercial viability cannot be validated until a multi-year long-term perforation dataset is considered. Table 3 consolidates the major DLE across key indicators. The maturity level indicated in Table 3 represents the maturity of each technology class and does not correspond to individual commercial projects which may differ from the general technology category.

Table 2. Top DLE field deployments projects [215–226].

Developer	Project/Location	Brine Type	DLE Method	TRL	Stage	Performance/Output
Lilac Solutions	Great Salt Lake, UT, USA	Continental lake brine	Ion Exchange/IX	8–9	Pilot to Pre-commercial	~87% Li recovery; >99.9% impurity rejection; planned ~5000 tpa LCE
Standard Lithium Ltd.	Southwest Arkansas (Smackover), AR, USA	Oilfield/continental brine	Sorption (Li-Pro™)	8	Demo to Commercial	~95% Li rec.; continuous ~20 m^3/h real brine; DFS shows > 20,000 tpa Li_2CO_3 potential
EnergySource Minerals/ATLiS	Salton Sea, CA, USA	Geothermal brine	Adsorption (ILiAD™)	8–9	Funding/Development	DOE conditional loan for ~20,000 tpa LiOH; demonstration modules
SLB (formerly Schlumberger)	Clayton Valley, NV, USA	Continental/brine	Integrated DLE and Concentration and Conversion	8	Demo	~96% Li rec.; brine 500× faster extraction vs. ponds
Prairie Lithium	Saskatchewan Pilot, Canada	Subsurface brine	Ion Exchange (Plix™)	7–8	Pilot	Ongoing pilot data; commercialization pathway
CleanTech Lithium	Laguna Verde, Chile	Salar/continental brine	Adsorbent DLE and conventional refine	7–8	Pilot	Pilot-scale Li_2CO_3 production; staged scale
YPF and XtraLit	Multiple Salar sites, Argentina	Salar brines	Ion Exchange/IX	6–7	Early Deployment	Announced multiple joint development licenses
Vulcan Energy Resources	Zero Carbon Lithium™, Germany	Geothermal brine	Adsorption DLE integrated with geothermal	8–9	Pre-commercial/ scaling	Production plans aligned with geothermal supply
EnergyX	Smackover Region, AR, USA	Oilfield/continental brine	Hybrid membrane and adsorption	6–7	Planning/development	Land acquisitions targeting ~10–12,500 tpa by 2028
Volt Lithium Corp.	Rainbow Lake/Keg River, Canada	Oilfield/brine	Proprietary DLE system	6–7	Demonstration/pilot	Demonstrated Li_2CO_3 production at small scale

Table 3. Comparative performance metrics in maturity of DLE methods [26,34,215,226,227].

DLE Technology	Selectivity	Typical Recovery Rate	Energy Consumption	Scalability	TRL
Ion Exchange	Very High	80–95%	Low	High due to continuous flow systems that allow industrial-scale throughput and easy expansion	6–8
Adsorption	High (Li^+ over Mg^+/Ca^{2+})	70–90%	Low-moderate	Highly scalable via modular packed-bed reactors, which can be expanded by adding parallel units	7–9
Solvent Extraction	Very high (tunable ligands)	85–98%	Moderate	Medium because it is limited by recycling, handling, and containment of large organic solvent volumes	5–7
Membrane separation	Moderate (NF, RO/ED/BPM)	40–70%	Low-high	High because membrane modules are modular and are scaled via additional stacks	4–6
Electrochemical Methods	Very high (Li^+ selective)	60–90%	Moderate-high	Medium in scalability, as it is constrained by current distribution, electrode stack size, and long-term cycling stability.	3–5

5. DLE Advantages and Challenges

Direct lithium extraction is a process intensified alternative in lithium recovery from brines compared to conventional solar evaporation. DLE systems operate under controlled processing conditions, therefore reducing lithium extraction times to hours or days.

5.1. System-Level Advantages of DLE

At the system level, DLE offers several operational advantages. DLE processes decouple Li extraction from climatic conditions, allowing for rapid throughput control, and they have higher recovery efficiency due to their selective capture and controlled regeneration, expanded resource accessibility, reduced surface footprint, and modular scalability [12,17,81,228–230]. However, DLE is not a single technology process; rather, it consists of several technological processes that are applied to different resource types, which results in a reduction in time, therefore enabling continuous or semi-continuous operation, and allowing operators to adjust process parameters depending on the feeding chemistry from the

season dilution, reservoir drawdown, or reinjection dynamics. Its technology readiness levels vary from (TRL 3–9). In addition, the energy intensity, reagent consumption, durability, and scalability differ significantly among the technology classes [61,64,139,153,231–233].

5.2. Technical and Economic Constraints in DLE Deployment

Beyond the operational technology benefits in pilot-scale and laboratory settings, DLE faces several systemic constraints that influence DLE scalability and affect their successful integration into the Li supply chain. The following constraints (Table 4) are scale-up and manufacturing, feed dilution and matrix complexity, fouling and scaling, reagent and water intensity, media durability, waste management, energy–water tradeoffs, and economic sensitivity.

Table 4. Technical and economic deployment challenges [4,6,12,15,17,42,168,169,171,183,212,234–239].

Challenge Category	Description	Deployment Implications	Mitigation Strategies
Scale-up limitations	Transition from pilot or demonstration phases to multi-kiloton scale and multi-site deployment	Requires use of modular architecture, standardized manufacturing processes, and resilient supply chains	Modular plant design; standardized and scalable manufacturing approaches resulting in flexible deployment across sites
Feed concentration constraints	Presence of Low Li concentration in various brines	High volumetric throughput increases capital and operational expenditures (CAPEX/OPEX)	Pre-concentration steps (evaporation, membrane filtration); hybrid DLE–conventional systems which reduces volumetric throughput and associated capital and operating costs
Matrix complexity and competing ions	High level of Mg^{2+}, Ca^{2+}, Na^{+}, silica, organics, borates and transition metals	Reduces selectivity, increases the intensity of pretreatment processes	Improved pretreatment (filtration, softening, organics removal) strategies; development of more selective sorbents to maintain lithium recovery efficiency
Fouling and scaling	Occurrence of silica, carbonate, organics, biofouling and sulfate precipitation	Shortens media life; increases maintenance	The use of anti-scalant to inhibit mineral precipitation along with periodic cleaning and regeneration to restore performance and remove accumulated deposits
Reagent and Water Intensity	Acid/base and wash-water demand	Potentially offsets sustainability gains	This can be reduced via closed-loop reagent recycling and water recovery systems; low chemical or electrochemical extraction pathways to minimize consumable demand
Media Durability	Sorbent/membrane/electrode degradation	Drives replacement frequency and OPEX	Development of chemically robust sorbents and membranes; optimized regeneration strategies; controlled operating conditions
Waste Management	Brine concentrates, spent regenerants and residues	Regulatory and disposal challenges and may lead to cost implications	Waste minimization; byproduct recovery; brine reinjection and on-site treatment
Energy–Water–Carbon Tradeoffs	Variable demands for energy, heat and water	Requires integrated TEA-LCA to prevent burden shifting and accurately assess the true benefits to climate and water resources.	Heat recovery to improve efficiency; process integration; coupling with renewable energy sources
Economic Sensitivity	Dependence on Li price and site conditions	Influences investment risk and scalability	Flexible and modular deployment; cost reduction through efficiency; long-term supply agreements that stabilize costs and revenues

6. Outlook

6.1. Artificial Intelligence (AI) Innovations in Direct Lithium Extraction (DLE)

AI and machine learning (ML) are now emerging as the next phase of innovation in DLE. The era of digitalization and AI has been applied to several fields, which has complemented traditional experimental and modeling techniques by handling complex nonlinear relationships among materials, operational conditions, and performance results [240]. Machine learning powered nanofiltration models have been utilized to predict membrane behavior and optimize separation efficiency, while ML-guided multi-objective optimization frameworks have improved selective lithium recovery from complex brines and battery-derived feedstocks. These enabling technologies can accelerate the development, optimization, techno-economic predictability, and industrial feasibility of Direct

Lithium Extraction (DLE) systems and other aspects that are difficult to capture with conventional techniques only across complex brine chemistries [241–243].

6.2. AI-Accelerated Materials Discovery and Sorbent Design

Machine learning has been applied in reducing trial-and-error experimentation by rapidly screening compositional variables and identifying high-performance dopant configurations [244]. Zhang et al., [242] applied ML to rapidly determine high-performance dopant modifications of aluminum-based lithium adsorbents tailored for salt lake brines, and this improved adsorption capacity by nearly 40% compared with conventional empirical optimization approaches. Similarly, Abba et al. [245] applied Shapley Additive exPlanations (SHAP) and other Explainable AI (XAI) tools to predict adsorption energy in crown ether-based hierarchical 2D nanomaterials for the efficient recovery of Li^+ ions. Such hybrid computational approaches provide mechanistic insights and enable closed-loop material discovery processes, thereby shortening development cycles for next-generation DLE sorbents and membranes.

6.3. Predictive Modeling of Adsorption and Membrane Performance

In a recent study, Xu et al. [241] applied several tree-based ensemble models (Random Forest, gradient boosting, XGBoost) to evaluate the impact of 16 parameters on lithium adsorption. XGBoost demonstrated the best performance with an R2 of 0.98 in forecasting lithium uptake from unconventional waters, while SHAP analysis revealed that operational parameters were the most influential, followed by adsorbent parameters and coexisting-ion concentrations. Ji et al. [246] demonstrated ML-assisted modeling of lithium permeation and Li^+/Mg^{2+} selectivity in nanofiltration membranes. They employed SHAP and partial dependence analyses to clarify how features such as water contact angle, membrane molecular weight cut off, and transmembrane pressure affect both lithium permeation and Li^+/Mg^{2+} selectivity [191,247]. As more research is conducted, these AI studies can serve as a predictive layer across DLE technologies supporting parameter optimization and operational stability.

6.4. AI in Resource Evaluation, System-Level Optimization, and Digital Integration

Beyond modeling and accelerated materials discovery, AI is influencing both upstream resource assessment and downstream system-level optimization in DLE. In the resource domain, the application of ML models has enhanced accurate estimation of economically recoverable lithium concentrations in formations like the Smackover by integrating geochemical datasets with predictive analytics [243]. In addition, AI has also been utilized in revolutionizing the mining industry, as it is playing a huge role in prioritizing mineral recovery aids to achieve long-term sustainability, safety, efficiency and profitability via AI-assisted brine-mining frameworks [248]. At the system level, multi-objective optimization guided by ML has already led to enhancements in lithium recovery from spent batteries, while simultaneously reducing chemical usage and waste generation [249]. Several industrial applications of AI such as predictive maintenance, supply-chain optimization, and automated process control indicate that digital twins and reinforcement learning-based controllers will become integral to future DLE plants [250].

7. Conclusions

The review delves into various types of Li resources and extraction pathways, which include conventional Li resources, unconventional Li resources and DLE methods. The major emphasis of this review is on how DLE methods can be utilized to overcome the Li production and supply chain issues. This review provides a detailed overview of various DLE methods which include adsorption, ion exchange, solvent extraction, membrane

separation, and electrochemical extraction. The key drivers of the DLE methods include growing Li demand, price volatility, need for faster production, sustainability, brine versatility, and localized supply chains. The innovations in DLE methods can enable the effective extraction of Li from brine sources within a very short period (hours/days) compared to traditional Li extraction methods. From a sustainability point of view, DLE offers various advantages such as minimal environmental footprints and less water and land usage. Field deployment of DLE methods marks a crucial advancement from laboratory validation to commercial industry implementation. The review also outlines the top commercial field development DLE projects' advances, such as Lilac Solutions, Standard Lithium Ltd., ATLiS, SLB, Prairie Lithium, CleanTech Lithium, YPF, XtraLit, Vulcan Energy Resources, EnergyX, and Volt Lithium Corp. This review also reports on the advantages of the DLE methods and the technological constraints that need to be addressed for the full-scale adoption of DLE methods into the commercial LI production and supply chains. Additionally, development efforts and ongoing research should be focused on addressing the systemic constraints, such as scale-up, feed dilution, matrix complexity, fouling, reagent and water intensity, media durability, waste management, energy-water tradeoffs, and economic sensitivity for full scale DLE field deployments. The review also outlines how AI can be utilized for enabling innovation in DLE in terms of material discovery, performance of the methods, predictive modeling, resource evaluation, system-level optimization, and digital integration. Nonetheless, there are several limitations of AI deployment in DLE, which include limited standardized datasets across brine chemistries, poor model transferability, restricted access to industrial performance datasets, and insufficient long-term durability data. As DLE transforms from pilot projects to large-scale commercial operations, overcoming these barriers will require collaborative data-sharing frameworks and hybrid modeling strategies. Overall, this review offers a significant perspective for researchers, policymakers, and industry leaders aiming to advance DLE methods for building sustainable and efficient lithium production and supply chains.

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