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Review

Recent Advances and Future Prospects of Lithium Recovery from Low-Grade Lithium Resources: A Review

Jihan Gu [1,2], Binjun Liang [2,*], Xianping Luo [1], Xin Zhang [3], Weiquan Yuan [2], Bin Xiao [2] and Xuekun Tang [1,*]

[1] School of Resource and Environment Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China; gujihan@gnust.edu.cn (J.G.); luoxianping9491@163.com (X.L.)
[2] Ganzhou Innovative Center for Clean and Efficient Utilization Technologies of Recalcitrant Solid Resources, School of Resources and Civil Engineering, Gannan University of Science and Technology, Ganzhou 341000, China; ywqsdut@163.com (W.Y.); 9320220063@gnust.edu.cn (B.X.)
[3] School of Minerals Processing & Bioengineering, Central South University, Changsha 410083, China; zhangxinnv@csu.edu.cn
* Correspondence: 9320171002@gnust.edu.cn (B.L.); txk0797@126.com (X.T.)

Abstract: The growing demand for lithium, driven by the widespread adoption of electric vehicles and renewable energy storage systems, has sparked interest in developing low-grade lithium resources. This comprehensive review explores the types, distribution, extraction technologies, challenges, and future prospects of low-grade lithium resources. This article focuses on low-grade lithium sources such as clays, brines, coal, and coal by-products, and analyzes the principles, advantages, and limitations of key extraction techniques, including acid-alkaline leaching, bioleaching, adsorption, and membrane separation. Furthermore, this review discusses the technical, economic, and environmental sustainability challenges associated with developing low-grade lithium resources and proposes corresponding strategies. Future research should focus on improving the selectivity and efficiency of extraction and processing technologies, optimizing separation processes, and developing green and cost-effective extraction methods. Establishing supportive policy frameworks, strengthening international cooperation, and knowledge sharing are crucial for promoting the sustainable development of low-grade lithium resources. This review provides stakeholders with comprehensive insights and recommendations for addressing the growing lithium demand and achieving the Sustainable Development Goals.

Keywords: low-grade lithium resources; extraction technologies; bioleaching; adsorption; membrane separation; sustainable development

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1. Introduction

Lithium, a silvery-white light metal element with the symbol Li in the periodic table, is the lightest among the alkali metals and possesses unique physicochemical properties [1]. With an atomic number of 3, a relative atomic mass of 6.941, a density of 0.534 g/cm^3, a melting point of 180.5 °C, and a boiling point of 1342 °C [2]. Lithium has a high specific heat capacity and thermal conductivity, and it is also one of the most flammable metals [1,2].

Although lithium is widely distributed in nature, it exists in the form of compounds due to its high reactivity [3]. As shown in Figure 1a, lithium resources can be classified into three main categories: pegmatite, sedimentary, and brine deposits [4]. Pegmatite deposits include minerals such as spodumen, lepidolite, petalite, zinnwaldite, amblygonite, and eucryptite [5]. Sedimentary lithium deposits comprise smectites, illites, jadarite, searlesite, zeolites, and other combinations [6]. Brine deposits, which account for the liquid lithium

resources, can be further divided into salars, oilfield brines, geothermal brines, and ocean water [7,8].

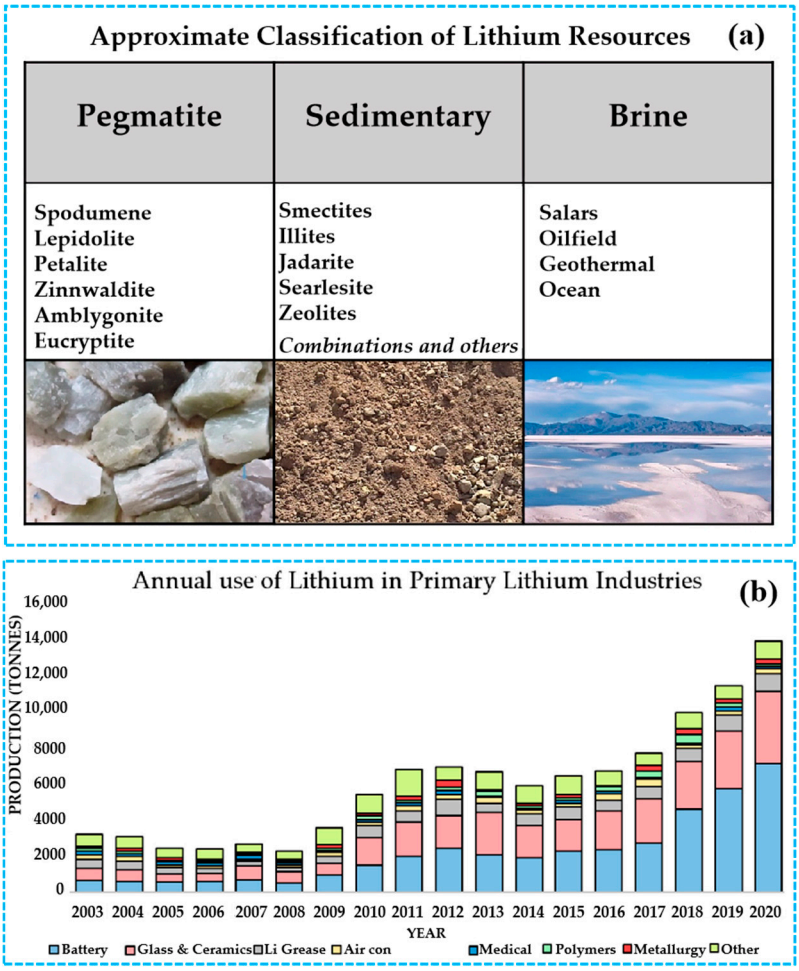


Figure 1. Global lithium resources distribution and industry utilization trends, (**a**) approximate classification of lithium resources, adapted from "*The Sedimentary Lithium Opportunity*" by Alex Grant, Principal of Jade Cove Partners, San Francisco, USA [4]; (**b**) Annual use of lithium in primary lithium industries from 2003 to 2020 [9].

Lithium's versatility has led to its use in various applications across different industries, with a significant focus on lithium-ion batteries, as depicted in Figure 1b. The consumption of lithium in batteries has seen a remarkable increase, particularly from 2016 onwards, due to the widespread adoption of portable electronic devices, electric vehicles, and renewable energy storage systems. Lithium-ion batteries are preferred in these applications because of their high energy density, long cycle life, and low self-discharge rate. In addition to batteries, lithium is used in the production of heat-resistant glass, special ceramics, lubricating greases, air conditioning systems, and has potential applications in the medical field and aerospace industry [9].

The growing demand for lithium, driven by its crucial role in sustainable energy solutions and modern technology, has solidified its position as a critical element in the global economy [10]. Lithium-ion batteries (LIBs) have become the cornerstone of this shift, powering electric vehicles and enabling the integration of renewable energy sources through energy storage systems [11,12]. As the world continues to embrace sustainable energy solutions, the upward trajectory of lithium use is expected to persist [10,13]. However, this

increasing demand for lithium presents a significant challenge, as the current reliance on high-grade lithium deposits is not sustainable in the long run [14].

The looming shortage of high-grade lithium reserves has sparked growing interest in exploring alternative lithium sources, particularly low-grade lithium resources, such as clays, low-concentration brines, coal and coal by-products, and industrial waste streams [15,16]. Land-based lithium reserves are expected to be depleted by 2080 at the current consumption rate, making the development of low-grade lithium resources crucial for ensuring a stable supply of lithium in the future [17]. Exploring these low-grade sources offers several potential benefits, including resource diversification, reduced environmental impacts, and the creation of new economic opportunities [16].

However, the development of low-grade lithium resources is not without its challenges. The techno-economic feasibility of low-grade sources compared to high-grade ones remains a critical consideration, as they generally require more complex and potentially costlier extraction processes [18,19]. Advancements in extraction methods, purification techniques, and bioleaching are making low-grade lithium extraction increasingly feasible [20–22], but further research and development are necessary to fully optimize these processes and ensure their competitiveness with traditional high-grade sources [23].

This review aims to provide a comprehensive overview of recent advances and future prospects in the field of low-grade lithium resources, bridging the gap in the current literature. This review is organized into sections covering various low-grade lithium sources, recent technological advancements in lithium extraction, techno-economic feasibility and environmental implications, and concludes with a summary of key findings and recommendations for future research directions.

By examining the potential of low-grade lithium resources and the latest developments in extraction technologies, this review contributes to the ongoing efforts to ensure a sustainable and secure supply of lithium for the growing needs of modern technology. The insights gained from this review will inform future research and development efforts, guiding the industry towards more efficient and environmentally friendly practices in the extraction and processing of low-grade lithium resources.

2. Types and Distribution of Low-Grade Lithium Resources

2.1. Lithium-Bearing Clays

Lithium-bearing clays, such as hectorite and montmorillonite, represent an important category of low-grade lithium resources. These clay deposits are characterized by their ability to host lithium within their mineral structure, with lithium typically found within the crystal structure of clay minerals [24]. While the lithium content in these deposits is generally lower compared to high-grade deposits, clay deposits can be found in various geological settings, making them a widespread potential source of lithium [25].

However, extracting lithium from clays presents several challenges. The process often requires more sophisticated and energy-intensive methods compared to brine or hard rock deposits [26]. Some extraction processes may also require significant amounts of water, which can be problematic in arid regions [27]. Furthermore, the lower lithium concentration in these deposits can make extraction less economically attractive compared to high-grade deposits [28].

2.2. Low-Grade Brines

Low-grade brines, including those found in salt lakes, geothermal waters, oilfield brines, and highly mineralized underground waters, represent another significant category of low-grade lithium resources [29,30]. These brines typically have lower lithium concentrations compared to the high-grade brines found in the “Lithium Triangle” of South

America (Chile, Argentina, and Bolivia) [31,32]. However, they can be found in various settings and often contain other valuable elements such as potassium, magnesium, and boron [29,33–35]. Extracting lithium from low-grade brines presents unique challenges. Traditional extraction methods, such as solar evaporation, are often not economically viable for these resources due to the low lithium concentration and the need to process larger volumes of brine [36]. The presence of other elements can also complicate the extraction process and require additional purification steps [33,37].

Furthermore, brine evaporation, a common concentration method, is highly dependent on climate conditions, which can limit the geographical scope of extraction [33,38]. The presence of contaminants, such as hydrocarbons in oilfield brines, can also complicate the extraction process [31,39]. Researchers are exploring innovative extraction techniques to make these resources economically feasible, such as the combination of evaporation and solvent extraction (SX) processes [31]. However, the effectiveness of these methods can vary between synthetic and real brines, highlighting the complexity of working with real-world low-grade brine resources and the need for further research and development [40–42].

2.3. Coal and Coal By-Products

Coal and its by-products have emerged as promising alternative sources of lithium. While the lithium content in coal is generally low, some coal deposits have shown the anomalous enrichment of lithium [16]. For instance, the No. 21 coal from the Hebi No. 6 mine in the Anhe Coalfield, China, has a lithium concentration coefficient (CC) value of 6.6 on average compared to common world coals [43]. This enrichment makes certain coal deposits potentially viable sources of lithium. Lithium in coal is primarily associated with aluminosilicates, mainly clay minerals, which may contain significant amounts of titanium [43,44].

Coal combustion by-products, particularly fly ash and bottom ash, have also shown promise as lithium sources [16,45,46]. Fly ash often contains higher lithium concentrations compared to the feed coal, while bottom ash, although less studied, may have an even higher lithium content than fly ash [16,45]. The occurrence of lithium in these coal ashes is related to the enrichment of lithium in the inorganic components of coal during the combustion process [47].

Another potential source of lithium from coal-related materials is coal mine brines [48]. These brines, formed when groundwater interacts with coal seams and surrounding rocks, can contain dissolved lithium that may be economically extractable [49]. The concentration of lithium in coal mine brines can vary significantly depending on the geological setting and the composition of the coal and associated rocks [50].

The utilization of coal and its by-products as alternative sources of lithium presents opportunities for sustainable resource management, waste valorization, and the diversification of the lithium supply chain [45]. However, the relatively low concentration of lithium in these resources compared to conventional sources and the need to balance lithium extraction with the environmental impacts of the coal industry remain important considerations for future research and development efforts [45,51].

2.4. Other Low-Grade Lithium Resources

In addition to the aforementioned resources, there are other low-grade lithium sources that have gained attention in recent years. Low-grade solid potash ore, particularly in the shallow part of Mahai Salt Lake in the Qaidam Basin, contains considerable reserves of low-grade solid potash resources with abundant lithium brine resulting from solid–liquid conversion and mining [15]. The lithium in these ores is primarily deposited on soluble salt minerals in silt or clay, necessitating specific extraction techniques [36].

Electronic waste, or e-waste, is another emerging low-grade source of lithium and other critical metals. As the demand for electronic devices continues to grow, so does the amount of e-waste generated [52]. Extracting lithium and other metals from e-waste presents both an environmental challenge and an economic opportunity [53,54]. Innovative approaches like bioleaching, which uses beneficial microorganisms to extract metals, are showing promise as more sustainable and cost-effective alternatives to traditional methods [55,56].

In conclusion, the diversity of low-grade lithium resources presents both challenges and opportunities for the lithium industry. As demand for lithium continues to grow, developing efficient and sustainable extraction methods for these low-grade resources will be crucial in ensuring a stable and diverse lithium supply chain [36]. Future research and development efforts should focus on optimizing extraction techniques for each specific type of low-grade resource, balancing economic viability with environmental sustainability [36,57].

3. Technologies for Low-Grade Lithium Recovery

The growing demand for lithium has spurred the development of various technologies to recover this critical metal from low-grade resources. These methods aim to efficiently and selectively extract lithium while minimizing the environmental impact and cost. Among the most promising approaches are hydrometallurgical [58], solvent extraction [59], adsorption [60,61], and membrane separation techniques [21], as well as emerging technologies such as precipitation [62,63], electrochemical methods [21,64], biotechnology [58], and nanotechnology [61]. The following sections will discuss these technologies in detail, focusing on their principles, advantages, limitations, and potential applications in low-grade lithium recovery.

3.1. Leaching Methods

Leaching is a crucial step in the hydrometallurgical processing of low-grade lithium resources, as it enables the transfer of lithium from the solid phase to the aqueous phase. The choice of leaching method depends on factors such as the type of lithium-bearing material, the presence of impurities, and the downstream processing requirements. The most common leaching methods for lithium recovery include acid leaching [65], alkaline leaching [66], combined roasting–leaching approaches [67], and bioleaching, which will be discussed in detail in the following subsections.

Hydrometallurgical methods offer advantages in efficiency, selectivity, and environmental impact for recovering lithium from low-grade sources compared to traditional pyrometallurgical processes [68–71]. As shown in Figure 2a, a typical hydrometallurgical process for lithium recovery from spent batteries includes leaching, solvent extraction, and precipitation steps to obtain purified lithium salts [72].

In addition to the conventional acid and alkaline leaching methods, bioleaching has emerged as an eco-friendly alternative for lithium recovery (Figure 2b). Bioleaching utilizes microorganisms to facilitate the dissolution of lithium from solid materials through the production of organic acids, inorganic acids, and other metabolites. This approach has been successfully applied to recover lithium from spent lithium-ion batteries and lithium-bearing ores, demonstrating its potential as a sustainable and low-cost leaching technology.

The following subsections will provide a more detailed discussion on the principles, advantages, and limitations of each leaching method, as well as their recent applications in lithium recovery from various low-grade resources.

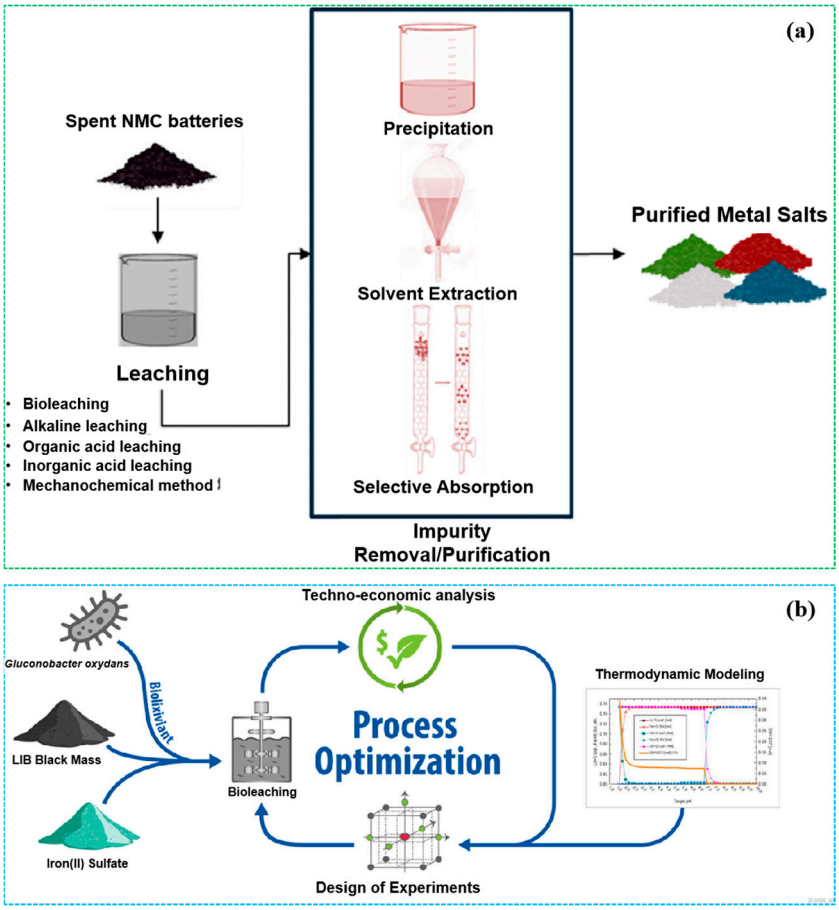


Figure 2. Schematic diagram of the leaching process for lithium resources: (**a**) acid and alkaline leaching [72]; and (**b**) bioleaching [73].

3.1.1. Acid Leaching

Acid and alkaline leaching are fundamental techniques for extracting lithium from low-grade sources, particularly clay-based deposits. These techniques correspond to the leaching step in Figure 2a.

Acid leaching uses strong acids like H_2SO_4 or HCl to dissolve lithium-bearing minerals, as shown in the reaction for spodumene dissolution:

$$LiAlSi_2O_6 + 4H^+ \rightarrow Li^+ + Al^{3+} + 2SiO_2 + 2H_2O \quad (1)$$

$$LiNi_xCo_yMn_zO_2 + 4H^+ \rightarrow Li^+ + xNi^{2+} + yCo^{2+} + zMn^{2+} + 2H_2O \quad (2)$$

Recent studies have explored various acid leaching techniques for lithium recovery from coal-based sources. Xie et al. [74] investigated lithium recovery from coal gangue utilizing acid baking followed by water leaching. Under optimal conditions using 70 wt% H_2SO_4, a baking temperature of 180 °C, and a baking time of 1 h, followed by leaching at 25 °C for 1 h, the lithium leaching rate reached 84.42%. Another study by Chen et al. [75] developed an efficient approach for lithium and aluminum recovery from coal fly ash using a combination of pre-desilication and an intensified acid leaching process. Under optimal conditions of 6 mol/L HCl, a 1:20 solid-to-liquid ratio, 120 °C, and 4 h, they achieved leaching efficiencies of 82.23% for lithium and 76.72% for aluminum. These findings demonstrate the potential of acid leaching techniques in extracting valuable elements from coal-based sources.

In addition, a novel pyrite reduction-sulfuric acid leaching process was developed to recover valuable metals from spent LIBs by Su et al. [65]. As shown in Figure 3, the

spent NCM powder, consisting of metals like Ni, Co, Mn, and Li, undergoes a shrinking core model reaction in the leaching solution. By optimizing parameters such as H_2SO_4 concentration, L/S ratio, pyrite dosage, temperature, and time, leaching efficiencies of 98%~99.9% were achieved. Kinetic studies revealed that the process is controlled by internal diffusion, with activation energies of 20–30 kJ/mol for each metal. Moreover, the synergistic reduction mechanism of Fe and S in pyrite was elucidated in depth. This eco-friendly and cost-effective approach provides a promising alternative to traditional acid leaching.

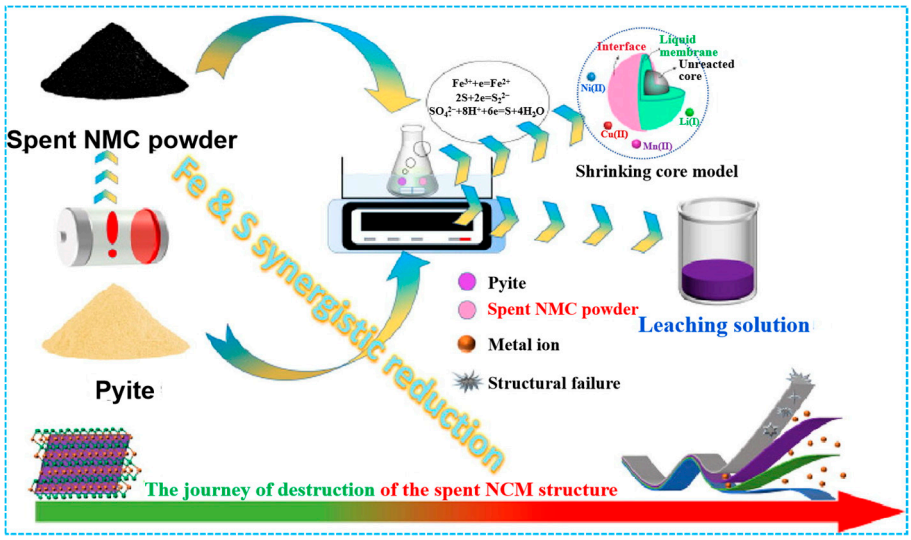


Figure 3. Schematic diagram of the acid and alkaline leaching process for recovering valuable metals from spent lithium-ion batteries [65].

3.1.2. Alkaline Leaching

Alkaline leaching uses basic solutions like NaOH or KOH. The spodumene reaction with NaOH is:

$$LiAlSi_2O_6 + NaOH \rightarrow LiOH + NaAlSiO_4 + SiO_2 \quad (3)$$

Recent studies have explored various alkaline leaching techniques for lithium recovery from different sources. Stopic et al. [76] investigated lithium extraction from lepidolite, spodumene, and petalite using mechanochemical treatment in alkaline media. They found that petalite's crystal structure was particularly suitable for this process, resulting in a substantial lithium extraction of 84.9%, and almost complete conversion to hydrosodalite after 120 min of ball milling. In another study, Xing et al. [66] developed a novel process for the clean and efficient extraction of lithium from α-spodumene coupled with the synthesis of hydroxysodalite zeolite. Using hydrothermal alkaline treatment, they achieved a lithium extraction efficiency of 95.8% under optimum conditions: temperature of 250 °C, NaOH concentration of 600 g/L, and a treatment time of 4 h.

The alkaline process for extracting lithium from spodumene has gained interest due to its potential advantages over the acid process. In the alkaline process, the mineral concentrate is roasted with lime or limestone, forming a clinker which is then leached with water, filtered, and crystallized as lithium hydroxide monohydrate. This method can provide advantages by replacing expensive chemicals such as sulfuric acid and soda ash with more affordable, domestically produced products like limestone or hydrated lime [77].

3.1.3. Combined Roasting–Leaching Methods

In addition to traditional acid and alkaline leaching, combined roasting-leaching methods have also been explored for lithium recovery from specific waste materials. For

example, Wu et al. [67] proposed a sodium carbonate roasting-acid leaching method to separate and recover lithium from spent lithium-containing aluminum electrolyte. As shown in Figure 4, under optimized conditions (1.10 times stoichiometric Na_2CO_3, roasted at 650 °C for 2.5 h; 2 mol/L HNO_3, L/S = 10, leached at 60 °C for 3 h), a 73.1% lithium leaching efficiency was obtained. During roasting, Na_2CO_3 promotes the conversion of Na_2LiAlF_6 to easily soluble LiF, enhancing lithium leaching. The lithium content in the leaching residue decreased from 2.20% to 0.71%, allowing it to be recycled as raw material for electrolysis cells. After neutralization and purification, lithium was recovered from the leachate as Li_2CO_3.

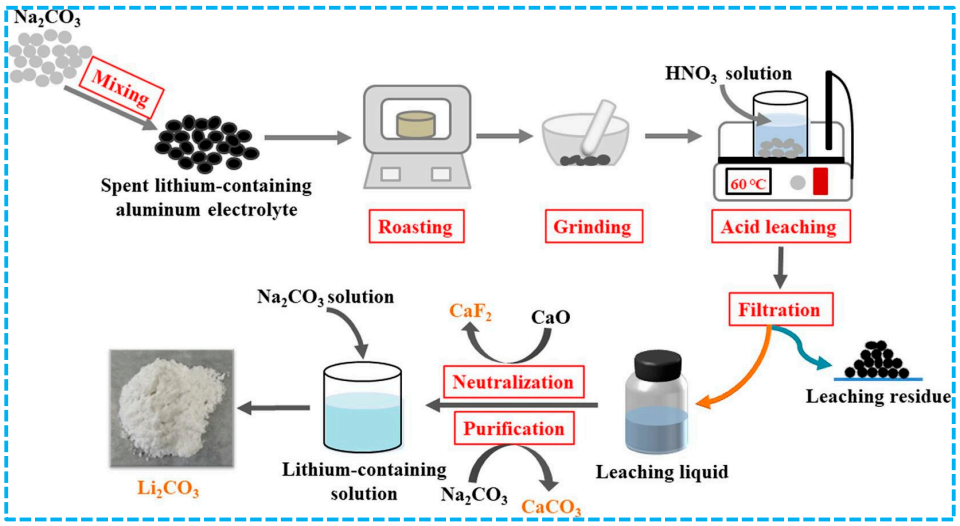


Figure 4. Flowchart of the recycling process for recovering lithium from spent lithium-containing aluminum electrolyte [67].

This combined roasting–leaching approach takes advantage of both pyrometallurgical and hydrometallurgical processes, offering a tailored solution for specific waste materials. The choice of an appropriate leaching method depends on factors like the specific lithium-bearing materials, impurities, and downstream processing requirements.

3.1.4. Bioleaching

Bioleaching represents an environmentally friendly approach for lithium extraction from ores and waste materials through the action of microorganisms. These microorganisms can facilitate lithium dissolution either through direct mechanisms (microbial oxidation/reduction) or indirect mechanisms (production of organic/inorganic acids).

Figure 5 illustrates the key biochemical mechanisms involved in the removal of metals from spent lithium-ion batteries (LIBs) through bioleaching [78]. The process is based on the interactions between microbes and the LIB particles, which lead to various biochemical reactions that promote metal leaching. Sulfate-reducing bacteria (SRB) can reduce sulfate to hydrogen sulfide (H_2S), which then reacts with metal ions (e.g., Fe^{3+}) to form soluble metal sulfides, thereby enhancing metal dissolution. Iron-oxidizing bacteria, such as *A. ferrooxidans*, can oxidize Fe^{2+} to Fe^{3+}, a strong oxidant that accelerates metal leaching. Fungi, like *A. niger*, produce complexolysis agents, such as citric, oxalic, and gluconic acids, which form soluble complexes with metal ions and promote their leaching. Additionally, microorganisms can produce organic ligands (e.g., siderophores) and inorganic ligands (e.g., ferricyanide ions) that form soluble metal–organic/inorganic complexes, further enhancing metal leaching. The synergistic effect of these biochemical processes improves the ability of microorganisms to leach metals from spent LIBs, making bioleaching an efficient and eco-friendly metal recovery technique.

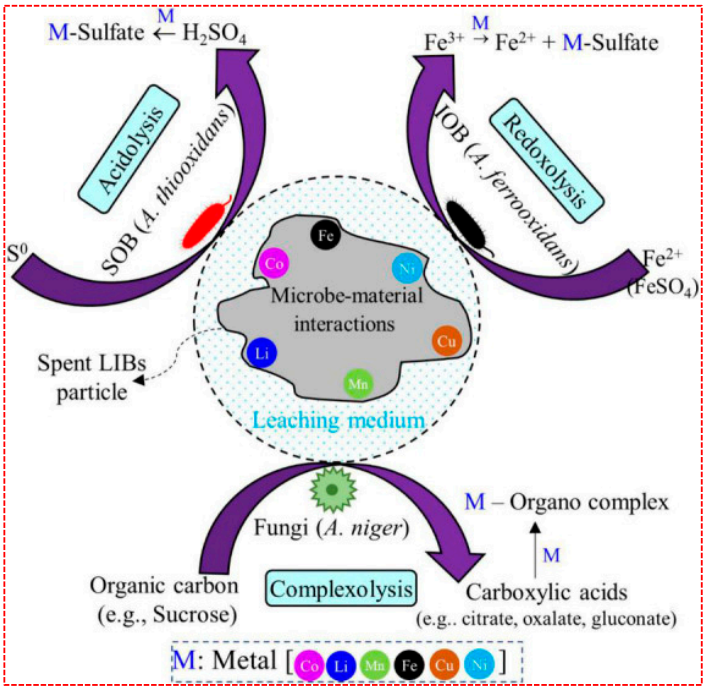


Figure 5. Key biochemical mechanisms for the removal of metals from spent LIBs [78].

Various microorganisms have been employed in lithium bioleaching, demonstrating their potential for lithium recovery from different materials. Table 1 summarizes the representative species, leaching mechanisms, lithium extraction efficiencies, and applicable materials for each type of microorganism.

Table 1. Microorganisms used in lithium bioleaching and their extraction efficiencies.

Microorganism Type	Representative Species	Leaching Mechanism	Lithium Extraction Efficiency	Applicable Materials	Ref.
Bacteria	*Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*	Oxidation of sulfur and iron compounds, producing sulfuric acid and ferric iron	Up to 100%	Spent lithium-ion batteries	[79]
Fungi	*Penicillium chrysogenum*	Production of organic acids, particularly gluconic acid	Up to 73.31%	Spent lithium-ion batteries	[80]
	Penicillium purpurogenum	Production of organic acids (gluconic and citric acids)	10.8 mg % dry weight (accumulated in biomass), 1.26 ppm (in leach liquor)	Spodumene ore	[81]
	Aspergillus niger	Production of organic acids (gluconic and citric acids)	5.1 mg % dry weight (accumulated in biomass), 0.75 ppm (in leach liquor)	Spodumene ore	
Yeast	*Rhodotorula rubra*	Production of capsular exopolymers	16.7 mg % dry weight (accumulated in biomass), 1.53 ppm (in leach liquor)	Spodumene ore	
Mixed cultures	*A. ferrooxidans* and *A. thiooxidans*	Synergistic effect of iron and sulfur oxidation	Up to 80%	Spent lithium-ion batteries	[82]
	A. ferrooxidans and *R. rubra* (bacterial-yeast)	Synergistic effect of autotrophic bacteria and heterotrophic yeast	Not specified	Lepidolite	[83]

As shown in Table 1, bacteria, fungi, yeasts, and mixed cultures have been successfully applied in lithium bioleaching. *Acidithiobacillus* species are the most commonly used bacteria, capable of oxidizing sulfur and iron compounds to produce sulfuric acid and ferric iron, which act as leaching agents. Fungal strains, such as Penicillium and Aspergillus species, facilitate lithium leaching through the production of organic acids, particularly gluconic and citric acids. The yeast Rhodotorula rubra has been found to produce capsular exopolymers that aid in lithium leaching. Mixed cultures, combining the synergistic effects of different microorganisms, have also been explored to enhance the leaching performance. Bioleaching has been applied to both spent lithium-ion batteries and lithium-bearing ores, with lithium extraction efficiencies ranging from 5.1 mg % dry weight to 100%, depending on the microorganism and the material being leached.

After the leaching process, various separation and purification methods are employed to selectively recover lithium from the leachate, which will be discussed in the following section.

3.2. Separation and Purification Methods

Following the leaching process, various separation and purification techniques have been developed and studied for selective lithium recovery, as illustrated in Figure 6 [16]. These methods can be broadly categorized into four main approaches: solvent extraction [84,85], ion exchange [86], membrane separation [87], and adsorption-based technologies [20].

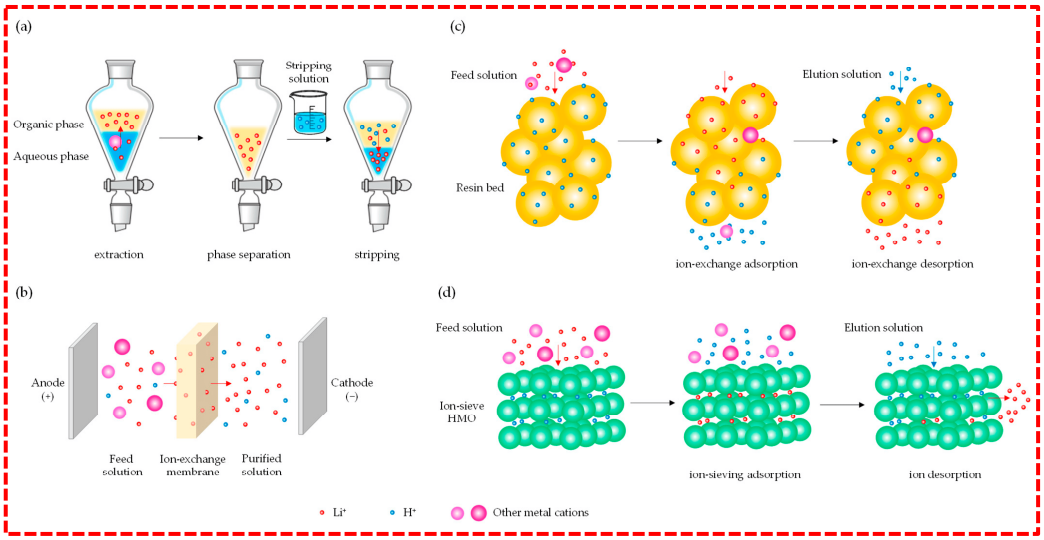


Figure 6. Schemes of lithium-ion separation methods from coal ash fly leachate: (**a**) solvent extraction, (**b**) electrodialysis with ion-exchange membrane, (**c**) ion-exchange with resin, and (**d**) ion-sieving. Copyright of Ref. [16].

3.2.1. Solvent Extraction

Solvent extraction has demonstrated clear advantages in the selective separation of metal ions from leachate solutions [88]. As shown in Figure 6a, the solvent extraction process typically consists of three core units: extraction, phase separation, and stripping. The selection of extractants is a decisive factor influencing separation efficiency.

Wesselborg et al. [89] successfully achieved the highly selective separation of lithium from other metals (Co, Ni, Mn) in spent lithium-ion battery leachate using tributyl phosphate (TBP) as the extractant and $FeCl_3$ as a synergistic extractant. The introduction of $FeCl_3$ significantly enhanced the efficiency and selectivity of lithium extraction by TBP. This innovative synergistic extraction method not only expands the application scope of

solvent extraction but also provides new insights for developing green and efficient battery recycling processes.

3.2.2. Membrane Separation Technologies

Membrane separation technologies have gained extensive attention in the field of lithium separation due to their high efficiency and energy-saving advantages [90–92]. Advances have been made in novel membrane modules and membrane-coupled processes (Figure 6b).

Wagh et al. [87] developed a membrane solvent extraction (MSX) process by coupling solvent extraction with membrane separation using Di(2-ethylhexyl)phosphate (D2EHPA) as the carrier for the separation and purification of lithium from clay mineral leachate. As illustrated in Figure 7, the MSX system consists of a hollow fiber membrane module with D2EHPA impregnated in the pores of the hollow fibers. The process first involves the adsorption of Li^+ from the leachate using $Al(OH)_3$ to form a lithium aluminum double-hydroxide sulfate (LDH sulfate) precipitate, which is then dissolved in dilute sulfuric acid to prepare a lithium-containing feed solution. The feed solution is circulated through the shell side of the hollow fiber module, while the stripping solution (2 mol/L H_2SO_4) flows countercurrently through the lumen side. Under optimized conditions (pH = 3, 30% D2EHPA/isopar as the organic phase in the membrane pores), the MSX process achieved a lithium recovery of 92% with a purity of ≥94%. Compared with traditional extraction processes, the MSX process offers advantages such as fast mass transfer rates and low energy consumption, showing great potential for applications in lithium-ion batteries and clean energy fields.

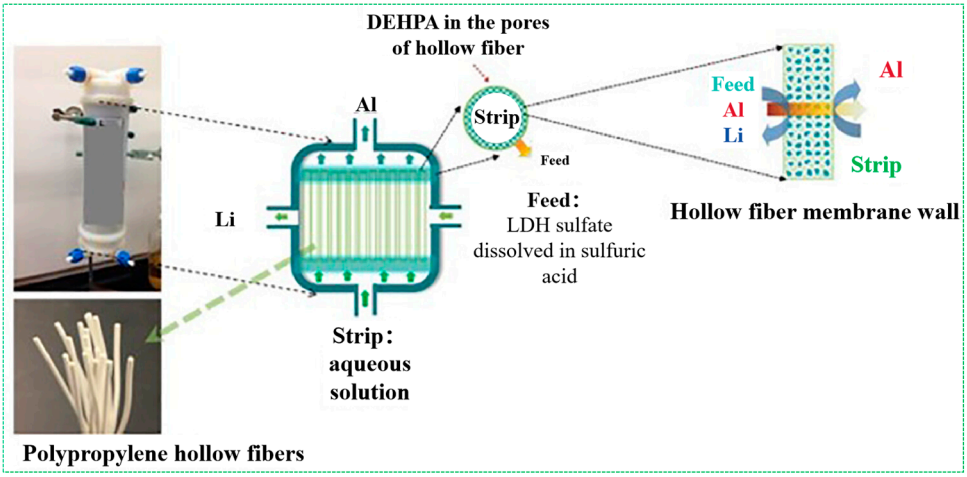


Figure 7. Schematic of the MSX system used to separate Li from Al in LDH sulfate [87].

3.2.3. Adsorption-Based Methods

Adsorption-based methods, including ion exchange, ion-sieving, and other adsorption techniques, have shown promising prospects for lithium purification from various aqueous resources. These methods rely on the selective interaction between lithium ions and the adsorbent materials

(a) Ion Exchange

Ion exchange technology has shown promising prospects for lithium purification from aqueous resources such as salt lake brines, seawater, and geothermal water [86]. As illustrated in Figure 6c, the ion exchange process typically involves two steps: selective adsorption and elution of lithium ions. Compared with traditional extraction methods, its environmentally friendly nature and low cost have become increasingly prominent [93,94].

Nishihama et al. [95] successfully recovered high-purity lithium carbonate (>99.9% purity) from seawater using a two-stage ion exchange chromatography process with granular λ-MnO_2 as the adsorbent. The first stage employed a fixed bed for lithium enrichment, achieving a preliminary lithium concentration of 33%. The second stage involved the removal of divalent metal ions using a strong acid cation exchange resin, followed by the removal of Na^+/K^+ using a β-diketone/TOPO impregnated resin, and finally precipitating high-purity Li_2CO_3 using a saturated $(NH4)_2CO_3$ solution. This innovative multi-stage ion exchange process holds promise for widespread application in the high-value utilization of lithium resources.

(b) Ion-sieving Technology

Ion-sieving technology is an emerging lithium separation method that has developed in recent years [96–98]. Its principle is to achieve the selective separation of Li^+ using materials with specific pore sizes or structures (Figure 6d). Significant progress has been made in lithium manganese oxide (LMO)-based ion-sieving materials [98,99]. In particular, the lithium-ion sieve material ($H_2Mn_2O_4$) derived from spinel-type $LiMn_2O_4$ after acid treatment exhibits excellent adsorption selectivity for Li^+ in aqueous solutions, showing good application prospects for extracting lithium from seawater and brines [100,101].

To enhance the separation efficiency, Luo et al. [102] developed a novel hybrid membrane by incorporating a lithium-ion sieve, hydrogen manganese oxide (HMO), into anion-exchange membranes (AEMs). The composite membrane, denoted as 20%HMO@m-PTP, exhibited high Li^+ flux (0.48 mol/m^2·h) and Li^+/Mg^{2+} selectivity ($\beta Li^+/Mg^{2+}$ = 14.1). As illustrated in Figure 8, the hybrid membrane achieves Li^+/Mg^{2+} separation through a combination of anion-exchange-driven transport and the lithium-ion sieving effect of HMO. Cations (Li^+ and Mg^{2+}) are transported through the anion-exchange membrane driven by the concentration gradient, while the HMO selectively allows Li^+ to pass through, resulting in the efficient separation of Li^+ from Mg^{2+}. This hybrid membrane system, driven by anion-exchange and cation-concentration gradient, combined with the lithium-ion sieving effect of HMO, provides new insights into the development of high-flux and high-selectivity materials for lithium extraction.

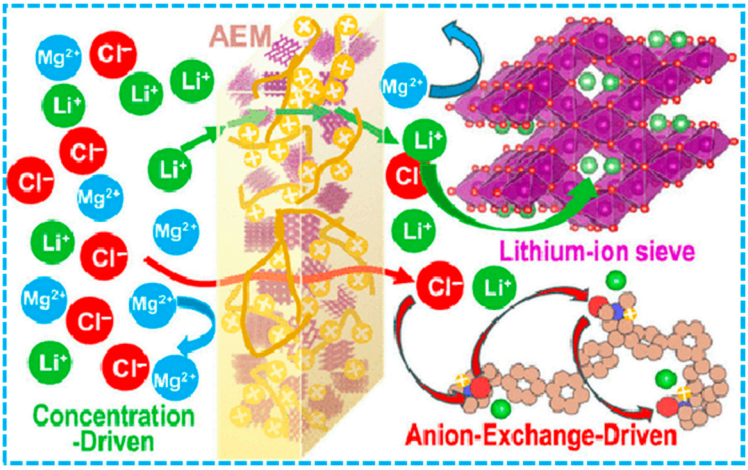


Figure 8. Schematic illustration of the Li^+/Mg^{2+} separation mechanism in the anion-exchange- and cation-concentration-driven hybrid membrane incorporating a lithium-ion sieve (HMO) [102].

Recent advances in metal–organic frameworks (MOFs) have further expanded the possibilities of ion-sieving technology. For instance, researchers developed a novel light-responsive lithium adsorbent by integrating polyspiropyran (PSP) with UiO-66 MOF (Figure 9A). This design combines the size-sieving capability of MOFs with light-triggered

regeneration functionality. The successful synthesis was confirmed by XRD patterns showing a preserved crystal structure (Figure 9B) and FT-IR spectra indicating the incorporation of PSP units (Figure 9C). The modification significantly altered the material's surface properties, as evidenced by the reduced BET surface area from 1175.0 to 42.6 m^2 g^{-1} (Figure 9D) and the light-responsive surface wettability (Figure 9E).

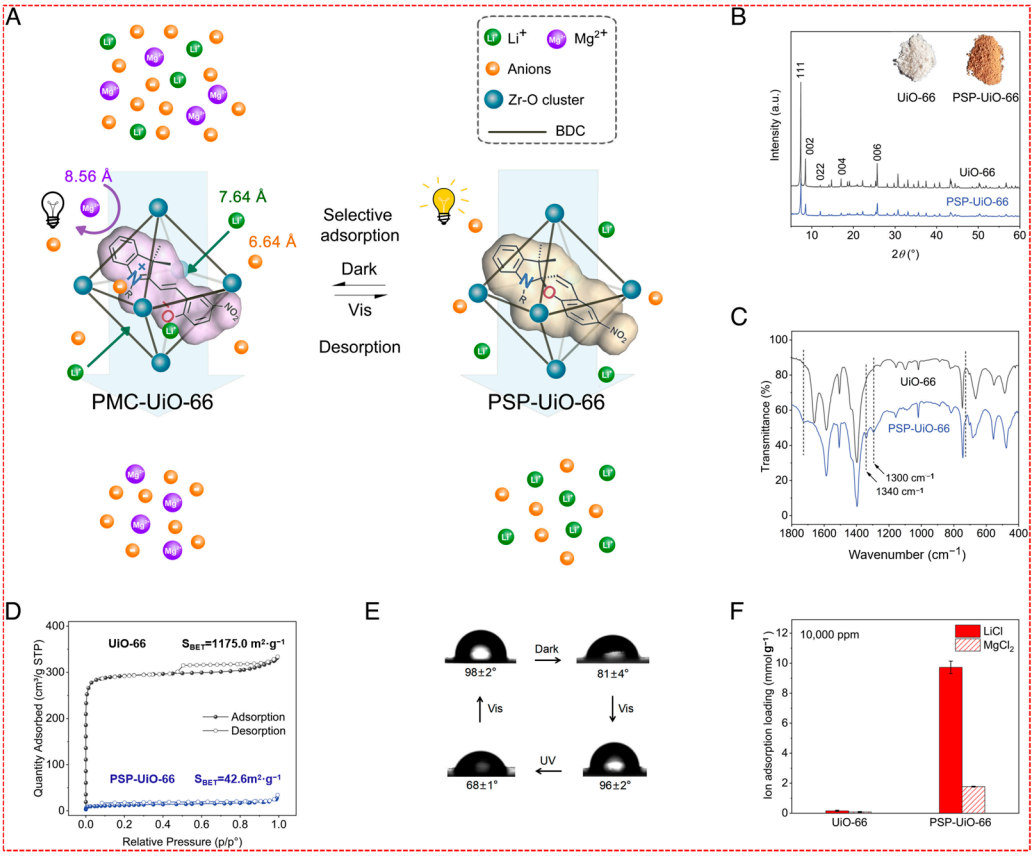


Figure 9. Sieving adsorption of lithium in PSP-UiO-66. (**A**) Schematic illustration of the mechanism of selective lithium salt adsorption by PSP-UiO-66 in the dark and desorption under sunlight irradiation. (**B**) XRD patterns of UiO-66 and PSP-UiO-66. The inset of B is the optical image of UiO-66 and PSP-UiO-66. (**C**) FT-IR spectra of UiO-66 and PSP-UiO-66. (**D**) N_2 adsorption–desorption isotherms of UiO-66 and PSP-UiO-66. (**E**) The cyclic water contact angles of PSP-UiO-66 measured under dark, Vis, and UV light conditions. (**F**) Ion adsorption loading of UiO-66 and PSP-UiO-66 tested in 10,000 ppm LiCl and $MgCl_2$ solutions. The error bars indicate SD.

Most importantly, PSP-UiO-66 demonstrated exceptional selective adsorption performance. In solutions containing 10,000 ppm of both LiCl and $MgCl_2$, it achieved a LiCl adsorption capacity of approximately 10 mmol g^{-1} while showing minimal $MgCl_2$ uptake (Figure 9F). This performance significantly surpasses previously reported values of 0.2–8.5 mmol g^{-1}. The material exhibited Li^+/Mg^{2+} selectivity ranging from 5.8 to 29 in synthetic brines with varying Mg/Li ratios, while offering the additional advantage of rapid sunlight-triggered regeneration within 6 min. These developments in ion-sieving materials, combining precise pore size control with stimuli-responsive properties, represent promising advances towards more efficient and sustainable lithium extraction processes.

These developments in ion-sieving materials, combining precise pore size control with stimuli-responsive properties, represent promising advances towards more efficient and sustainable lithium extraction processes.

(c) Electrostatic Adsorption

Electrostatic adsorption occurs when lithium ions are attracted to the charged sur-face of the adsorbent through coulombic interactions [103]. This process is particularly effective for adsorbents with high surface charge density, such as layered double-hydroxides (LDHs) and metal oxides [104].

Song et al. [105] investigated the use of Ca-alginate beads as a biosorbent for the recovery of Li(I), Sr(II), and La(III) ions from aqueous solutions. The adsorption process was found to be primarily driven by electrostatic attraction between the negatively charged carboxyl groups (-COO-) on the alginate beads' surface and the positively charged metal ions, forming coordination bonds. The maximum adsorption capacity for Li(I) was 17.79 mg/g under optimal conditions. The adsorption kinetics followed the pseudo-second-order model, indicating chemisorption as the rate-limiting step, while the adsorption isotherms fit the Langmuir model, suggesting monolayer adsorption. FTIR and XPS analyses confirmed the interaction between metal ions and carboxyl groups. The Ca-alginate beads also demonstrated good regeneration performance, maintaining above 80% of the initial adsorption capacity after five adsorption–desorption cycles. This study highlights the potential of using low-cost, environmentally friendly biosorbents for the electrostatic adsorption and recovery of lithium ions from aqueous solutions.

(d) Ion Imprinting Technology

Ion imprinting technology is a powerful technique for creating highly selective adsorbents for lithium recovery. This approach involves the synthesis of polymeric materials with specific recognition sites that are complementary in size, shape, and functionality to the target lithium ions [106]. The synthesis process typically involves the polymerization of functional monomers around a lithium ion template, followed by the removal of the template to leave behind selective binding sites [107].

For example, Qi et al. [108] developed a lithium ion-imprinted polymer (Li-IIP) using bulk polymerization for lithium extraction from salt lake brines (Figure 10). Using Li^+ as the template ion and benzo-15-crown-5 as the selective ligand, they synthesized the polymer with methacrylic acid as the functional monomer and ethylene glycol dimethacrylate as the crosslinker. The prepared Li-IIP exhibited an impressive adsorption capacity of 30.53 $mg \cdot g^{-1}$ at 300 $mg \cdot L^{-1}$ Li^+ concentration and demonstrated good selectivity towards Li^+ in the presence of competing ions (Na^+, K^+, Ca^{2+}, and Mg^{2+}). The material also showed excellent reusability, maintaining 89.20% of its adsorption capacity after eight cycles.

Further advancing this field, Li et al. [109] developed an innovative method to address the growing global demand for lithium resources and the need for sustainable, environmentally friendly recycling processes. This study synthesized a novel electrode material by combining ion imprinting technology with capacitive deionization, thoroughly characterized using scanning electron microscopy and Fourier-transform infrared spectroscopy, while density functional theory was employed to elucidate the adsorption mechanism and water cluster formation. The material demonstrated an impressive performance with a maximum adsorption capacity of 36.94 mg/g at 600 mg/L Li^+ concentration, exhibiting excellent selectivity in complex solutions with separation factors of 2.07, 9.82, 1.80, and 8.45 for Na^+, K^+, Mg^{2+}, and Al^{3+}, respectively. The material maintained 91.81% of its initial Li^+ adsorption capacity after five regeneration cycles, while electrochemical adsorption more than doubled the Li^+ adsorption capacity compared to conventional physical adsorption, attributed to the energy provided for deprotonation, which enabled the better exposure of crown ether molecule cavities and the enrichment of active sites.

In summary, various innovative methods and materials have emerged in the field of lithium separation and purification technologies in recent years, providing new avenues for the efficient separation and purification of lithium from complex systems. Future research should focus on the relationship between separation mechanisms, material structures, and

properties, as well as process optimization, to develop green, efficient, and universally applicable lithium separation and purification technologies. These advancements will help address the bottleneck problem of the high-value utilization of lithium resources from the source.

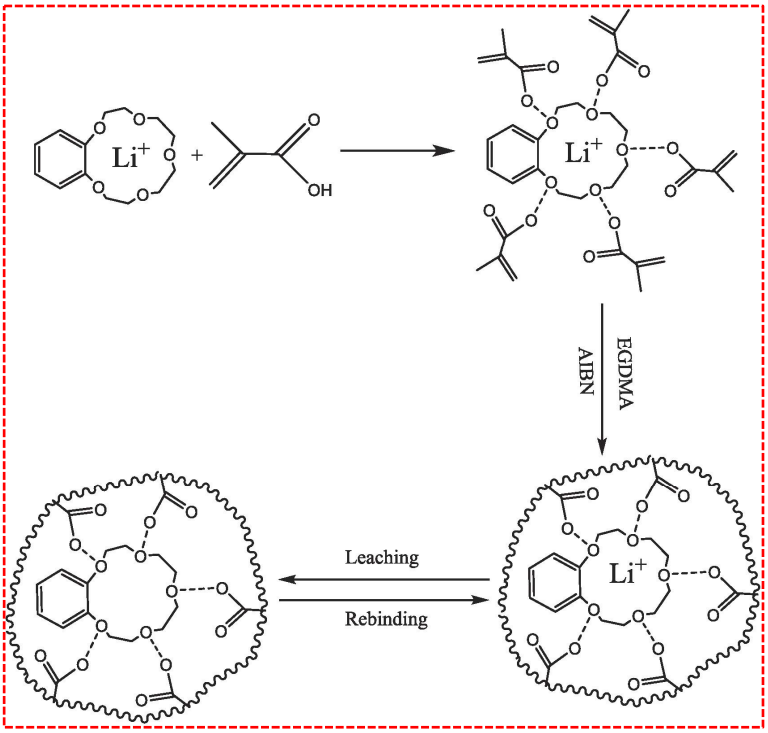


Figure 10. Schematic diagram of Li-IIP preparation [108].

4. Challenges and Feasibility of Lithium Recovery from Low-Grade Resources

The development of low-grade lithium resources presents a range of challenges that must be addressed to ensure the feasibility and sustainability of lithium recovery. Table 2 summarizes the main technical, economic, and environmental challenges and opportunities in low-grade lithium resource development. This section explores these aspects in detail, focusing on the key considerations for achieving sustainable and economically viable lithium recovery from low-grade sources.

Table 2. Challenges and opportunities in low-grade lithium resource development.

Aspect	Challenges	Opportunities
Technical	1. Low lithium concentrations (<100 mg/L) 2. Presence of impurities (e.g., high Mg/Li ratio) 3. Resource characteristic variations 4. Low efficiency of conventional extraction methods	1. Development of highly selective and efficient extraction techniques 2. Emerging direct lithium extraction (DLE) technologies, particularly electrochemically mediated methods
Economic	1. High-energy consumption and costs of traditional methods 2. Scaling and operational costs 3. Market volatility and price fluctuations	1. Cost reduction through innovative technologies (e.g., membrane-less electrochemical cells) 2. Pilot-scale trials demonstrating feasibility of large-scale operations 3. Growing global demand for lithium driving price increases

Table 2. *Cont.*

Aspect	Challenges	Opportunities
Environmental and Sustainability	1. Environmental impact of traditional extraction methods (e.g., evaporation ponds) 2. Water resource management in water-scarce regions 3. Social impact on local communities	1. Environmentally friendly alternatives (e.g., electrochemical de-intercalation of lithium) 2. Innovative technologies reducing water consumption and utilizing osmotic energy 3. Exploring green alternatives and energy-efficient extraction methods 4. Development of closed-loop recycling systems for sustainable lithium production 5. Assessing and managing social impacts, ensuring benefits for local communities

4.1. Technical Challenges

Low-grade lithium resources pose several technical challenges that must be overcome to achieve efficient and cost-effective extraction. These challenges include low lithium concentrations, the presence of impurities, resource characteristic variations, and the efficiency of extraction technologies.

4.1.1. Low Lithium Concentrations

Low lithium concentrations in low-grade resources present a significant technical challenge. Studies indicate that lithium concentrations in low-grade brines are typically below 100 mg/L, which substantially increases the complexity and cost of extraction processes [31]. For instance, the lithium concentration in Dead Sea brine can be as low as 0.15 mmol, necessitating highly selective and efficient extraction techniques. These low concentrations not only increase the volume of brine that needs to be processed but also reduce the efficiency of conventional extraction methods [110–112].

4.1.2. Presence of Impurities

The presence of impurities is another major challenge in extracting lithium from low-grade resources. Research shows that the lithium extraction efficiency in real brines is significantly lower than in synthetic brines, at around 32% compared to 91% [113]. This discrepancy is primarily attributed to the complex impurities present in real brines. For example, the presence of magnesium ions is particularly problematic, with the Mg/Li molar ratio in Dead Sea brine reaching as high as 3258:1 [114]. These impurities not only interfere with the extraction process but can also lead to reduced product purity, necessitating additional purification steps [115].

4.1.3. Resource Characteristic Variations

Low-grade lithium resources exhibit significant variations in their characteristics, presenting unique challenges for extraction processes. For example, lithium concentrations can vary widely, ranging from 0.1 to 400 mg/L in geothermal brines, 200 to 1400 mg/L in continental brines, and about 0.17 ppm in seawater [116–118]. Additionally, the chemical composition of these resources, particularly continental brines, can differ greatly, with various types classified as carbonate, sodium sulfate, magnesium sulfate, or chloride brines [119]. These diverse characteristics necessitate the development of flexible extraction technologies that can adapt to specific resource properties while maintaining efficiency and selectivity across different resource types [115].

4.1.4. Efficiency of Extraction Technologies

The lithium industry faces a critical challenge in resource extraction efficiency. Traditional evaporation methods are inefficient in lithium extraction, with losses of up to

50% even in high-grade brines containing about 2000 ppm lithium [36,120]. Direct lithium extraction (DLE) technology offers significant improvements, achieving over 90% lithium recovery, reducing impurities by over 99%, and showing promise for meeting growing lithium demand from various low-concentration sources like geothermal brines [21]. DLE also aims to reduce the environmental impact compared to traditional methods. In particular, Stanford University's redox-couple electrodialysis method, which uses an electrochemical process to selectively extract lithium ions from brine, shows potential for cutting costs by over 40% and reducing electricity consumption by over 90% compared to conventional methods [121]. These innovative solutions are crucial for addressing the technical challenges posed by low-grade lithium resources and ensuring a sustainable lithium supply.

4.2. Economic Feasibility

In addition to the technical challenges, the economic feasibility of low-grade lithium resource development must also be considered. This section examines the cost-effectiveness of recovery technologies, scaling and operational costs, the impact of market volatility, and the role of policy support and incentives in promoting the development of low-grade lithium resources.

4.2.1. Cost-Effectiveness of Recovery Technologies

Assessing the cost efficiency of current recovery methods is crucial in determining the economic viability of low-grade lithium resource development. Traditional hydrometallurgical methods, while mature, may face high energy consumption and cost issues when dealing with low-grade resources [21,31]. In contrast, emerging electrochemical extraction methods have the potential to reduce energy consumption and operational costs [122]. For instance, a study developed a decoupled membraneless electrochemical cell design that achieved up to 21.5% energy savings by effectively utilizing the osmotic energy of brines [123]. Such innovations can significantly improve the economic feasibility of low-grade resource development.

4.2.2. Scaling and Operational Costs

Scaling lithium recovery technologies from laboratory to industrial applications is a significant challenge. Research indicates that multiple factors need to be considered in the scaling process, including feedstock transportation, processing capacity, and infrastructure requirements [124–126]. For example, a pilot-scale cell using electrodes with a surface area of 33.75 m^2 successfully achieved an 84.0% lithium recovery rate from Dead Sea brine [123]. Such scaling trials provide valuable data for assessing the feasibility of large-scale operations while highlighting the importance of maintaining high efficiency while controlling costs [127,128].

4.2.3. Market Volatility Impact

The volatility of lithium prices has a significant impact on the economic feasibility of low-grade resource development. With the growing demand for electric vehicles and renewable energy storage systems, global lithium demand is projected to reach 5.11 Mt by 2050 [36]. This demand growth may drive price increases, making low-grade resource development more attractive [129]. However, price instability also increases investment risks, and developers need to consider long-term market trends and potential price fluctuations [130,131].

The economic feasibility of low-grade lithium resource development depends on a combination of factors, including the cost-effectiveness of recovery technologies, scaling and operational costs, market volatility, and policy support [132,133]. By carefully consid-

ering these factors and implementing appropriate strategies, the industry can ensure the economic viability of low-grade resource development.

4.3. Environmental and Sustainability Concerns

While addressing technical and economic challenges is crucial, the environmental and sustainability concerns surrounding low-grade lithium resource development cannot be overlooked [31,134,135]. This section explores the environmental impact of recovery processes, water resource management, sustainability considerations, and the social impact of low-grade lithium resource development.

4.3.1. Environmental Impact of Recovery Processes

Assessing the environmental footprint of different recovery methods is key to ensuring sustainable lithium production. Traditional lithium extraction methods, such as evaporation pond technology, while cost-effective, can have significant impacts on local ecosystems [136]. In contrast, emerging electrochemical extraction methods offer more environmentally friendly alternatives. For example, the electrochemical de-intercalation of lithium (EDM) is considered an environmentally friendly, highly selective, and cost-effective technique [137,138]. This method can significantly reduce water consumption and chemical use, thereby lowering the environmental impact [137].

4.3.2. Water Resource Management

Water resource management is a critical environmental challenge in low-grade lithium resource development, especially in water-scarce regions. New extraction technologies are exploring ways to reduce water consumption. For instance, the membraneless electrochemical cell design not only extracts lithium from low-concentration brines but also utilizes the osmotic energy of brines, achieving energy savings [123]. This innovative approach not only improves extraction efficiency but also reduces the dependence on freshwater resources, which is particularly significant for lithium resource development in water-scarce areas [139].

4.3.3. Sustainability Considerations

Exploring green alternatives and energy-efficient extraction methods to minimize environmental damage is a current research focus. The application of electro-driven materials and processes in lithium recovery is becoming an important research direction, as they offer the potential to reduce energy consumption and environmental impacts [140]. Additionally, the development of closed-loop recycling systems, particularly for lithium-ion batteries and other lithium-containing e-waste, is becoming a key strategy for achieving sustainable lithium production [141]. These methods can not only reduce dependence on primary resources but also significantly lower the environmental burden of waste management [142].

Addressing environmental and sustainability concerns is essential for the responsible development of low-grade lithium resources. By implementing environmentally friendly recovery processes, effective water resource management, sustainable practices, and considering the social impact, the industry can ensure that the development of low-grade lithium resources aligns with the principles of sustainability [143].

In conclusion, the development of low-grade lithium resources presents a range of challenges and opportunities. By addressing the technical challenges, ensuring economic feasibility, and prioritizing environmental and sustainability concerns, the lithium industry can unlock the potential of low-grade resources and meet the growing global demand for lithium in a responsible and sustainable manner [144].

While the challenges and limitations discussed in this section are significant, it is important to note that ongoing research and development efforts are focused on addressing these issues. Section 5 will explore promising solutions, future research directions, and policy recommendations aimed at overcoming the technical, economic, and environmental challenges associated with the development of low-grade lithium resources, such as advanced extraction and processing technologies (Section 5.1.1), sustainable practices and life cycle assessment (Section 5.1.2), and supportive policy frameworks (Section 5.2).

5. Future Outlook and Recommendations

The development of low-grade lithium resources presents both challenges and opportunities for the lithium industry. To ensure a sustainable and secure supply of lithium in the face of growing global demand, it is essential to invest in research and development, establish supportive policy frameworks, and foster international cooperation. This section explores the key areas for future research, policy recommendations, and market trends that will shape the low-grade lithium resource industry in the coming years.

5.1. Research and Development Opportunities

Advancing extraction and processing technologies and integrating sustainability considerations are crucial for unlocking the potential of low-grade lithium resources [22,145]. This subsection highlights the key areas for research and innovation in lithium extraction and processing, as well as the importance of collaborative efforts between academia and industry.

5.1.1. Advancing Extraction and Processing Technologies

The future of low-grade lithium resource development relies heavily on the continuous advancements in extraction and processing technologies. Key areas for research and innovation include improving the selectivity and efficiency of lithium extraction from complex brines and other low-grade sources [140], developing novel sorbents and membranes capable of effectively separating lithium from other ions [146], particularly in the presence of high magnesium concentrations [147], and exploring electrochemical methods for direct lithium extraction (DLE) that offer higher efficiency and a lower environmental impact [36]. Additionally, investigating the potential of biotechnology in lithium extraction, such as the use of lithium-accumulating microorganisms, could open up new avenues for sustainable lithium recovery [78].

Collaborative efforts between academia and industry are crucial for translating laboratory successes into commercially viable processes. Joint research initiatives should focus on scaling up promising technologies from the bench-scale to pilot plant operations [148], conducting field trials in diverse geological settings to test the adaptability of new extraction methods [149], and developing modular and flexible extraction systems that can be tailored to different low-grade lithium resources [150]. These collaborative endeavors will accelerate the development and deployment of advanced extraction and processing technologies, enabling the economically viable and environmentally sustainable exploitation of low-grade lithium resources [2].

5.1.2. Sustainable Practices and Life Cycle Assessment

Integrating sustainability considerations into the development of lithium extraction and processing technologies is paramount. Research opportunities in this area include conducting comprehensive life cycle assessments (LCAs) of various lithium extraction and processing methods to identify environmental hotspots and improvement opportunities [151], developing closed-loop systems that minimize waste and maximize resource recovery, investigating energy-efficient processes and the integration of renewable energy

sources in lithium extraction operations, and exploring water-conserving technologies, particularly for operations in water-scarce regions [152].

To ensure that sustainability is at the forefront of technology development, it is essential to assess the long-term environmental impacts of different extraction methods on local ecosystems and communities [153]. Developing standardized sustainability metrics for the lithium industry will enable meaningful comparisons between different production methods and sites, driving continuous improvement and accountability [154]. By prioritizing sustainability from the outset, the lithium industry can minimize its environmental footprint and contribute to the global transition towards a more sustainable future [155].

5.2. Policy Framework for Sustainable Development

Establishing a supportive policy framework is essential for promoting the sustainable development of low-grade lithium resources. This subsection discusses the role of incentives, regulations, and international cooperation in shaping the future of the lithium industry.

5.2.1. Incentives and Regulations

To support the sustainable development of low-grade lithium resources, policymakers should implement incentives for research and development in efficient, environmentally friendly extraction technologies. This can include tax incentives for companies investing in sustainable lithium extraction technologies, grants, and subsidies for research institutions and companies working on innovative extraction methods, and streamlined permitting processes for projects that meet stringent environmental and social standards [156].

In parallel, developing regulatory frameworks that balance environmental protection with the need for lithium resource development is crucial. These frameworks should establish clear standards for sustainable lithium production, including water use, carbon emissions, and social impact metrics [157]. Mandatory sustainability reporting for lithium producers can increase transparency and drive continuous improvement [158]. By creating a policy environment that rewards sustainable practices and encourages responsible lithium production, governments can play a vital role in shaping the future of the lithium industry [159].

5.2.2. International Cooperation and Knowledge Sharing

The global nature of the lithium market and the shared challenges in low-grade resource development necessitate strong international cooperation. Establishing international research consortia to tackle common technical challenges in low-grade lithium extraction [149], creating platforms for knowledge sharing between established lithium-producing regions and emerging players, and developing global best practices for sustainable lithium production and resource management are essential steps in fostering collaboration and accelerating progress [160].

To facilitate international cooperation, policymakers should work towards harmonizing standards and regulations to facilitate international trade and investment in the lithium sector [161]. Initiatives such as international conferences and workshops focused on low-grade lithium resource development, joint training programs to build capacity in emerging lithium-producing countries, and collaborative projects between countries with different types of low-grade lithium resources can further promote knowledge sharing and technical exchange [162]. The development of open-access databases on lithium resources and extraction technologies can also accelerate global research efforts and encourage collaboration among stakeholders [163].

5.3. Projected Industry Growth and Market Trends

Understanding the projected growth and market dynamics of the lithium industry is crucial for stakeholders involved in low-grade lithium resource development. This subsection examines the demand and production outlook for lithium and the key factors influencing the market.

5.3.1. Demand and Production Outlook

The low-grade lithium recovery sector is expected to play an increasingly crucial role in meeting the growing global demand for lithium. According to one source, the lithium market is expected to grow from 184,000 TPA (tonnes per annum) of lithium carbonate to 534,000 TPA by 2025 [164]. As conventional high-grade resources become strained, the industry must shift its focus towards the development of low-grade lithium sources to ensure a sustainable and reliable supply chain [36].

The geographical distribution of lithium production is also likely to shift as low-grade resources become economically viable, with new players entering the market. Many countries are placing increasing emphasis on domestic lithium production to secure supply chains, potentially driving investment in low-grade resource development [165]. These trends highlight the importance of developing sustainable and efficient extraction technologies to unlock the potential of low-grade lithium resources worldwide [36,165].

5.3.2. Market Dynamics and Influencing Factors

The lithium market is subject to various dynamics and influencing factors that can impact the development of low-grade resources. Fluctuations in lithium prices, driven by changes in supply and demand, can significantly affect the economic viability of low-grade resource projects [166]. Technological breakthroughs in extraction and processing methods could suddenly make certain low-grade resources more attractive, reshaping the competitive landscape [167].

Moreover, evolving battery technologies and their specific lithium requirements can influence the demand for different types of lithium products, such as lithium hydroxide or lithium carbonate [168]. As battery manufacturers seek to improve energy density, safety, and longevity, their preferences for specific lithium compounds may change, affecting the value and marketability of different low-grade lithium resources. Understanding and anticipating these market dynamics will be crucial for stakeholders involved in low-grade lithium resource development [169].

6. Conclusions

The sustainable development of low-grade lithium resources is crucial for meeting the growing global demand for lithium, driven by the accelerating adoption of electric vehicles and renewable energy storage systems. This review has highlighted the importance of advancing extraction and processing technologies, integrating sustainability considerations, and fostering collaborative research and development efforts to unlock the potential of these resources.

The path forward requires a multi-faceted approach, involving technological innovation, supportive policy frameworks, and international cooperation. Governments, industry, and academia must work together to develop and deploy advanced extraction and processing methods that are both economically viable and environmentally sustainable. Policymakers have a critical role to play in creating incentives for sustainable practices, establishing regulatory frameworks that balance resource development with environmental protection, and facilitating knowledge sharing and collaboration at the global level.

As the world transitions towards a low-carbon future, the responsible development of low-grade lithium resources will be essential for ensuring a secure and sustainable supply of this critical metal. By prioritizing sustainability, investing in research and development, and fostering a spirit of collaboration and knowledge sharing, the lithium industry can contribute meaningfully to the global effort to build a more sustainable and resilient energy system. The insights and recommendations provided in this review aim to guide stakeholders in navigating the complexities of low-grade lithium resource development and charting a course towards a more sustainable future.

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References

1. Prasad, N.E.; Gokhale, A.; Wanhill, R.J.H. *Aluminum-Lithium Alloys: Processing, Properties, and Applications*; Butterworth-Heinemann: Oxford, UK, 2013; ISBN 978-0-12-401679-8.
2. Aljarrah, S.; Al-Rawajfeh, A.E.; Shahid, M.K. Qamar Ul Islam Recent Innovations and Patents of Lithium Extraction Techniques-from Various Lithium Bearing Solutions. *Recent Innov. Chem. Eng. RICE* **2023**, *16*, 241–259. [CrossRef]
3. Kudryavtsev, P. Lithium in Nature, Application, Methods of Extraction. *Sci. Isr. Technol. Advant.* **2016**, *18*, 3–63.
4. Grant, A. The Sedimentary Lithium Opportunity. Available online: https://www.jadecove.com/research/sedimentarylithium (accessed on 18 December 2024).
5. Pavlyshyn, V.I.; Cherniyenko, N.M. LITHIUM in the SUBSOIL of UKRAINE Part 1. Distribution and Forms of Finding Lithium in Mineral Complexes of Ukraine. *Mineral. J.* **2023**, *45*, 3–20. [CrossRef]
6. Ma, Y.; Qin, X.; Pan, T.; Chen, J.; Jiang, Z.; Ding, C.; Zhang, D.; Zhang, F.; Feng, N.; Liu, C.; et al. Sedimentary Environment and Source Analysis of Sedimentary Lithium Deposits in Dezong Mahai Salt Lake, Qaidam Basin. *Sustainability* **2024**, *16*, 10561. [CrossRef]
7. Abdullayev, B.; Askarova, N.; Toshkodirova, R.; Rifky, M.; Ayakulov, N.; Kurbanov, B.; Samadiy, M. Recent Developments in the Extraction of Lithium from Water Resources. *AJC* **2024**, *36*, 275–280. [CrossRef]
8. Wang, C.; Zheng, M.; Zhang, X.; Wu, Q.; Liu, X.; Ren, J.; Chen, S. Geothermal-type Lithium Resources in Southern Xizang, China. *Acta Geol. Sin.* **2021**, *95*, 860–872. [CrossRef]
9. Kavanagh, L.; Keohane, J.; Garcia Cabellos, G.; Lloyd, A.; Cleary, J. Global Lithium Sources—Industrial Use and Future in the Electric Vehicle Industry: A Review. *Resources* **2018**, *7*, 57. [CrossRef]
10. Graham, J.D.; Rupp, J.A.; Brungard, E. Lithium in the Green Energy Transition: The Quest for Both Sustainability and Security. *Sustainability* **2021**, *13*, 11274. [CrossRef]
11. Chen, T.; Jin, Y.; Lv, H.; Yang, A.; Liu, M.; Chen, B.; Xie, Y.; Chen, Q. Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Trans. Tianjin Univ.* **2020**, *26*, 208–217. [CrossRef]
12. Li, H. Application of Lithium Batteries, Hydrogen Fuel Cells and Solar Energy in Transportation Field. *ACE* **2023**, *26*, 245–251. [CrossRef]

13. Ghorbani, Y.; Zhang, S.E.; Bourdeau, J.E.; Chipangamate, N.S.; Rose, D.H.; Valodia, I.; Nwaila, G.T. The Strategic Role of Lithium in the Green Energy Transition: Towards an OPEC-Style Framework for Green Energy-Mineral Exporting Countries (GEMEC). *Resour. Policy* **2024**, *90*, 104737. [CrossRef]
14. Zanoletti, A.; Bresolin, B.M.; Bontempi, E. Building a Circular Economy for Lithium: Addressing Global Challenges. *Glob. Chall.* **2024**, *8*, 2400250. [CrossRef] [PubMed]
15. Cui, Z.; Zhao, Y.; Zhang, Y.; Liu, J.; Hu, Y.; Hu, S.; Wang, Q. Experimental Study of Lithium Extraction in the Solid-Liquid Conversion of Low-Grade Solid Potash Ore. *Minerals* **2024**, *14*, 116. [CrossRef]
16. Rudnik, E. Coal and Coal By-Products as Unconventional Lithium Sources: A Review of Occurrence Modes and Hydrometallurgical Strategies for Metal Recovery. *Minerals* **2024**, *14*, 849. [CrossRef]
17. McShane, E.J.; Gardner, E.J. (Invited) Electroflow: Sustainable Electrochemical Lithium Chemical Production. *Electrochem. Soc. Meet. Abstr.* **2024**, *245*, 1483. [CrossRef]
18. Xie, R.; Zhao, Z.; Tong, X.; Xie, X.; Song, Q.; Fan, P. Review of the Research on the Development and Utilization of Clay-Type Lithium Resources. *Particuology* **2024**, *87*, 46–53. [CrossRef]
19. Liu, Y.; Ma, B.; Lü, Y.; Wang, C.; Chen, Y. A Review of Lithium Extraction from Natural Resources. *Int. J. Miner. Metall. Mater.* **2023**, *30*, 209–224. [CrossRef]
20. Reich, R.; Slunitschek, K.; Danisi, R.M.; Eiche, E.; Kolb, J. Lithium Extraction Techniques and the Application Potential of Different Sorbents for Lithium Recovery from Brines. *Miner. Process. Extr. Metall. Rev.* **2023**, *44*, 261–280. [CrossRef]
21. Salaudeen, H.D.; Salaudeen, T.A.; Onaopemipo, Y. Olubunmi Samuel Review of Methods for Lithium Extraction from Geothermal Brines. *World J. Adv. Res. Rev.* **2024**, *24*, 948–955. [CrossRef]
22. Paul, A.; Lizhen, G.; Recheal, T.; Ali, S. Sustainable Lithium and Cobalt Recovery from Spent Lithium-Ion Batteries: Best Practices for the Future. A Review. *J. Anal. Tech. Res.* **2024**, *6*, 43–77. [CrossRef]
23. Jose, S.A.; Stoll, J.L.; Smith, T.; Jackson, C.; Dieleman, T.; Leath, E.; Eastwood, N.; Menezes, P.L. Critical Review of Lithium Recovery Methods: Advancements, Challenges, and Future Directions. *Processes* **2024**, *12*, 2203. [CrossRef]
24. Zhong, W.; Yang, L.; Rao, F.; Tong, L.; Feng, H. Efficient Extraction of Lithium from Calcined Kaolin Lithium Clay with Dilute Sulfuric Acid. *Minerals* **2024**, *14*, 359. [CrossRef]
25. Liu, J.; Xu, R.; Sun, W.; Wang, L.; Zhang, Y. Lithium Extraction from Lithium-Bearing Clay Minerals by Calcination-Leaching Method. *Minerals* **2024**, *14*, 248. [CrossRef]
26. Potts, E. The Clayton Valley Lithium Project: Empowering America's Lithium Independence. *Innovation News Network*, 19 January 2024.
27. Lithium Extraction from Clays Is a Reality: Perez Garibay. Available online: https://mexicobusiness.news/mining/news/lithium-extraction-clays-reality-perez-garibay (accessed on 13 November 2024).
28. Energy, U.-B.L.U.D. Chemists Invent a More Efficient Way to Extract Lithium from Mining Sites, Oil Fields, Used Batteries. Available online: https://www.ornl.gov/news/chemists-invent-more-efficient-way-extract-lithium-mining-sites-oil-fields-used-batteries (accessed on 13 November 2024).
29. Disu, B.; Rafati, R.; Haddad, A.S.; Fierus, N. Lithium Extraction From North Sea Oilfield Brines Using Ion Exchange Membranes. In Proceedings of the SPE Offshore Europe Conference & Exhibition, Aberdeen, Scotland, UK, 5–6 September 2023; p. D021S004R001.
30. Shi, Z.; Tan, H.; Xue, F.; Li, Y.; Zhang, X.; Cong, P.; Santosh, M.; Zhang, Y. Hydrochemical Evolution and Source Mechanisms Governing the Unusual Lithium and Boron Enrichment in Salt Lakes of Northern Tibet. *Geological Society of America Bulletin* **2024**, *136*, 5174–5190. [CrossRef]
31. Ochromowicz, K.; Zabłocka-Malicka, M.; Chojnacka, I.; Worsa-Kozak, M. Assessing the Viability of Integrating Evaporation and Solvent Extraction Systems for Lithium Recovery from Low-Grade Brines. *Processes* **2024**, *12*, 1453. [CrossRef]
32. Torres, D.; Pérez, K.; Galleguillos Madrid, F.M.; Leiva, W.H.; Gálvez, E.; Salinas-Rodríguez, E.; Gallegos, S.; Jamett, I.; Castillo, J.; Saldana, M.; et al. Salar de Atacama Lithium and Potassium Productive Process. *Metals* **2024**, *14*, 1095. [CrossRef]
33. Ma, Y.; Huang, S.; Liu, X.; Li, K.; Ma, X.; Zhang, Z.; Li, S.; Xie, J.; Du, Y.; Fu, Z. Separation Study of Magnesium–Lithium from Low-Mg/Li Brine. *Energy Technol.* **2024**, *Early View*, 2400398. [CrossRef]
34. Bäuerle, M.; Herrmann, L.; Jeschull, F. Battery Electrode-Based Lithium Recovery from Geothermal Brines. *Electrochem. Soc. Meet. Abstr.* **2023**, *244*, 1357. [CrossRef]
35. Smith, C.L.; Meier, A.L.; Downey, H.D. *Lithium in the Brines of Fish Lake Valley and Columbus Salt Marsh, Nevada*; U.S. Geological Survey: Reston, VA, USA, 1977.
36. Murphy, O.; Haji, M.N. A Review of Technologies for Direct Lithium Extraction from Low Li+ Concentration Aqueous Solutions. *Front. Chem. Eng.* **2022**, *4*, 1008680. [CrossRef]
37. Zhu, R.; Wang, S.; Srinivasakannan, C.; Li, S.; Yin, S.; Zhang, L.; Jiang, X.; Zhou, G.; Zhang, N. Lithium Extraction from Salt Lake Brines with High Magnesium/Lithium Ratio: A Review. *Environ. Chem. Lett.* **2023**, *21*, 1611–1626. [CrossRef]
38. Ding, T.; Zheng, M.; Nie, Z.; Ma, L.; Ye, C.; Wu, Q.; Zhao, Y.; Yang, D.; Wang, K. Impact of Regional Climate Change on the Development of Lithium Resources in Zabuye Salt Lake, Tibet. *Front. Earth Sci.* **2022**, *10*, 865158. [CrossRef]

39. Danso, D.K.; Bicerano, J.; Heller, D.P.; Barati, R.G. Development of Polyelectrolyte Complex Nanoparticles for Direct Lithium Extraction from Oilfield Brines. In Proceedings of the SPE Energy Transition Symposium, Houston, TX, USA, 5 August 2024; p. D021S009R001.
40. Bao, L.; Xu, Z.; Guo, W.; Lin, S.; Sun, S. Enhancement of Lithium Extraction from Low Grade Brines by High Hydrophilic Blend Membrane Using MnO2 Ion Sieve as Adsorbents. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *674*, 131884. [CrossRef]
41. Pan, Y.; Zhang, Y.; Su, H.; Yu, J.; Lin, S. Enhancing Lithium Extraction from Low Grade Salt Lake Brines Using High Powder Loading Aluminum-Based Adsorbent Granules. *Desalination* **2024**, *583*, 117696. [CrossRef]
42. Zhang, X.; Li, Z.; Liu, J.; Xu, F.; Zheng, L.; De Wolf, S.; Lai, Z.; Lu, X. Solar-Driven Ultrafast Lithium Extraction from Low-Grade Brine Using Microfluidics-Mediated Vortex in Scalable Electrochemical Reactors. *Chem. Eng. J.* **2023**, *454*, 140074. [CrossRef]
43. Wei, Y.; He, W.; Qin, G.; Fan, M.; Cao, D. Lithium Enrichment in the No. 21 Coal of the Hebi No. 6 Mine, Anhe Coalfield, Henan Province, China. *Minerals* **2020**, *10*, 521. [CrossRef]
44. Han, P.; Zhao, F.; Liu, D.; Zhang, Q.; Zhang, Q.; Ullah, S. Occurrence and Favorable Enrichment Environment of Lithium in Gaoping Coal Measures: Evidence from Mineralogy and Geochemistry. *Appl. Sci.* **2024**, *14*, 7298. [CrossRef]
45. Qin, S.; Zhao, C.; Li, Y.; Zhang, Y. Review of Coal as a Promising Source of Lithium. *Int. J. Oil Gas Coal Technol. IJOGCT* **2015**, *9*, 215. [CrossRef]
46. Ma, Z.; Shan, X.; Cheng, F. Distribution Characteristics of Valuable Elements, Al, Li, and Ga, and Rare Earth Elements in Feed Coal, Fly Ash, and Bottom Ash from a 300 MW Circulating Fluidized Bed Boiler. *ACS Omega* **2019**, *4*, 6854–6863. [CrossRef]
47. Li, Y.; Man, J.; Cheng, L.; Panchal, B. Lithium Activation Pretreatment Mechanism and Leaching Process from Coal Fly Ash. *Energy Explor. Exploit.* **2024**, *42*, 476–491. [CrossRef]
48. Robinson, A.; Flynn, S.; Acikalin, S.; Stewart, G. Non-Arid Brine Sources of Li: Using Mine Waters of the North Pennines, England to Test near-Surface Measurements as a Tool for Assessing the Li Resource of Hydrothermal Brines in Granitic Systems. In Proceedings of the Goldschmidt2023 Abstracts, Lyon, France, 9–14 July 2023.
49. Rinder, T.; Dietzel, M.; Stammeier, J.A.; Leis, A.; Bedoya-González, D.; Hilberg, S. Geochemistry of Coal Mine Drainage, Groundwater, and Brines from the Ibbenbüren Mine, Germany: A Coupled Elemental-Isotopic Approach. *Appl. Geochem.* **2020**, *121*, 104693. [CrossRef]
50. Chen, G.; Sun, Y.; Xu, Z.; Yuan, H.; Yi, H. Long-Term Groundwater Geochemical Evolution Induced by Coal Mining Activities—A Case Study of Floor Confined Limestone Aquifer in Yaoqiao Coal Mine, Jiangsu, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 96252–96271. [CrossRef] [PubMed]
51. Mousavinezhad, S.; Nili, S.; Fahimi, A.; Vahidi, E. Environmental Impact Assessment of Direct Lithium Extraction from Brine Resources: Global Warming Potential, Land Use, Water Consumption, and Charting Sustainable Scenarios. *Resour. Conserv. Recycl.* **2024**, *205*, 107583. [CrossRef]
52. Mahran, G.M.A.; Gado, M.A.; Fathy, W.M.; ElDeeb, A.B. Eco-Friendly Recycling of Lithium Batteries for Extraction of High-Purity Metals. *Materials* **2023**, *16*, 4662. [CrossRef] [PubMed]
53. Roy, J.J.; Rarotra, S.; Krikstolaityte, V.; Zhuoran, K.W.; Cindy, Y.D.; Tan, X.Y.; Carboni, M.; Meyer, D.; Yan, Q.; Srinivasan, M. Green Recycling Methods to Treat Lithium-Ion Batteries E-Waste: A Circular Approach to Sustainability. *Adv. Mater.* **2022**, *34*, 2103346. [CrossRef]
54. Javed, A.; Singh, J. Process Intensification for Sustainable Extraction of Metals from E-Waste: Challenges and Opportunities. *Environ. Sci. Pollut. Res.* **2023**, *31*, 9886–9919. [CrossRef]
55. Jiang, M.; He, S.; Zhang, Y. Bioleaching Extraction of Valuable Metal From E-Wastes: A MiniReview. *Recent Innov. Chem. Eng. RICE* **2023**, *16*, 306–323. [CrossRef]
56. Adetunji, A.I.; Oberholster, P.J.; Erasmus, M. Bioleaching of Metals from E-Waste Using Microorganisms: A Review. *Minerals* **2023**, *13*, 828. [CrossRef]
57. Jena, S.; Tripathy, S.; Mandre, N.; Venugopal, R.; Farrokhpay, S. Sustainable Use of Copper Resources: Beneficiation of Low-Grade Copper Ores. *Minerals* **2022**, *12*, 545. [CrossRef]
58. Pakostova, E.; Graves, J.; Latvyte, E.; Maddalena, G.; Horsfall, L. A Novel Closed-Loop Biotechnology for Recovery of Cobalt from a Lithium-Ion Battery Active Cathode Material. *Microbiology* **2024**, *170*, 001475. [CrossRef]
59. Wu, J.; Xiao, L.; Shen, L.; Ran, J.-J.; Zhong, H.; Zhu, Y.-R.; Chen, H. Recent Advancements in Hydrometallurgical Recycling Technologies of Spent Lithium-Ion Battery Cathode Materials. *Rare Met.* **2024**, *43*, 879–899. [CrossRef]
60. Xu, P.; Hong, J.; Qian, X.; Xu, Z.; Xia, H.; Tao, X.; Xu, Z.; Ni, Q.-Q. Materials for Lithium Recovery from Salt Lake Brine. *J. Mater. Sci.* **2021**, *56*, 16–63. [CrossRef]
61. Sun, J.; Liang, D.; Meng, X.; Li, Z. Recent Advances in Lithium Extraction Using Electrode Materials of Li-Ion Battery from Brine/Seawater. *Processes* **2022**, *10*, 2654. [CrossRef]
62. He, J.; Cao, Y.; Wang, X.; Zhao, C.; Huang, J.; Long, W.; Zhou, Z.; Dong, P.; Zhang, Y.; Wang, D.; et al. Short-Process Regeneration of Highly Stable Spherical $LiCoO_2$ Cathode Materials from Spent Lithium-Ion Batteries through Carbonate Precipitation. *Chem. A Eur. J.* **2024**, *30*, e202303424. [CrossRef] [PubMed]

63. Zheng, R.; Zhao, L.; Wang, W.; Liu, Y.; Ma, Q.; Mu, D.; Li, R.; Dai, C. Optimized Li and Fe Recovery from Spent Lithium-Ion Batteries via a Solution-Precipitation Method. *RSC Adv.* **2016**, *6*, 43613–43625. [CrossRef]
64. Aboelazm, E.A.A.; Mohamed, N.; Ali, G.A.M.; Makhlouf, A.S.H.; Chong, K.F. Recycling of Cobalt Oxides Electrodes from Spent Lithium-Ion Batteries by Electrochemical Method. In *Waste Recycling Technologies for Nanomaterials Manufacturing*; Makhlouf, A.S.H., Ali, G.A.M., Eds.; Topics in Mining, Metallurgy and Materials Engineering; Springer International Publishing: Cham, Switzerland, 2021; pp. 91–123, ISBN 978-3-030-68030-5.
65. Su, F.; Zhou, X.; Liu, X.; Yang, J.; Tang, J.; Yang, W.; Li, Z.; Wang, H.; Ma, Y. Efficient Recovery of Valuable Metals from Spent Lithium-Ion Batteries by Pyrite Method with Hydrometallurgy Process. *Chem. Eng. J.* **2023**, *455*, 140914. [CrossRef]
66. Xing, P.; Wang, C.; Zeng, L.; Ma, B.; Wang, L.; Chen, Y.; Yang, C. Lithium Extraction and Hydroxysodalite Zeolite Synthesis by Hydrothermal Conversion of α-Spodumene. *ACS Sustain. Chem. Eng.* **2019**, *7*, 9498–9505. [CrossRef]
67. Wu, S.; Tao, W.; Zheng, Y.; Ge, H.; He, J.; Yang, Y.; Wang, Z. A Novel Approach for Lithium Recovery from Waste Lithium-Containing Aluminum Electrolyte by a Roasting-Leaching Process. *Waste Manag.* **2021**, *134*, 89–99. [CrossRef]
68. Zhang, T.; Dao, J.; Wang, J.; Guo, Y.; Wan, R.; Li, C.; Zhou, X.; Zhang, Z. Highly Efficient Recovery of Waste LiNixCoyMnzO2 Cathode Materials Using a Process Involving Pyrometallurgy and Hydrometallurgy. *Front. Environ. Sci. Eng.* **2024**, *18*, 25. [CrossRef]
69. Liu, A.; Hu, G.; Wu, Y.; Guo, F. Life Cycle Environmental Impacts of Pyrometallurgical and Hydrometallurgical Recovery Processes for Spent Lithium-Ion Batteries: Present and Future Perspectives. *Clean. Technol. Environ. Policy* **2023**, *26*, 381–400. [CrossRef]
70. Ashoka Sahadevan, S.; Usen Nazreen, M.S.; Sankarasubramanian, S.; Ramani, V.K. Lithium-Ion Battery Recycling: Ternary Deep Eutectic Solvents Enable Efficient and Selective Electrochemical Recovery of Critical Component Metals. *Electrochem. Soc. Meet. Abstr.* **2024**, *245*, 2955. [CrossRef]
71. Dong, Y.; Ji, H.; Wu, X.; Zheng, N.; Wang, J.; Ji, G.; Chen, Y.; Zhou, G.; Liang, Z. Trends of Sustainable Recycling Technology for Lithium-ion Batteries: Metal Recovery from Conventional Metallurgical Processes to Innovative Direct Recycling. *MetalMat* **2024**, *1*, e5. [CrossRef]
72. Davis, K.; Demopoulos, G.P. Hydrometallurgical Recycling Technologies for NMC Li-Ion Battery Cathodes: Current Industrial Practice and New R&D Trends. *RSC Sustain.* **2023**, *1*, 1932–1951. [CrossRef]
73. Alipanah, M.; Jin, H.; Zhou, Q.; Barboza, C.; Gazzo, D.; Thompson, V.; Fujita, Y.; Liu, J.; Anderko, A.; Reed, D. Sustainable Bioleaching of Lithium-Ion Batteries for Critical Metal Recovery: Process Optimization through Design of Experiments and Thermodynamic Modeling. *Resour. Conserv. Recycl.* **2023**, *199*, 107293. [CrossRef]
74. Xie, Y.; Ni, C.; Han, Z.; Liao, J.; Xie, W.; Zhong, H.; He, Z. Recovery of Lithium from Coal Gangue Utilizing Acid Baking Followed by Water Leaching. *Int. J. Coal Prep. Util.* **2024**, *44*, 82–94. [CrossRef]
75. Chen, H.; Wen, Z.; Pan, J.; Zhang, L.; He, X.; Valeev, D.; Zhou, C. Study on Leaching Behavior Differences of Rare Earth Elements from Coal Fly Ash during Microwave-Assisted HCl Leaching. *Int. J. Coal Prep. Util.* **2023**, *43*, 1993–2015. [CrossRef]
76. Necke, T.; Stein, J.; Kleebe, H.-J.; Balke-Grünewald, B. Lithium Extraction and Zeolite Synthesis via Mechanochemical Treatment of the Silicate Minerals Lepidolite, Spodumene, and Petalite. *Minerals* **2023**, *13*, 1030. [CrossRef]
77. Braga, P.; França, S.; Neumann, R.; Rodriguez, M.; Rosales, G. Alkaline Process for Extracting Lithium from Spodumene. *ChemistrySelect* **2024**, *9*, e202304480.
78. Biswal, B.K.; Balasubramanian, R. Recovery of Valuable Metals from Spent Lithium-Ion Batteries Using Microbial Agents for Bioleaching: A Review. *Front. Microbiol.* **2023**, *14*, 1197081. [CrossRef]
79. Lalropuia, L.; Kucera, J.; Rassy, W.Y.; Pakostova, E.; Schild, D.; Mandl, M.; Kremser, K.; Guebitz, G.M. Metal Recovery from Spent Lithium-Ion Batteries via Two-Step Bioleaching Using Adapted Chemolithotrophs from an Acidic Mine Pit Lake. *Front. Microbiol.* **2024**, *15*, 1347072. [CrossRef]
80. Kazemian, Z.; Larypoor, M.; Marandi, R. Evaluation of Myco-Leaching Potential of Valuable Metals from Spent Lithium Battery by *Penicillium Chrysogenum* and *Aspergillus Niger*. *Int. J. Environ. Anal. Chem.* **2023**, *103*, 514–527. [CrossRef]
81. Rezza, I.; Salinas, E.; Calvente, V.; Benuzzi, D.; Tosetti, M.I.S.D. Extraction of Lithium from Spodumene by Bioleaching. *Lett. Appl. Microbiol.* **1997**, *25*, 172–176. [CrossRef] [PubMed]
82. Panda, S.; Dembele, S.; Mishra, S.; Akcil, A.; Agcasulu, İ.; Hazrati, E.; Tuncuk, A.; Malavasi, P.; Gaydardzhiev, S. Small-scale and Scale-up Bioleaching of Li, Co, Ni and Mn from Spent Lithium-ion Batteries. *J. Chem. Technol. Biotechnol.* **2024**, *99*, 1069–1082. [CrossRef]
83. Marcinčáková, R.; Kaduková, J.; Mražíková, A. Bioleaching of Lithium from Lepidolite by the Mixture of Rhodotorula Rubra and Acidithiobacillus Ferrooxidans. *J. Pol. Miner. Eng. Soc.* **2015**, *16*, 85–88. [CrossRef]
84. Xing, M.; Zhang, F.; Zheng, P.; Wang, Y.; Zhao, L.; Xu, C. Selective Recovery of Lithium from High-Aluminum Fly Ash by Using Alkali-Dissolution-Assisted HBTA–TOPO Synergistic Extraction. *J. Clean. Prod.* **2024**, *434*, 139998. [CrossRef]
85. Cui, L.; Feng, L.; Yuan, H.; Cheng, H.; Cheng, F. Efficient Recovery of Aluminum, Lithium, Iron and Gallium from Coal Fly Ash Leachate via Coextraction and Stepwise Stripping. *Resour. Conserv. Recycl.* **2024**, *202*, 107380. [CrossRef]

86. Samadiy, M.; Deng, T. Lithium Recovery from Water Resources by Ion Exchange and Sorption Method. *J. Chem. Soc. Pak.* **2021**, *43*, 406. [CrossRef]
87. Wagh, P.; Islam, S.Z.; Lamichhane, T.N.; Bhave, R.R.; Paranthaman, M.P. Separation of Lithium from Aluminum-Containing Clay Mineral Leachate Solution Using Energy-Efficient Membrane Solvent Extraction. *ACS Omega* **2023**, *8*, 46523–46527. [CrossRef]
88. Tang, Y.-C.; Wang, J.-Z.; Shen, Y.-H. Separation of Valuable Metals in The Recycling of Lithium Batteries via Solvent Extraction. *Minerals* **2023**, *13*, 285. [CrossRef]
89. Wesselborg, T.; Virolainen, S.; Sainio, T. Recovery of Lithium from Leach Solutions of Battery Waste Using Direct Solvent Extraction with TBP and FeCl3. *Hydrometallurgy* **2021**, *202*, 105593. [CrossRef]
90. Botelho Junior, A.B.; Tenório, J.A.S.; Espinosa, D.C.R. Separation of Critical Metals by Membrane Technology under a Circular Economy Framework: A Review of the State-of-the-Art. *Processes* **2023**, *11*, 1256. [CrossRef]
91. Han, J.; Zeng, X.; Wang, K.; Huang, Y.; Meng, Q.; Zhou, L.; Li, Z.; Liu, R.; Zhen, C. Research progress and prospect of membrane method in seawater/brine extraction of lithium. *Acta Mater. Compos. Sin.* **2022**, *39*, 2106–2120. [CrossRef]
92. Wang, R.; Alghanayem, R.; Lin, S. Multipass Nanofiltration for Lithium Separation with High Selectivity and Recovery. *Environ. Sci. Technol.* **2023**, *57*, 14464–14471. [CrossRef] [PubMed]
93. Li, Y.; Sun, M.; Cao, Y.; Yu, K.; Fan, Z.; Cao, Y. Designing Low Toxic Deep Eutectic Solvents for the Green Recycle of Lithium-Ion Batteries Cathodes. *ChemSusChem* **2024**, *17*, e202301953. [CrossRef] [PubMed]
94. Seroka, N.S.; Luo, H.; Khotseng, L. Biochar-Derived Anode Materials for Lithium-Ion Batteries: A Review. *Batteries* **2024**, *10*, 144. [CrossRef]
95. Nishihama, S.; Onishi, K.; Yoshizuka, K. Selective Recovery Process of Lithium from Seawater Using Integrated Ion Exchange Methods. *Solvent Extr. Ion Exch.* **2011**, *29*, 421–431. [CrossRef]
96. Gao, J.; Du, Z.; Zhao, Q.; Guo, Y.; Cheng, F. Enhanced Li+ Adsorption by Magnetically Recyclable Iron-Doped Lithium Manganese Oxide Ion-Sieve: Synthesis, Characterization, Adsorption Kinetics and Isotherm. *J. Mater. Res. Technol.* **2021**, *13*, 228–240. [CrossRef]
97. Wang, S.; Chao, X.; Huang, X. A Review of Titanium-Based Lithium-Ion Sieve. In Proceedings of the 2023 8th International Conference on Power and Renewable Energy (ICPRE), Shanghai, China, 22–25 September 2023; pp. 1980–1985.
98. Roobavannan, S.; Choo, Y.; Truong, D.Q.; Han, D.S.; Shon, H.K.; Naidu, G. Seawater Lithium Mining by Zeolitic Imidazolate Framework Encapsulated Manganese Oxide Ion Sieve Nanomaterial. *Chem. Eng. J.* **2023**, *474*, 145957. [CrossRef]
99. Wang, S.; Gao, Y.; Gao, F.; Dong, J.; Zhang, P.; Chen, G. Enhanced Lithium Adsorption on an Anion- and Cation-Codoped Lithium Manganese Oxide Ion Sieve with a Thin Fluoride-Protective Coating Layer. *Ind. Eng. Chem. Res.* **2024**, *63*, 9527–9537. [CrossRef]
100. Shang, X.; Liu, J.; Hu, B.; Nie, P.; Yang, J.; Zhang, B.; Wang, Y.; Zhan, F.; Qiu, J. CNT-Strung $LiMn_2O_4$ for Lithium Extraction with High Selectivity and Stability. *Small Methods* **2022**, *6*, 2200508. [CrossRef]
101. Yang, S.S.; Liu, X.; Shen, J.N.; Gao, C.J. Comparison Study of PVDF-HMn_2O_4 and PES-HMn_2O_4 Membrane-Type Adsorbents for Lithium Adsorption/Desorption. *AMM* **2014**, *633–634*, 517–520. [CrossRef]
102. Luo, G.; Wu, Y.; Zeng, X.; Zhou, W.; Wang, P.; Zhang, W. Lithium-Ion-Sieve-Embedded Hybrid Membranes for Anion-Exchange- and Cation-Concentration-Driven Li/Mg Separation. *ACS Appl. Mater. Interfaces* **2024**, *16*, 66911–66920. [CrossRef] [PubMed]
103. Jang, S.; Shin, G.R.; Kim, S.-C. Electrostatic Adsorption of Uniformly Charged Sphere Ions Confined between Two Charged Plates. *J. Korean Phys. Soc.* **2019**, *74*, 30–35. [CrossRef]
104. Qian, C.; Zheng, M.; Zhang, Y.; Xing, E.; Gui, B. Adsorption Performance and Mechanism of Li+ from Brines Using Lithium/Aluminum Layered Double Hydroxides-SiO2 Bauxite Composite Adsorbents. *Front. Chem.* **2023**, *11*, 1265290. [CrossRef] [PubMed]
105. Song, D.; Park, S.-J.; Kang, H.W.; Park, S.B.; Han, J.-I. Recovery of Lithium(I), Strontium(II), and Lanthanum(III) Using Ca–Alginate Beads. *J. Chem. Eng. Data* **2013**, *58*, 2455–2464. [CrossRef]
106. Zhi, K.; Duan, J.; Zhang, J.; Huang, L.; Guo, L.; Wang, L. Progress and Prospect of Ion Imprinting Technology in Targeted Extraction of Lithium. *Polymers* **2024**, *16*, 833. [CrossRef]
107. Huang, Y.; Wang, R. Highly Effective and Low-Cost Ion-Imprinted Polymers Loaded on Pretreated Vermiculite for Lithium Recovery. *Ind. Eng. Chem. Res.* **2019**, *58*, 12216–12225. [CrossRef]
108. Qi, D.; Jin, D.; Tu, Y.; Zhou, Z.; Du, C.; Ren, Z. Synthesis of Lithium Ion-Imprinted Polymers for Selective Recovery of Lithium Ions from Salt Lake Brines. *Sep. Purif. Technol.* **2024**, *340*, 126661. [CrossRef]
109. Li, Y.; Han, N.; He, Q.; Peng, H.; Wu, X.; Meng, Z.; Miao, Z. Nitrogen-Doped Substrate Material Ion Imprinting–Capacitive Deionization Selective Recovery of Lithium Ions from Acidic Solutions. *Environ. Sci. Pollut. Res.* **2024**, *31*, 27949–27960. [CrossRef]
110. Prachi Patel Device Extracts Lithium from Dead Sea Brine. *C&EN Glob. Enterp.* **2024**, *102*, 5. [CrossRef]
111. Alsabbagh, A.; Aljarrah, S.; Almahasneh, M. Lithium Enrichment Optimization from Dead Sea End Brine by Chemical Precipitation Technique. *Miner. Eng.* **2021**, *170*, 107038. [CrossRef]
112. Aljarrah, S.; Alsabbagh, A.; Almahasneh, M. Selective Recovery of Lithium from Dead Sea End Brines Using UBK10 Ion Exchange Resin. *Can. J. Chem. Eng.* **2023**, *101*, 1185–1194. [CrossRef]

113. Lajoie-Leroux, F.; Dessemond, C.; Soucy, G.; Laroche, N.; Magnan, J.-F. Impact of the Impurities on Lithium Extraction from β-Spodumene in the Sulfuric Acid Process. *Miner. Eng.* **2018**, *129*, 1–8. [CrossRef]
114. Guo, Z.-Y.; Ji, Z.-Y.; Chen, H.-Y.; Liu, J.; Zhao, Y.-Y.; Li, F.; Yuan, J.-S. Effect of Impurity Ions in the Electrosorption Lithium Extraction Process: Generation and Restriction of "Selective Concentration Polarization". *ACS Sustain. Chem. Eng.* **2020**, *8*, 11834–11844. [CrossRef]
115. Li, Z.; Mercken, J.; Li, X.; Riaño, S.; Binnemans, K. Efficient and Sustainable Removal of Magnesium from Brines for Lithium/Magnesium Separation Using Binary Extractants. *ACS Sustain. Chem. Eng.* **2019**, *7*, 19225–19234. [CrossRef]
116. Herrmann, L.; Ehrenberg, H.; Graczyk-Zajac, M.; Kaymakci, E.; Kölbel, T.; Kölbel, L.; Tübke, J. Lithium Recovery from Geothermal Brine—An Investigation into the Desorption of Lithium Ions Using Manganese Oxide Adsorbents. *Energy Adv.* **2022**, *1*, 877–885. [CrossRef]
117. Dobson, P.; Araya, N.; Brounce, M.; Busse, M.; Camarillo, M.; English, L.; Humphreys, J.; Kalderon-Asael, B.; McKibben, M.; Millstein, D.; et al. *Characterizing the Geothermal Lithium Resource at the Salton Sea*; Lawrence Berkeley National Laboratory (LBNL): Berkeley, CA, USA, 2023; LBNL-2001557.
118. Types of Lithium Brine Deposits | INN. Available online: https://investingnews.com/daily/resource-investing/battery-metals-investing/lithium-investing/lithium-deposit-types-brine-pegmatite-and-sedimentary/ (accessed on 18 November 2024).
119. Li, Q.; Fan, Q.; Wang, J.; Qin, Z.; Zhang, X.; Wei, H.; Du, Y.; Shan, F. Hydrochemistry, Distribution and Formation of Lithium-Rich Brines in Salt Lakes on the Qinghai-Tibetan Plateau. *Minerals* **2019**, *9*, 528. [CrossRef]
120. Valdez, S.K.; Flores, H.R.; Orce, A.M.; KwokLeung, H. Influence of The Evaporation Rate Over Lithium Recovery From Brines. *World J. Res. Rev.* **2016**, *3*, 66–70.
121. Xu, R.; Xiao, X.; Zhang, G.; Ye, Y.; Zhang, P.; Yang, Y.; Shuchi, S.B.; Cui, Y. Continuous Lithium Extraction from Brine by Efficient Redox-Couple Electrodialysis. *Matter* **2024**, *7*, 3876–3890. [CrossRef]
122. Forte, F.; Moscardini, E.; Coletta, J.; Toro, L.; Yurramendi, L.; Hidalgo, J.; Ipiñazar, E.; Siriwardana, A.; Riano, S.; Peeters, N.; et al. First Economically and Environmentally Viable Mobile Commercial Metallurgical Plant Based on Advanced Hydrometallurgical and Electrochemical Technologies Able to Produce Cobalt Metal from Spent Lithium-Ion Batteries. *Open Res. Eur.* **2024**, *4*, 32. [CrossRef]
123. Li, Z.; Chen, I.-C.; Cao, L.; Liu, X.; Huang, K.-W.; Lai, Z. Lithium Extraction from Brine through a Decoupled and Membrane-Free Electrochemical Cell Design. *Science* **2024**, *385*, 1438–1444. [CrossRef]
124. Nunes, L.J.R. Exploring the Present and Future of Biomass Recovery Units: Technological Innovation, Policy Incentives and Economic Challenges. *Biofuels* **2024**, *15*, 375–387. [CrossRef]
125. Alipanah, M.; Saha, A.K.; Vahidi, E.; Jin, H. Value Recovery from Spent Lithium-Ion Batteries: A Review on Technologies, Environmental Impacts, Economics, and Supply Chain. *CTR Clean Technol. Recycl.* **2021**, *1*, 152–184. [CrossRef]
126. Varshney, K.P.; Malhotra, S. Recovery of Lithium from Waste Lithium-Ion Batteries-A Review. *Res. J. Chem. Environ.* **2023**, *27*, 187–196. [CrossRef]
127. Yanagida, A.; Webb, E.; Harris, C.E.; Christenson, M.; Comfort, S. Using Electrochemical Oxidation to Remove PFAS in Simulated Investigation-Derived Waste (IDW): Laboratory and Pilot-Scale Experiments. *Water* **2022**, *14*, 2708. [CrossRef]
128. Trigueros, E.; Ramos, C.; Alonso-Riaño, P.; Beltrán, S.; Sanz, M.T. Subcritical Water Treatment for Valorization of the Red Algae Residue after Agar Extraction: Scale-Up from Laboratory to Pilot Plant. *Ind. Eng. Chem. Res.* **2023**, *62*, 3503–3514. [CrossRef] [PubMed]
129. Zhang, S. Challenges and Opportunities of Recycling Cathode Materials from Spent Li-Ion Battery. *Int. J. Eng. Technol. IJET* **2024**, *16*, 204–210. [CrossRef]
130. Flores Fernández, C.; Alba, R. Water or Mineral Resource? Legal Interpretations and Hydrosocial Configurations of Lithium Mining in Chile. *Front. Water* **2023**, *5*, 1075139. [CrossRef]
131. Yan, Z. Research on Lithium Battery Recycling and Utilization. *IJMSTS Int. J. Mater. Sci. Technol. Stud.* **2024**, *1*, 1–8. [CrossRef]
132. Xu, P.; Tan, D.H.S.; Jiao, B.; Gao, H.; Yu, X.; Chen, Z. A Materials Perspective on Direct Recycling of Lithium-Ion Batteries: Principles, Challenges and Opportunities. *Adv. Funct. Mater.* **2023**, *33*, 2213168. [CrossRef]
133. Ji, H.; Wang, J.; Ma, J.; Cheng, H.-M.; Zhou, G. Fundamentals, Status and Challenges of Direct Recycling Technologies for Lithium Ion Batteries. *Chem. Soc. Rev.* **2023**, *52*, 8194–8244. [CrossRef]
134. Murdock, B.E.; Toghill, K.E.; Tapia-Ruiz, N. A Perspective on the Sustainability of Cathode Materials Used in Lithium-Ion Batteries. *Adv. Energy Mater.* **2021**, *11*, 2102028. [CrossRef]
135. Wang, L.; Wu, H.; Hu, Y.; Yu, Y.; Huang, K. Environmental Sustainability Assessment of Typical Cathode Materials of Lithium-Ion Battery Based on Three LCA Approaches. *Processes* **2019**, *7*, 83. [CrossRef]
136. Vera, M.L.; Torres, W.R.; Galli, C.I.; Chagnes, A.; Flexer, V. Environmental Impact of Direct Lithium Extraction from Brines. *Nat. Rev. Earth Environ.* **2023**, *4*, 149–165. [CrossRef]
137. Wang, Y.; Zhang, G.; Dong, G.; Zheng, H. Research Progress of Working Electrode in Electrochemical Extraction of Lithium from Brine. *Batteries* **2022**, *8*, 225. [CrossRef]

138. Wan, Z.; Liu, Z.; Xiao, Y.; Ruan, Q.; Wang, Q.; Zhang, H.; Yao, M.; Zhang, Y. Self-Oxidated Hybrid Conductive Network Enables Efficient Electrochemical Lithium Extraction Under High-Altitude Environment. *Small* **2024**, *Early View*, 2406607. [CrossRef]
139. Wang, S.; Yu, X.; Hu, X. Electrochemical Lithium Extraction with Gas Flushing of Porous Electrodes. *Nanomaterials* **2023**, *13*, 1471. [CrossRef]
140. Dong, Q.; Gang, H.; Xu, J.; Li, Z.; Wang, Z. The Technologies of Electrochemical Lithium Extraction Process from Lithium-Containing Solutions. *J. Exp. Theor. Anal. JETA* **2024**, *2*, 91–102. [CrossRef]
141. Pražanová, A.; Knap, V.; Stroe, D.-I. Literature Review, Recycling of Lithium-Ion Batteries from Electric Vehicles, Part II: Environmental and Economic Perspective. *Energies* **2022**, *15*, 7356. [CrossRef]
142. Jungi, H.; Podder, S.; Girase, H.; Mitra, J. Sustainable Combination of Waste with Waste: Utilization of Biomass to Recover Critical Metals from Spent Lithium Ion Batteries. *Batter. Supercaps* **2024**, *Early View*, e202400518. [CrossRef]
143. Cerrillo-Gonzalez, M.; Villen-Guzman, M.; Vereda-Alonso, C.; Rodriguez-Maroto, J.; Paz-Garcia, J. Towards Sustainable Lithium-Ion Battery Recycling: Advancements in Circular Hydrometallurgy. *Processes* **2024**, *12*, 1485. [CrossRef]
144. Sahu, S.; Devi, N. Hydrometallurgical Treatment of Spent Lithium Ion Batteries Using Environmentally Friendly Leachant and Extractant. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 3303–3315. [CrossRef]
145. Korra, C.; Sadhana, V.A.; Khandewal, A. A Framework for Sustainable Lithium-Ion Battery Recycling Facilities, Vol 1. *IJERSTE* **2023**, *13*, 164–170. [CrossRef]
146. Hou, J.; Zhang, H.; Thornton, A.W.; Hill, A.J.; Wang, H.; Konstas, K. Lithium Extraction by Emerging Metal–Organic Framework-Based Membranes. *Adv. Funct. Mater.* **2021**, *31*, 2105991. [CrossRef]
147. Lalasari, L.H.; Sulistiyono, E.; Harjanto, S.; Irawan, Y.; Firdiyono, F.; Arini, T.; Andriyah, L.; Suharyanto, A.; Natasha, N.C.; Yunita, F.E. The Effect of pH and Sodium Silicate Dosage on the Separation of Magnesium and Lithium from Artificial Brine Water Using Chemical Precipitation Techniques. *Metalurgi* **2023**, *38*, 101. [CrossRef]
148. Fu, W.; Meng, L.; Qu, J. Sintering Mechanism and Leaching Kinetics of Low-Grade Mixed Lithium Ore and Limestone. *Metals* **2024**, *14*, 1075. [CrossRef]
149. Lebit, H.; Brunner, B.; Kharitonova, N.; Deemer, E. Direct Lithium Extraction from Geothermal Brines: The New Oil. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 5–8 May 2024; p. D011S011R006.
150. Vega-Muratalla, V.O.; Ramírez-Márquez, C.; Lira-Barragán, L.F.; Ponce-Ortega, J.M. Review of Lithium as a Strategic Resource for Electric Vehicle Battery Production: Availability, Extraction, and Future Prospects. *Resources* **2024**, *13*, 148. [CrossRef]
151. Du, S.; Gao, F.; Nie, Z.; Liu, Y.; Sun, B.; Gong, X. Comparison of Electric Vehicle Lithium-Ion Battery Recycling Allocation Methods. *Environ. Sci. Technol.* **2022**, *56*, 17977–17987. [CrossRef]
152. Frith, J.T.; Lacey, M.J.; Ulissi, U. A Non-Academic Perspective on the Future of Lithium-Based Batteries. *Nat. Commun.* **2023**, *14*, 420. [CrossRef]
153. Popien, J.-L.; Thies, C.; Barke, A.; Spengler, T.S. Comparative Sustainability Assessment of Lithium-Ion, Lithium-Sulfur, and All-Solid-State Traction Batteries. *Int. J. Life Cycle Assess.* **2023**, *28*, 462–477. [CrossRef]
154. Ferreira, D.; Baltazar, M.E.; Santos, L. Developing a Comprehensive Framework for Assessing Airports' Environmental Sustainability. *Sustainability* **2024**, *16*, 6651. [CrossRef]
155. Abghoui, Y. Hydrogen Fuel Cells vs. Lithium-Ion Batteries in Electric Vehicles. *Electrochem. Soc. Meet. Abstr.* **2024**, *245*, 631. [CrossRef]
156. Buravleva, Y.; Tang, D.; Bethel, B.J. Incentivizing Innovation: The Causal Role of Government Subsidies on Lithium-Ion Battery Research and Development. *Sustainability* **2021**, *13*, 8309. [CrossRef]
157. Esiri, A.E.; Kwakye, J.M.; Ekechukwu, D.E.; Ogundipe, O.B. Augusta Heavens Ikevuje Assessing the Environmental Footprint of the Electric Vehicle Supply Chain. *Magna Sci. Adv. Res. Rev.* **2023**, *8*, 219–227. [CrossRef]
158. Di Leo, A.; Sfodera, F.; Cucari, N.; Mattia, G.; Dezi, L. Sustainability Reporting Practices: An Explorative Analysis of Luxury Fashion Brands. *Manag. Decis.* **2023**, *61*, 1274–1297. [CrossRef]
159. Zhao, X.; Khelifi, F.; Casale, M.; Cavallo, A.; Padoan, E.; Yang, K.; Dino, G.A. Critical Raw Materials Supply: Challenges and Potentialities to Exploit Rare Earth Elements from Siliceous Stones and Extractive Waste. *Resources* **2024**, *13*, 97. [CrossRef]
160. Petavratzi, E.; Sanchez-Lopez, D.; Hughes, A.; Stacey, J.; Ford, J.; Butcher, A. The Impacts of Environmental, Social and Governance (ESG) Issues in Achieving Sustainable Lithium Supply in the Lithium Triangle. *Miner. Econ.* **2022**, *35*, 673–699. [CrossRef]
161. Radchuk, O. Comparative Analysis of Ukrainian and International Standards in the Context of Mining Tailings Dam Design Requirements. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1376*, 012027. [CrossRef]
162. Gardiner, N.J.; Jowitt, S.M.; Sykes, J.P. Lithium: Critical, or Not so Critical? *Geoenergy* **2024**, *2*, geoenergy2023-045. [CrossRef]
163. Feng, Q.C.; Ren, Z.J.; Chen, Q.S. The "Rock Candy" Approach for Direct Lithium Extraction. In Proceedings of the 2023 IEEE Integrated STEM Education Conference (ISEC), Laurel, MD, USA, 11 March 2023; pp. 367–374.
164. Murodjon, S.; Yu, X.; Li, M.; Duo, J.; Deng, T. Lithium Recovery from Brines Including Seawater, Salt Lake Brine, Underground Water and Geothermal Water. In *Thermodynamics and Energy Engineering*; Vizureanu, P., Ed.; IntechOpen: London, UK, 2020; ISBN 978-1-83880-568-5.

165. Kalungi, P.; Yao, Z.; Huang, H. Aspects of Nickel, Cobalt and Lithium, the Three Key Elements for Li-Ion Batteries: An Overview on Resources, Demands, and Production. *Materials* **2024**, *17*, 4389. [CrossRef]
166. Hasselwander, S.; Meyer, M.; Österle, I. Techno-Economic Analysis of Different Battery Cell Chemistries for the Passenger Vehicle Market. *Batteries* **2023**, *9*, 379. [CrossRef]
167. Harper, G.D.J.; Kendrick, E.; Anderson, P.A.; Mrozik, W.; Christensen, P.; Lambert, S.; Greenwood, D.; Das, P.K.; Ahmeid, M.; Milojevic, Z.; et al. Roadmap for a Sustainable Circular Economy in Lithium-Ion and Future Battery Technologies. *J. Phys. Energy* **2023**, *5*, 021501. [CrossRef]
168. Chala, T.G.; Kornilich, D.O. A Statistical Analysis of the National Market of Lithium-Ion Batteries and the Influence of the Aggression of the Russian Federation on Its Development. *Probl. Econ.* **2024**, *1*, 146–152. [CrossRef]
169. Zou, Q.; Yi, C.; Wang, K.; Yin, X.; Zhang, Y. Global LNG Market: Supply-Demand and Economic Analysis. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *983*, 012051. [CrossRef]

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