

Review

Zeolite-Based Adsorbents as Next-Generation Materials for Sustainable Lithium Recovery Technologies

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Abstract

The rapid growth of electric mobility, renewable-energy storage, and portable electronics has sharply increased global lithium demand. Conventional lithium extraction methods, including hard-rock mining and brine evaporation, are land-intensive, slow, water-consumptive, and carbon-intensive. Adsorption has therefore received substantial attention for lithium recovery, due to its simple operation, cost-effectiveness, and facile scalability. In this regard, zeolite-based adsorbents have emerged as promising next-generation materials, mainly because of their crystalline frameworks, tunable pore architectures, ion-exchange functionality, and exceptional thermal and chemical stability. Existing reviews on adsorption-based lithium recovery have predominantly focused on polymeric materials, ion-exchange resins, and lithium-ion sieves (including lithium manganese oxide-based, titanium-based, and aluminum hydroxide-based adsorbents). To fill this gap, we present a dedicated and comprehensive review of zeolite-based adsorbents for sustainable lithium recovery from non-conventional lithium resources such as brines, geothermal fluids, seawaters, and battery-recycling leachates. By systematically and rigorously analyzing existing studies on this topic, we identify five guiding design principles: (i) zeolite framework charge density, (ii) zeolite framework topology and pore architecture (iii) morphology (size and shape), (iv) zeolite-based hybrid materials, and (v) operational design parameters (e.g., pH and temperature). Each design element is discussed in depth to clarify how lithium adsorption capacity and selectivity, transport behavior, and adsorption mechanisms can be controlled across diverse feedstocks. We further discuss the advantages, limitations, and future research needs for zeolite-based lithium capture. To the best of our knowledge, this is the first review centered on zeolite-based materials for lithium recovery. The knowledge and insights provided here aim to drive researchers into advancing zeolite-based adsorbents toward sustainable, next-generation lithium recovery technologies.

Keywords: lithium recovery; adsorption; ion-exchange; adsorbent; zeolite; material design; sustainable process; non-conventional lithium resources

Academic Editors: Rui Wang,
Xinpeng Liu, Yunqian Ma, Kai
Zhang and Mahshab Sheraz

Received: 22 June 2026

Revised: 7 July 2026

Accepted: 9 July 2026

Published: 11 July 2026

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1. Introduction

The rapid growth of electric vehicles, portable electronics, and grid-scale energy storage has sharply increased lithium (Li) demand. This surge stems from the exceptional physicochemical properties of Li, including its highly negative redox potential, low atomic weight, high specific heat capacity, and superior energy density relative to other

elements, making it the preferred charge carrier in modern electrochemical energy-storage systems [1–5]. Today, Li is used predominantly in Li-ion batteries for electric vehicles and stationary energy storage (Figure 1). Global Li production has risen from ~3700 metric tons (MT) in 1970 to over 100,000 MT in 2021, reflecting its central role in the energy transition [6,7]. By 2030, Li demand is projected to exceed 2 million MT, with batteries accounting for nearly 95% of total consumption [6,7].

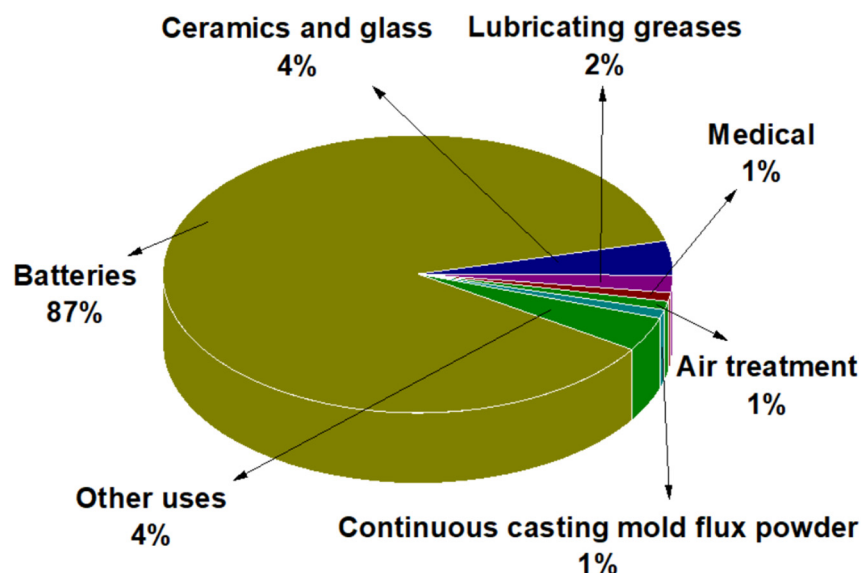


Figure 1. Global end uses of lithium in 2025, sourced from the United States Geological Survey (USGS) [6].

Conventional Li resources include continental brines, hard-rock ores, and Li-bearing clays (Figure 2) [8,9]. High-grade salar brines in Chile, Argentina and Bolivia are the largest commercial source [10], while hard-rock ores such as spodumene-rich pegmatites in Australia, Canada, and China provide the second major pathway [10]. Clays such as hectorite and smectite in the United States and Mexico are also important Li resources [10]. Despite their maturity, these routes are constrained by high energy demand, complex processing, high cost, and progressive resource depletion of high-quality reserves [4]. Non-conventional Li resources are increasingly explored to expand supply and improve resource security. Low-quality continental brines differ from high-grade salars and are emerging alternative feedstocks [10,11]. Geothermal brines provide continuous fluid production and co-generated renewable power, enabling integrated direct Li extraction [12]. Oilfield brines and produced waters offer vast but chemically complex resources with highly variable Li concentrations [9]. Seawater contains an enormous Li inventory, despite extremely low concentrations ($\sim 0.17 \text{ mg L}^{-1}$) [3,13,14]. End-of-life Li-ion batteries also serve as important secondary resources with circular-economy strategies [15–17]. Although these unconventional resources hold significant promise, Li recovery from them remains technologically immature and faces major challenges, underscoring the need for highly efficient, selective, and sustainable separation methods.

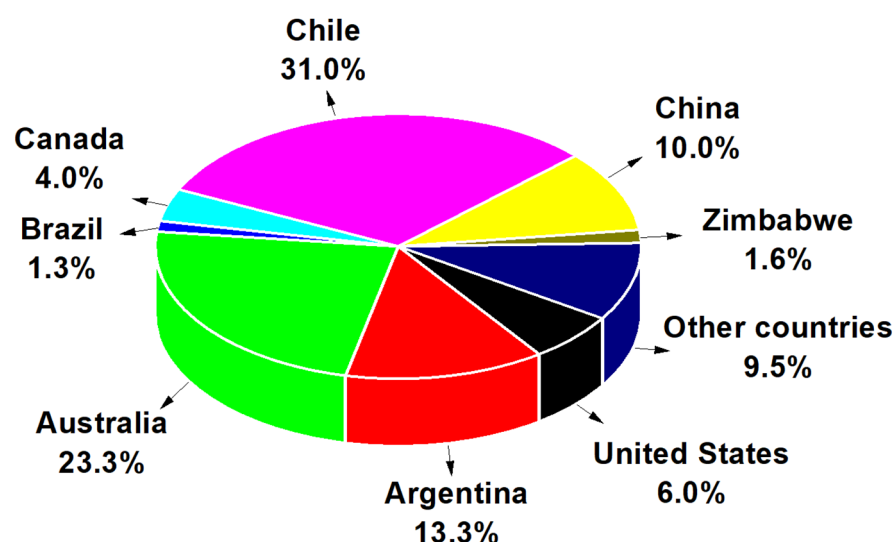


Figure 2. Lithium reserves by countries as a percentage of global reserves in 2025, sourced from the USGS [6].

To selectively separate Li from unconventional Li resources, several technologies have been developed, including precipitation, solvent extraction, membrane separation, electrochemical methods, and adsorption [4,7,11,12,14,15,18,19]. Precipitation is simple and industrially mature, but performs poorly in high magnesium-to-Li (Mg/Li) brines [19,20]. Solvent extraction offers high Li selectivity and relatively low energy demand, yet is hindered by interference from multivalent cations such as Ca^{2+} and Mg^{2+} , organic contaminants, solvent cost and stability, and equipment corrosion issues [4,19]. Membrane separation can separate Li through charge and size exclusion, but faces fouling, selectivity–permeability trade-off, and limited capacity in complex waters [4,19]. Electrochemical methods provide strong selectivity in dilute, multicomponent brines. Nevertheless, these methods remain constrained by electrode degradation, side reactions, energy consumption, and scale-up difficulties [4,19]. In contrast, adsorption-based separation has emerged as a leading strategy for Li recovery by providing (i) higher Li selectivity and recovery efficiency, (ii) cost-effectiveness, (iii) operational simplicity and scalability, and (iv) environmental sustainability, enabled by low chemical requirements and minimal waste generation [2–4,7,11,12,15,18,19].

Adsorbents are of central importance in determining the performance of adsorption-based Li recovery processes, spanning both organic and inorganic material platforms. These materials selectively capture Li^+ from multicomponent aqueous solutions through ion-exchange, surface complexation, or structural intercalation [1,2,4,16]. Organic adsorbents such as ion-exchange resin and polymeric materials have been employed for Li recovery, but their applications are hindered by relatively low Li selectivity, susceptibility to fouling, and limited reusability and stability under highly saline conditions [1,2,4]. Meanwhile, inorganic types of adsorbents (often referred to as Li-ion sieves (LISs)) such as Li manganese oxide (LMO)-based, titanium (Ti)-based (LTO), and aluminum (Al)-based adsorbents have been widely investigated in prior studies [1–3,19]. The Li recovery performance of these LIS adsorbents is summarized in Table 1. Among these, LMO-based adsorbents (e.g., $\lambda\text{-MnO}_2$ and $\text{Li}_2\text{Mn}_2\text{O}_5$) are the most extensively studied, owing to their high Li selectivity and well-defined spinel structures that preferentially intercalate Li^+ over larger or multivalent cations. However, their performance deteriorates due to Mn dissolution-induced structural degradation under acidic conditions required for Li desorption [2–4]. LTO-based adsorbents such as Li_2TiO_3 and H_2TiO_3 offer high Li selectivity and superior structural stability with negligible metal leaching. Nevertheless, their implementa-

tion remains challenged by high synthesis costs, slow Li uptake rates, and lower Li adsorption capacity relative to LMO-based adsorbents [2–4]. Aluminum (Al)-based hydroxide adsorbents consisting of $\text{LiCl}/\text{Al}(\text{OH})_3$ or Li-Al layered double hydroxides (LiAl-LDHs) provide additional pathways for Li^+ capture via surface complexation and tunable anion-exchange sites. These materials deliver advantages such as simple synthesis, low-cost raw materials, and preparation under mild synthetic conditions. However, they generally exhibit lower Li adsorption capacity and poorer Li selectivity than LTO- and LMO-based adsorbents. Although Al-based adsorbents are typically more stable than LMO-based materials, gradual performance decline could be an issue due to the partial loss of active sites and structural changes during repeated adsorption–desorption cycles [2–4,19].

Table 1. Lithium recovery performance of selected LIS-based adsorbents.

Adsorbent	Li Adsorption Conditions	Types of Li Solution	Li Uptake Capacity (mg g^{-1})	Equilibrium Time	Ref.
$\text{Li}_4\text{Mn}_5\text{O}_{12}$	10 mL of 70 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 30 °C; pH of 10.1	Brine that contains multiple cations (Mg/Li = 0.88)	7.1 ($\alpha_{\text{Li/Mg}} = 599$)	72 h	[21]
LiMn_2O_4	10 mL of 70 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 30 °C; pH of 10.1	Brine that contains multiple cations (Mg/Li = 0.89)	16.9 ($\alpha_{\text{Li/Mg}} = 1945$)	114 h	[22]
$\text{Li}_{1.6}\text{Mn}_{1.6}\text{O}_4$	500 mL of 900 times concentrated seawater; 0.1 g adsorbent; 25 °C; pH of 10.1	Seawater	10.1	48 h	[23]
$\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ $\text{LiAl}_{0.5}\text{Mn}_{1.5}\text{O}_4$ $\text{LiTi}_{0.5}\text{Mn}_{1.5}\text{O}_4$	50 mL of 347 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 25 °C; pH of 13	Li^+ -containing solution	10.7 20.2 9.4	24 h	[24]
Granular $\text{Li}_4\text{Mn}_5\text{O}_{12}$	Qarhan salt lake brine ($\text{Li}^+ = 73$ ppm); 25 °C; pH of 8.5	Salt lake brine (Mg/Li = 12.5)	4.9 ^b	5.5 h	[25]
O_3 -eluted HMn_2O_4	100 mL of LiOH solution with 100 ppm Li^+ ; 0.1 g adsorbent; 25 °C; pH of 11.5	Synthetic solution (Mg/Li = 0.030)	33.2 ($\alpha_{\text{Li/Mg}} = 2367$)	24 h	[26]
Mn-Ti-LIS	100 ppm LiCl solution; adsorbent-to-solution ratio of 500 mL g^{-1} ; 40 °C; pH of 12	LiCl solution	32.3	10 h	[27]
Li_2TiO_3	10 mL of 70 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 60 °C; pH of 9.19	Brine that contains multiple cations (Mg/Li = 1.43)	25.6 ($\alpha_{\text{Li/Mg}} = 814$)	144 h	[28]
PVB Resin- H_2TiO_3	276.6 mg L^{-1} Li^+ solution; 30 °C; pH of 8.68	Salt lake brine (Mg/Li = 111.7)	12.1 ^b	6 h	[29]
$\text{Li}_4\text{Ti}_5\text{O}_{12}$ @Shell	20 mL of 11.13 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 25 °C; pH of 13.10	Brine that contains multiple cations (Mg/Li = 1.12)	28.5 ($\alpha_{\text{Li/Mg}} = 4596$)	5 h	[30]
$\text{Li}_4\text{Ti}_5\text{O}_{12}$	50 mL of 120 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 25 °C; pH of 9.17	Li^+ ion-containing solution	39.4	120 h	[31]
H_2TiO_3	50 mL of 0.1 ppm LiCl solution; 0.1 g adsorbent; 25 °C; pH of 13	LiCl solution (Mg/Li = 111.7)	55.1 ($\alpha_{\text{Li/Mg}} = 2713$)	24 h	[32]
$\text{H}_4\text{Ti}_5\text{O}_{12}$	100 mL of 150 ppm LiCl solution; 100 mg adsorbent; 20 °C; pH of 12	Simulated brine (Mg/Li = 0.29)	32.1 ($\alpha_{\text{Li/Mg}} = 23.4$)	8 h	[33]
Fe-doped H_2TiO_3	50 mL of 168 mg L^{-1} Li^+ solution; 0.1 g adsorbent; 25 °C; pH 12	LiCl solution (Mg/Li = 15.4)	34.3 ($\alpha_{\text{Li/Mg}} = 224.9$)	14 h	[34]
LiAl-LDHs	60 mL of 399 mg L^{-1} Li^+ solution; 1 g adsorbent; 30 °C	Low-grade brine (Mg/Li = 301.6)	7.3 ($\alpha_{\text{Li/Mg}} = 125.3$)	2 h	[35]
Magnetic LiAl-LDHs	40 mL of 397 mg L^{-1} Li^+ solution; 1 g adsorbent; 25 °C	Low-grade brine (Mg/Li = 81.1)	6.0 ($\alpha_{\text{Li/Mg}} = 259$)	4 h	[36]
Fe-doped LiAl-LDHs	800 mg L^{-1} Li^+ solution; 50 °C	Simulated brine (LiCl/NaCl)	11.3	1 h	[37]
LiZnAl-LDH	20 g L^{-1} of adsorbents in brine solution; 25 °C	Salt lake brine ^a	13.4 ($\alpha_{\text{Li/Mg}} = 171$)	3 h	[38]
Li-Al- CO_3 LDH	800 ppm of Li^+ solution; solid–liquid ratio of 1:40; 50 °C	Simulated brine (LiCl/NaCl) (Mg/Li = 3.17)	18 ($\alpha_{\text{Li/Mg}} = 118$)	3 h	[39]
PDMS@Li/ZnAl-LDH	2 L of 100 mg L^{-1} Li^+ solution (2 L brine); 70 °C; pH of 7	Salt lake brine (Mg/Li = 0.51)	9.4 ($\alpha_{\text{Li/Mg}} = 175$)	2 h	[40]

^a No information on Mg/Li molar ratio; ^b Li selectivity to Mg ($\alpha_{\text{Li/Mg}}$) was not provided.

Zeolites are increasingly viewed as strong candidates for Li recovery because their crystalline, microporous frameworks offer highly tunable ion-exchange properties that can be engineered for Li⁺ selectivity [4,41,42]. Their well-defined pore structures, high surface areas, and negatively charged aluminosilicate frameworks create ion-exchange sites that can accommodate Li⁺. Li recovery performance of zeolite-based materials is summarized in Table 2. Compared with state-of-the-art LIS adsorbents such as LMO-, LTO- and Al-based materials (Table 1), zeolites generally exhibit lower Li adsorption capacities and selectivities mainly because their adsorption primarily relies on conventional cation-exchange mechanisms. Nevertheless, zeolites often show faster kinetics than LIS materials, owing to rapid ion-exchange behavior. In addition, zeolites possess exceptional thermal and chemical stability, which hold potential for operations in harsh environments such as geothermal fluids, oilfield brines, and seawaters where many adsorbents degrade [43–47]. From an economic perspective, zeolites are manufactured at substantially lower costs than their counterparts. Natural zeolites are abundant, inexpensive, and commercially available, while synthetic zeolites are also produced on a large industrial scale because of their long-established applications in catalysis, separation, and ion-exchange [42,48–50]. These features strongly support zeolites' potential for deployment in large-scale Li recovery systems. Although zeolites have been widely employed as highly reusable cation-exchangers in water treatment and separation processes [42,51], comprehensive evaluations of their long-term cycling stability and regeneration performance for Li recovery are still lacking. Overall, the unique combination of low cost, structural tunability, stability, and scalability positions zeolites as a promising platform for next-generation Li recovery technologies.

Table 2. Lithium recovery performance of zeolite-based adsorbents.

Adsorbent	Li Adsorption Conditions	Types of Li Solution	Li Uptake Capacity (mg g ⁻¹)	Equilibrium Time	Ref.
Clinoptilolite (natural)	10 mg L ⁻¹ Li ⁺ solution; 25 °C; pH of 9	Geothermal water	0.45	0.5 h	[43]
Na-X	10 mg L ⁻¹ Li ⁺ solution; 25 °C; pH of 9	Geothermal water	0.45	0.5 h	[43]
Clinoptilolite (natural)	15 mL of 0–5205 mg L ⁻¹ Li ⁺ solution; 2.5 g adsorbent; 25 °C; pH of 6–8	Brine that contains multiple cations	3900 ppm Li ⁺ recovered	-	[52]
SOD	50 mL of 100 mg L ⁻¹ Li ⁺ solution; 4 g/L adsorbent; 25 °C; pH of 6	Low-quality brine (Mg/Li = 100)	23.0 (18.7 for Mg/Li = 100) ^b	4 h	[53]
13X (powder)	100 mL of 500 mg L ⁻¹ Li ⁺ solution; 1 g adsorbent; 40 °C; pH of 9	Synthetic solution and geothermal brine (Mg/Li = 2.34)	20.3 ^b	1 min	[44]
13X (beads)	100 mL of 300 mg/L L ⁻¹ Li ⁺ solution; 1 g adsorbent; 60 °C; pH of 9	Synthetic solution and geothermal brine (Mg/Li = 2.34)	8.6 ^b	9 h	[44]
13X	Simulated battery leachate containing 20 mg L ⁻¹ Li ⁺ ; 12 g L ⁻¹ adsorbent; 25 °C; pH of 6.5	Spent battery leachates	~70% of Li ⁺ recovered	60 min	[54]
13X	Simulated battery leachate containing 20 mg L ⁻¹ Li ⁺ ; 5 g L ⁻¹ adsorbent; 25 °C; pH of 7–10	Spent battery leachates	~30% of Li ⁺ recovered	40 min	[55]
NaY	Simulated battery leachate containing 20 mg L ⁻¹ Li ⁺ ; 5 g L ⁻¹ adsorbent; 25 °C; pH of 7–10	Spent battery leachates	~30% of Li ⁺ recovered	40 min	[55]
GIS	50 mL of battery leachate containing Co ²⁺ , Ni ²⁺ , Mn ²⁺ and Li ⁺ ; 4 mg L ⁻¹ adsorbent; 0 °C	Spent battery leachate	>95% of Li ⁺ recovered	2 h	[56]

Hydroxycancrinite	50 mL of 0.5 mol L ⁻¹ Li ⁺ solution; 3 g adsorbent; 100 °C	Synthetic solution (LiCl)	Li uptake corresponding to 4.5 wt% of Li ₂ O on zeolites	24 h	[57]
5A (Na-form)	100 mL of 10.0 mg L ⁻¹ Li ⁺ solution; 1.0 g adsorbent; 40 °C	Synthetic solution (LiCl)	4.2 (at 40 °C) 5.0 (at 50 °C)	~24 h	[58]
5A (H-form)	100 mL of 10.0 mg L ⁻¹ Li ⁺ solution; 1.0 g adsorbent; 40 °C	Synthetic solution (LiCl)	2.1	~24 h	[58]
13X (Na-form)	100 mL of 10.0 mg L ⁻¹ Li ⁺ solution; 1.0 g adsorbent; 40 °C	Synthetic solution (LiCl)	11.4 (at 40 °C) 11.9 (at 50 °C)	~24 h	[58]
13X (H-form)	100 mL of 10.0 mg L ⁻¹ Li ⁺ solution; 1.0 g adsorbent; 40 °C	Synthetic solution (LiCl)	7.7	~24 h	[58]
NaA	50 mL of battery leachate containing Co ²⁺ and Li ⁺ ; 20 g L ⁻¹ adsorbent; 90 °C; pH of 6	Spent battery leachate	>95% of Co ²⁺ recovered; no Li ⁺ uptake	30 min	[59]
NaA	Simulated battery leachate containing 0.1 mol L ⁻¹ Li ⁺ ; 20–60 °C; pH of 2–7	Spent battery leachates	>95% of Li ⁺ recovered	4 h	[60]
NaA	Battery leachate containing Co ²⁺ , Ni ²⁺ , Mn ²⁺ and Li ⁺ ; 2–16 g L ⁻¹ adsorbent; 0–60 °C	Spent battery leachates	>95% of Li ⁺ recovered	10 h	[61]
Clinoptilolite–PAA composite	10 mg L ⁻¹ Li ⁺ solution; 25 °C; pH of 5	Geothermal water ^a	Li ⁺ uptake resulting in 5 mg L ⁻¹ Li ⁺ solution ^b	3 h	[43]
Zeolite–hydrogel composite	30 mL of 55 mg L ⁻¹ Li ⁺ solution; 1 g of adsorbent; 25 °C; pH of 6.12	Geothermal waters (Mg/Li = 0.015)	0.09 ^b	24 h	[46]
Nanofiber containing zeolite carrier (PAN CE@SiO ₂ /zeolite)	50 mL of 100 mg L ⁻¹ Li ⁺ solution; 25 mg adsorbent, 25 °C; pH of 6	Salt lake brine (Mg/Li = 0.019)	8.6 ($\alpha_{\text{Li/Mg}}$ = 8.9)	2.5 h	[47]
LiAl-LDHs/ZSM-5 Composite	Zeolite-to-Li ⁺ ratio of 2; 10 g L ⁻¹ of adsorbent; 25 °C; pH of 7	Salt lake brine (Mg/Li = 2.17)	6.2 ($\alpha_{\text{Li/Mg}}$ = 188)	4 h	[45]

^a No information on Mg/Li molar ratio; ^b Li selectivity to Mg ($\alpha_{\text{Li/Mg}}$) was not provided.

In this review, we present zeolites as a promising class of emerging adsorbents and systematically analyze recent progress in sustainable zeolite-based Li capture from non-conventional Li resources. While existing reviews have largely surveyed adsorption-based Li recovery, with an emphasis on LIS-based adsorbents (i.e., LMO, LTO, and Al-based materials) [2–4,9,14,16,17,19], polymeric adsorbents [3,16,17,19], and their hybrid materials [3,16,17,19], a comprehensive review and perspective that centers explicitly on zeolite-based strategies remains scarce. To the best of our knowledge, this is the first review article to provide a focused and comprehensive review of zeolite-based adsorbents for sustainable Li recovery. Our systematic and rigorous analysis of prior reports on this topic enables us to distill five guiding design principles that shape Li⁺ adsorption capacity and selectivity, transport behavior, and adsorption mechanisms: (i) framework charge density, (ii) framework topology and pore architecture, (iii) particle morphology (size and shape), (iv) zeolite-based hybrid materials, and (v) key operational design parameters, particularly temperature and solution pH. We also discuss current challenges and emerging opportunities, unlocking the full potential of zeolite-based systems in the future. Building on this foundation, this review aims to accelerate the development of advanced zeolite-based materials and adsorption processes, positioning them as durable, scalable, and sustainable platforms for next-generation Li recovery.

2. Zeolite Adsorbents

2.1. What Are Zeolites?

Zeolites are crystalline, microporous aluminosilicates that are characterized by a pore architecture built by a three-dimensional (3D) network of linked TO₄ tetrahedra (T = Si or Al) interconnected through O atoms. For a purely siliceous structure, the resulting struc-

ture is silica (SiO_2), with a complete charge balance with the structure. Nonetheless, when Al atoms are incorporated into the tetrahedrally coordinated silica framework, the 3+ charge of Al renders the zeolite framework negatively charged, due to charge difference between $(\text{AlO}_4)^{5-}$ and $(\text{SiO}_4)^{4-}$ tetrahedra (Figure 3a) [42,62]. This negative charge on the zeolite framework is balanced by introducing extra-framework cationic species inside the structures of the zeolite framework, keeping the overall framework neutral. These compensating cations can be metal cations. Noticeably, each Si-O-Al unit introduces a single negative charge on the zeolite framework, which is typically balanced by one monovalent charge-compensating cation (e.g., Na^+ or K^+). A single divalent cation such as Ca^{2+} or Mg^{2+} can be incorporated into zeolite lattices when two Al atoms are positioned near one another, and the framework presents two neighboring negative charges.

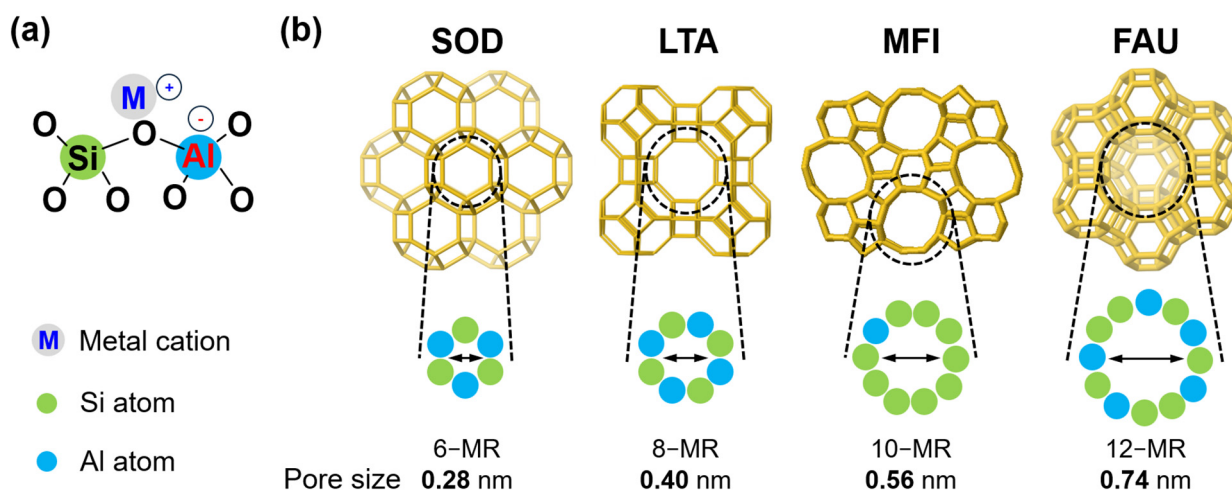


Figure 3. Schematic illustration of (a) ion-exchange site in zeolites and (b) representative zeolite frameworks and their pore architectures. MR stands for membered-ring, while dashed lines and arrows indicate the representative pore structures and their pore diameters, respectively.

A defining feature of zeolites is their framework-derived porosity, which has garnered considerable scientific and industrial interest. The flexibility of the T-O-T (T = Si or Al) bond angles enables diverse spatial arrangements of the tetrahedral building units, giving rise to a wide variety of porous framework architectures. Zeolite pore structures are conventionally classified according to the size and geometry of their pore channel apertures, which are defined by the number of tetrahedral T atoms forming each ring (Figure 3b). To date, more than 240 distinct zeolite framework types have been identified. Based on pore aperture size, zeolites are commonly categorized as small-pore (six-membered ring (6-MR) and 8-MR), medium-pore (10-MR), and large-pore (12-MR) frameworks (Table 3) [63]. Examples of small-pore zeolites are SOD (with 6-MR and ~0.28 nm pore size) and LTA (with 8-MR and ~0.40 nm pore size), whereas medium-pore structures such as MFI exhibit channels with diameters of ~0.56 nm. Large-pore frameworks, including FAU, feature pore windows ranging from ~0.74 nm [62,63]. This pore size classification is fundamental because the effective pore diameter affecting adsorption behavior relies not only on crystallographic ring size but also on framework composition, temperature, and extra-framework cations, all of which can alter accessible free volume and transport properties of adsorbates within the zeolite framework [64].

Table 3. Structural properties of some zeolites.

Name	Framework Topology	Pore Dimension	Extra-Framework Cation	Si/Al Ratio (SAR)
SOD	SOD	6-MR (0.28 nm × 0.28 nm)	Na ⁺	1.0
GIS	GIS	8-MR (0.31 nm × 0.45 nm); 8-MR (0.26 nm × 0.49 nm)	Na ⁺	1.0–1.5
3A (KA)	LTA	8-MR (~0.30 nm × ~0.30 nm)	Na ⁺ , K ⁺	1.0
4A (NaA)	LTA	8-MR (~0.40 nm × ~0.40 nm)	Na ⁺	1.0
5A (CaA)	LTA	8-MR (~0.50 nm × ~0.50 nm)	Na ⁺ , Ca ²⁺	1.0
ZSM-5	MFI	10-MR (0.53 nm × 0.56 nm)	Na ⁺ , NH ₄ ⁺ , H ⁺	≥12
BEA	BEA	12-MR (0.64 nm × 0.76 nm)	Na ⁺ , NH ₄ ⁺ , H ⁺	≥12
13X (NaX)	FAU	12-MR (0.74 nm × 0.74 nm); Supercage (~1.2 nm)	Na ⁺	1.0–1.5
NaY	FAU	12-MR (0.74 nm × 0.74 nm); Supercage (~1.2 nm)	Na ⁺	>1.5

2.2. Natural and Synthetic Zeolites

Zeolites are generally classified as natural or synthetic zeolites, based on their origin. Both classes have been actively explored as adsorbents for Li recovery from a wide range of resource streams. Natural zeolites are formed from volcanic or sedimentary environments. Common natural zeolites include clinoptilolite, mordenite, chabazite, and analcime, as listed in Table 4. They are abundant, inexpensive, and readily available, rendering them attractive for large-scale adsorption and ion-exchange applications [51,65,66]. However, natural zeolites often possess variations in composition, crystallinity, and pore structure depending on their geological origin [51,65,66]. On the other hand, synthetic zeolites are produced with high purity through controlled synthesis, allowing for precise tuning of pore size, Si/Al ratio (SAR), crystal morphology (size and shape), and extra-framework cation compositions for adsorption applications.

Table 4. Structural properties of some natural zeolites [41,51,65].

Name	Framework Topology	Pore Dimension	Extra-Framework Cations	Si/Al Ratio (SAR)
Analcime	ANA	8-MR (0.16 nm × 0.42 nm)	Na ⁺	2.0–3.0
Chabazite	CHA	8-MR (0.38 nm × 0.38 nm)	Ca ²⁺	1.4–4.2
Clinoptilolite	HEU	10-MR (0.31 nm × 0.75 nm) 8-MR (0.30 nm × 0.46 nm)	Na ⁺ , K ⁺	2.9–5.0
Erionite	ERI	8-MR (0.36 nm × 0.51 nm)	Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺	3.0–4.0
Ferrierite	FER	10-MR (0.42 nm × 0.54 nm) 8-MR (0.34 nm × 0.54 nm)	Na ⁺ , Mg ²⁺	3.8–6.1
Heulandite	HEU	10-MR (0.31 nm × 0.75 nm) 8-MR (0.30 nm × 0.46 nm)	Ca ²⁺	2.9–4.3
Hydroxycancrinite	CAN	6-MR (0.59 nm × 0.59 nm)	Na ⁺ , K ⁺ , Ca ²⁺	1.0–1.2
Laumontite	LAU	10-MR (0.40 nm × 0.53 nm)	Ca ²⁺	2.0–2.3
Mordenite	MOR	12-MR (0.65 nm × 0.70 nm) 8-MR (0.26 nm × 0.57 nm)	Na ⁺	4.2–5.8
Phillipsite	PHI	8-MR (0.38 nm × 0.38 nm) 8-MR (0.30 nm × 0.43 nm)	Na ⁺ , K ⁺ , Ca ²⁺	1.5–2.9

The desired type and properties of zeolites are significantly dependent upon the choice of synthesis method (Figure 4) [62,64,67]. Zeolite synthesis is traditionally carried out by conventional hydrothermal crystallization [62]. In this route, a gel containing silica, alumina, water, and an alkali source is heated under pressure so that crystals form over time. Structure-directing agents (SDAs) are often added to guide the framework that de-

velops. To date, hydrothermal synthesis remains the standard method for many common zeolites including SOD, CHA, LTA, MFI, BEA and FAU. But, conventional hydrothermal synthesis is slow and energy-intensive, and limited in structural and morphological control for certain types of zeolites [64,67]. Solvothermal synthesis follows synthetic principles similar to hydrothermal synthesis, but employs organic solvents instead of, or in combination with, water. Solvothermal methods often provide improved control over crystal morphology (particle size and shape); however, they are generally more expensive due to solvent costs and recovery requirements [67]. Ionothermal synthesis represents another alternative approach, in which ionic liquids serve as reaction media and, in some cases, as SDAs for zeolite crystallization. This method enables the preparation of unique zeolite and zeolite-type structures that are challenging to synthesize through conventional routes. However, the high cost of ionic liquids and the difficulty of product purification are currently major hurdles for large-scale implementation [67].

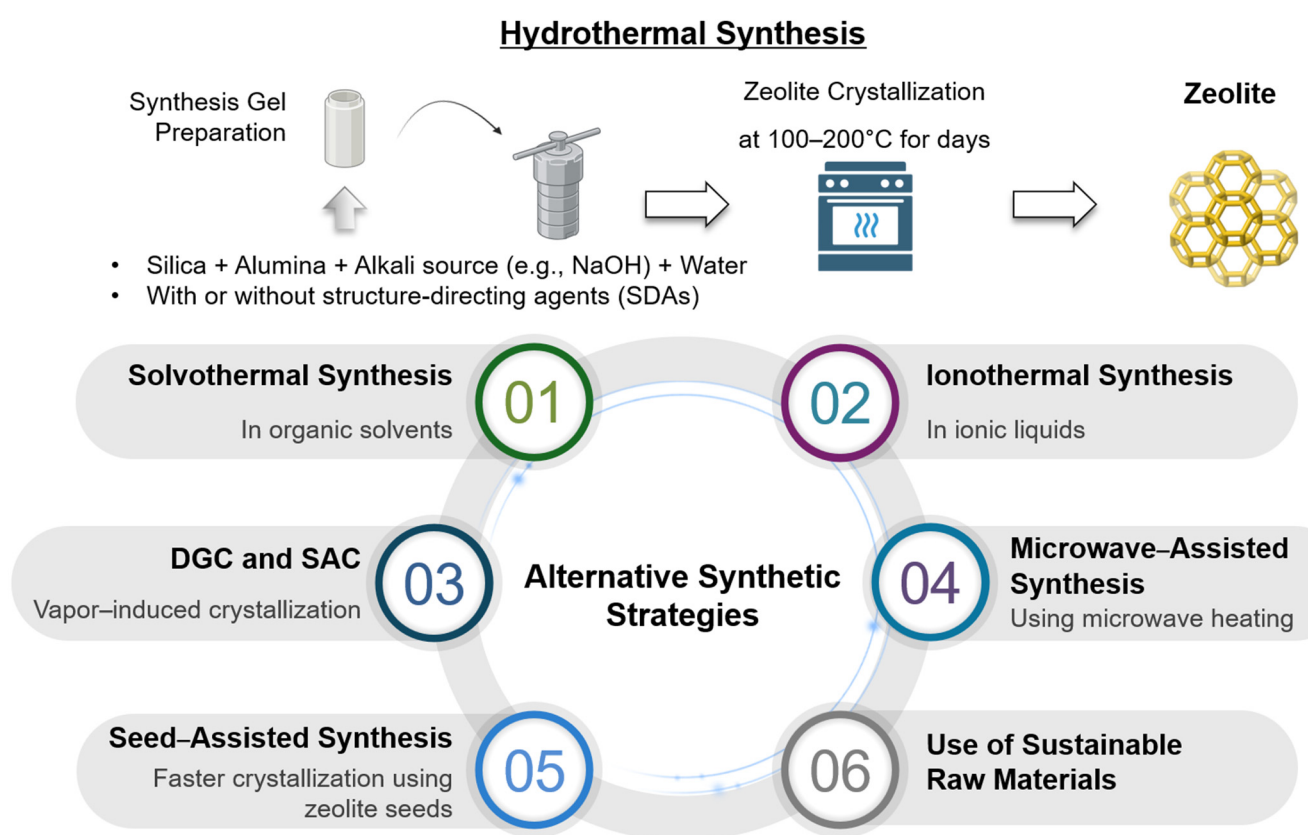


Figure 4. Schematic of various synthesis pathways to produce zeolite materials.

To reduce energy consumption and chemical usage, minimize waste generation, and improve sustainability, various alternative synthetic approaches have been developed, including dry-gel conversion (DGC) and steam-assisted conversion (SAC) methods, microwave-assisted crystallization, seed-assisted routes, and the use of sustainable raw materials (Figure 4) [64,67–69]. For DGC or SAC methods, a solid precursor gel is exposed to water vapor or steam rather than being fully immersed in liquid. These vapor-phase routes often achieve high zeolite product yields and provide improved control over particle size. However, narrower optimization windows of synthesis, compared to a hydrothermal method, could be an issue associated with zeolite crystallization under vapor-phase routes [69]. To accelerate zeolite crystallization, microwave-assisted hydrothermal synthesis applies microwave irradiation to heat precursor gels rapidly and uniformly. This enhances nucleation rates, shortens crystallization times from days to hours, and of-

ten produces smaller, more uniform crystals with improved phase purity. Nevertheless, challenges associated with synthesis reactor design and scale-up have limited its widespread industrial adoption [67]. Seed-assisted synthesis utilizes the addition of seed crystals to reduce the induction period required for zeolite nucleation, in turn significantly reducing zeolite crystallization times. This seeding often improves zeolite phase selectivity and allows for synthesis with reduced amounts of SDAs or even under SDA-free conditions. However, this synthetic strategy is generally limited to specific framework types and provides less flexibility in controlling zeolite structure [68]. The use of renewable and waste-derived raw materials has also become an important element of green and sustainable zeolite synthesis. Industrial by-products and agricultural wastes rich in silica and alumina, such as coal fly ash, rice husk ash, sugarcane bagasse ash, red mud, kaolin, and waste glass, can serve as effective alternative precursors. Converting these waste streams into zeolites simultaneously reduces landfill burdens, conserves natural mineral resources, and lowers production costs. However, challenges associated with feedstock heterogeneity, impurity management, and the control of zeolite framework composition and crystallinity remain to be addressed for sustainable zeolite synthesis [67,69].

3. Design Principles for Zeolite-Based Li Recovery

A coherent design platform for zeolite-based Li recovery emerges from five mutually reinforcing principles that steer Li^+ adsorption capacity, selectivity, transport behavior, and adsorption mechanisms: (i) framework charge density tuned by the Si/Al ratio (SAR), (ii) framework topology and pore architecture, (iii) particle morphology (size and shape), (iv) integration of zeolites with other materials to form zeolite-based composite or hybrid materials, and (v) key operational design parameters, particularly temperature and solution pH (Figure 5). Each of these principles is discussed below, in light of recent research (Table 2) aimed at advancing sustainable and efficient Li recovery.

Design Principles for Zeolite-Based Lithium Recovery

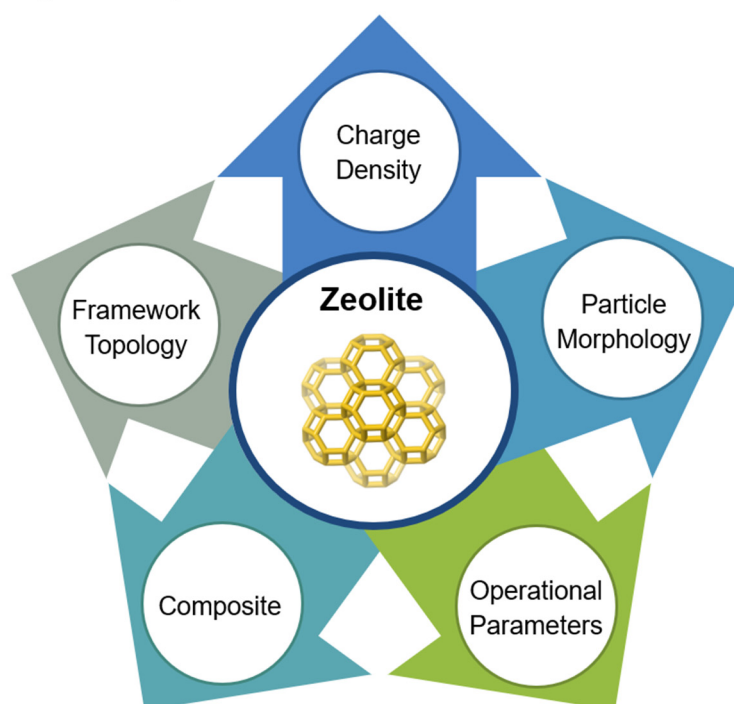


Figure 5. Schematic of the five guiding principles for rationally designing zeolite-based adsorbents as next-generation materials for sustainable lithium recovery technologies.

3.1. Framework Charge Density (Si/Al Ratio (SAR))

Framework charge density of zeolites (i.e., SAR) is a key determinant of Li^+ uptake capacity and selectivity. When Al atoms are tetrahedrally coordinated into zeolite frameworks, a net negative charge is balanced by typically exchangeable cations such as Na^+ , K^+ , NH_4^+ , H^+ , Ca^{2+} , or Mg^{2+} in their micropore channels (Figure 3a).

The Li extraction mechanism of zeolites principally originates from the ion-exchange process where Li^+ from aqueous solutions replaces these cations in zeolites [4,58]. According to Hoyer et al. [52], batch adsorption experiments were conducted across wide ranges of LiCl (0–750 mM) and NaCl (0.01–5 M) concentrations using natural zeolites that are mostly composed of 88–95% clinoptilolite. This study found that Li adsorption increased with increasing Li^+ concentration and decreasing Na^+ concentration, suggesting strong competition between Li^+ and Na^+ for exchange sites on zeolites. Maximum Li uptake of zeolites, which occurred at 750 mM LiCl and 0.01 M NaCl, was ~3900 ppm, revealing high Li removal efficiency from solution (up to ~65%). This study demonstrates that low-cost zeolite adsorbents can remove Li from saline environments; however, their inherently low Li^+ selectivity becomes a major limitation when high concentrations of competing cations (e.g., Na^+ , K^+ , Mg^{2+} , and Ca^{2+}) are present, as is typical in natural brines.

Framework charge density of zeolites is primarily determined by SAR [62,64]. Lower SAR values increase the negative charge of the aluminosilicate zeolite framework, thereby enhancing cation exchange capacity. For instance, Conte et al. investigated Li^+ and Co^{2+} uptake for LIB leachate applications and employed two FAU zeolites, i.e., 13X and NaY with SARs of 1.3 and 2.5, respectively, and both zeolites have Na^+ as extra-framework cations [54]. In Li uptake experiments in the presence of a single Li^+ (with a concentration of 20 mg L^{-1}), Li removal values of 78% and 60% were obtained on 13X and NaY, indicating that lower SAR increases Li capture capacity. Typically, a high negative framework charge density in low-silica zeolites (i.e., low SAR) generally promotes the preferential adsorption of divalent and trivalent cations over monovalent ions. Diez and colleagues demonstrated this behavior, who assessed Li^+ and Co^{2+} adsorption in mixed-ion solutions containing Li^+ (20 mg L^{-1}) and Co^{2+} (40 mg L^{-1}) [55]. Both 13X (FAU with SAR of 1.2) and NaY (FAU with SAR of 2.7) showed a strong preference for Co^{2+} , adsorbing $\sim 24.0 \text{ mg g}^{-1}$ of Co^{2+} , whereas Li^+ ion uptake was limited to only $\sim 0.30 \text{ mg g}^{-1}$ on both zeolites. Likewise, the preferential adsorption of Co^{2+} over Li^+ was also found on low-silica zeolites with SARs of 1.0–2.9 and various frameworks, including LTA, FAU, LTF and EMT, in the separation of Co^{2+} and Li^+ from spent LiCoO_2 batteries [59]. While zeolites inherently prefer divalent cations over Li^+ , this selectivity can be leveraged to remove divalent cations, eventually leaving Li^+ -enriched solution in applications such as spent battery leachates. Importantly, zeolites can still achieve selective Li^+ recovery from divalent cation-rich streams by engineering framework topology and pore architecture, and operational parameters such as temperature, as elaborated in Sections 3.2 and 3.5.

The type of extra-framework cation in zeolites has a substantial impact on Li uptake capacity. According to Navarrete-Casas et al., two synthetic zeolites of 5A (LTA with SAR of 1.0) and 13X possessing extra-framework cations of Na^+ and H^+ were chosen to study the ion-exchange of Li^+ with Na^+ and H^+ , respectively [58]. This study revealed that Li^+ ion-exchange was reversible and occurred much more readily with Na^+ than with H^+ . The replacement of Na^+ by Li^+ was more favorable both kinetically and thermodynamically, whereas ion-exchange of framework-associated H^+ was less favorable due to stronger proton interactions with the zeolite lattice. As a result, Na-form zeolites of 5A and 13X exhibited significantly greater Li uptake (4.2 mg g^{-1} and 11.4 mg g^{-1} , respectively) than their corresponding H-form zeolites (2.2 mg g^{-1} and 7.7 mg g^{-1} , respectively) in adsorption experiments under identical conditions at 40°C . Another example involves 13X in Li recovery using synthetic and geothermal brine [44]. This work reported that ion-exchange of

$\text{Li}^+\text{--Na}^+$ is dominant at Li^+ concentrations of less than $\sim 100\text{--}200\text{ mg L}^{-1}$. However, ion-exchange of $\text{H}^+\text{--Na}^+$ occurred predominantly at Li^+ concentrations greater than $\sim 100\text{--}200\text{ mg L}^{-1}$, reducing Li adsorption capacity. A decrease in pH observed during Li adsorption by 13X under these conditions suggested that protons were somehow involved in the ion-exchange, and the authors proposed $\text{H}^+\text{--Na}^+$ ion-exchange at a higher Li^+ concentration. Given the wide range of exchangeable cations that can be incorporated into zeolites, these examples illustrate that the nature of the extra-framework cation can act as a key factor governing Li^+ adsorption performance.

3.2. Framework Topology and Pore Architecture

Framework topology and pore architecture are critical to zeolite-based Li recovery, as they govern how ion-exchange sites are arranged and accessed, how strongly steric exclusion occurs, and how easily Li^+ ions move through the microporous network. These structural features ultimately determine Li^+ capacity and selectivity against competing ions, while also defining kinetics and adsorption mechanism for Li^+ .

The choice of zeolite framework structures strongly dictates Li^+ uptake capacity and mechanism. Specifically, zeolites 5A (LTA with SAR of 1.0; Na^+ only as extra-framework cations prepared after ion-exchange between $\text{Na}^+\text{--Ca}^{2+}$) and 13X (FAU with SAR of 1.2) showed total cation-exchange capacities of 2.72 and 3.54 meq g^{-1} , respectively, while Li capture values of 5.0 mg g^{-1} and 11.9 mg g^{-1} were observed for 5A and 13X, respectively, under identical adsorption conditions [58]. This indicates that 13X has a greater Li^+ ion-exchange capacity than 5A, despite possessing a higher SAR. Equilibrium isotherm analyses further revealed fundamentally different Li uptake mechanisms in the two zeolites. In zeolite 5A, only a single ion-exchange process was observed, with Li^+ primarily occupying anionic sites located on the external surface and within the accessible pore network. In contrast, zeolite 13X displayed two sequential exchange processes: an initial exchange at external sites followed by a second, more extensive exchange step in which Li^+ ions penetrated the three-dimensionally interconnected FAU supercages ($\sim 1.2\text{ nm}$) and occupied internal framework sites. Consequently, the larger and more accessible pore system of the FAU framework enabled greater Li^+ incorporation than the LTA framework.

Zeolite pore size is capable of precisely manipulating Li^+ selectivity in brine solutions by constraining ion accessibility, dehydration requirements, and transport through the microporous framework. Wang et al. highlighted this principle by demonstrating that SOD zeolites achieve selective Li recovery from low-quality brines with low Li concentrations ($<100\text{ mg L}^{-1}$) and high Mg/Li ratios (>100) [53], which remains challenging for conventional Li extraction technologies. The central premise of this work is that differences in ion-exchange kinetics between Li^+ and Mg^{2+} could be used to achieve selective Li adsorption. This concept was evaluated using three Na-form zeolites with SOD (6-MR; 0.28 nm pore size), NaA (LTA; 8-MR; 0.41 nm pore size), and NaX (FAU; 12-MR; 0.74 nm pore size). As a result, small-pore SOD exhibited strong kinetic selectivity for Li^+ over Mg^{2+} , although zeolites typically favor adsorption of divalent cations such as Mg^{2+} . This behavior arises from the narrow pores of SOD, which significantly slow the transport and ion-exchange of Mg^{2+} while allowing for faster Li^+ uptake. Specifically, SOD zeolites attained a Li^+ adsorption capacity of 2.7–3.7 mmol g^{-1} ($\sim 18.7\text{--}25.7\text{ mg g}^{-1}$) under high Mg/Li ratio conditions, demonstrating excellent performance for selective Li capture from brines. To explain the high Li^+ selectivity of SOD, adsorption experiments combined with density functional theory (DFT) calculations were conducted, and the authors proposed three sequential steps governing ion-exchange processes: (i) dehydration of hydrated metal ions (i.e., Li^+ or Mg^{2+}), (ii) migration through zeolite pores, and (iii) exchange with Na^+ located in the zeolite framework. Li^+ consistently shows lower energy barriers than Mg^{2+} across the three steps (i.e., dehydration, migration, and ion-exchange), while the higher dehy-

dration energy and slower mobility of Mg^{2+} within SOD cages suppress its uptake (Table 5). Therefore, $\text{Li}^+/\text{Mg}^{2+}$ separation stems from kinetic control as the primary mechanism, rather than equilibrium thermodynamics.

Table 5. Ionic radius, hydrated diameter, hydration free energy and hydrated ionic potential of metal cations [44,53,70,71].

Cation	Ionic Radius (Å)	Hydrated Diameter (Å)	Hydration Free Energy ^{a,c} (kJ mol ⁻¹)	Hydrated Ionic Potential ^{b,c} (e Å ⁻¹)
Li^+	0.74	6.92–7.60	−515	0.294
Na^+	1.14	5.99	−405	0.334
K^+	1.52	5.51	−295	0.364
Mg^{2+}	0.72	8.56	−1922	0.473
Ca^{2+}	1.15	8.25	−1306	0.485
Mn^{2+}	0.80	8.76	−1841	0.457
Co^{2+}	0.75	8.60	−1995	0.470
Sr^{2+}	1.328	8.24	−1443	0.485
Ba^{2+}	1.498	8.08	−1305	0.495

^a Hydration free energy is defined as the Gibbs free energy change for transferring an ion from gas phase into aqueous solution. This thermodynamic quantity reflects both enthalpic contributions (ion–water interactions) and entropic contributions associated with water restructuring [72]. ^b Hydrated ionic potential represents the effective charge density of a hydrated ion in water, defined as the ionic charge divided by its hydrated radius. This parameter captures how strongly an ion attracts and organizes surrounding water molecules. Ions with higher hydrated ionic potential generate more strongly bound, highly ordered hydration shells, and therefore face greater dehydration energy barriers [73,74]. Conversely, ions with lower hydrated ionic potential interact more weakly with water, leading to looser hydration shells and easier dehydration [73,74]. ^c Hydration free energy and hydrated ionic potential are closely correlated because they both reflect the strength of ion–water interactions, but they represent distinct quantities. Hydrated ionic potential is a geometric–electrostatic descriptor, while hydration free energy is a thermodynamic quantity. In general, higher hydrated ionic potential corresponds to more negative (i.e., stronger) hydration free energy [71,75].

Small-pore zeolites, when paired with sustainable zeolite synthesis routes, offer a low-cost and scalable pathway for accomplishing high Li recovery from multicomponent brine solutions that contain Li^+ , Na^+ , K^+ , Ca^{2+} and Mg^{2+} . Using various aluminosilicate wastes including feldspar, pyrophyllite, coal gangue and coal fly ash, Zhang et al. converted them into small-pore zeolites, i.e., hydroxycancrinite (CAN framework; 6-MR) [57]. It is worth noting that the crystallographic channel diameter of hydroxycancrinite is about 0.59 nm (Table 4), but the presence of OH^- groups and extra-framework Na^+ residing inside the channel can reduce the effective pore apertures to the ~0.28–0.30 nm range [76,77], which is the size actually experienced by diffusing ions. The resulting hydroxycancrinite zeolite revealed high crystallinity, uniform microporosity, and abundant exchangeable Na^+ sites with SAR of 1.1–3.8, providing a structurally favorable environment for selective Li^+ uptake. Consequently, this zeolite exhibited Li loadings of 4.5 wt% Li_2O in mixed-cation solutions, and up to 9.4 wt% Li_2O in pure LiCl solution. These Li contents surpass those of many typically found in many high-grade hard-rock Li ores (~1.5–4 wt% Li_2O), creating a dual benefit of a remarkable Li immobilization capacity and waste utilization.

3.3. Particle Morphology (Size and Shape)

Adsorbent particle morphology (size and shape) represents a key design consideration for developing effective highly Li-selective adsorbents, as it governs the efficiency of ion transport and site accessibility. When particles are small, the intracrystalline diffusion path is short, allowing Li^+ ions to reach adsorption active sites rapidly. Larger particles, in contrast, impose long diffusion pathways that slow Li^+ transport and reduce the fraction of sites that can participate in adsorption within practical contact times. This relationship was clearly illuminated by Reich et al. [44], who evaluated zeolite 13X in powder and bead forms for Li recovery from geothermal brine. As a result, increasing zeolite grain size from powder to beads led to a 58% reduction in Li^+ adsorption capacity, i.e., lowering capacity from 20.3 mg g^{-1} to 8.6 mg g^{-1} . Similar results were also obtained for Li recovery from simulated battery leachates using 13X in powder and pellet forms [54]. Powdered 13X exhibited significantly faster Li^+ uptake kinetics and a higher adsorption capacity than its pelletized counterpart. These differences were attributable to the shorter diffusion pathways and greater accessibility of ion-exchange sites in the powder form.

Zeolite particle shape could modulate Li adsorption performance by determining the external surface area and the accessibility of ion-exchange sites, although this aspect has received limited attention in the literature. Morphologies such as plate-like, needle-like, or nanosheet structures would expose more surface Na^+ sites and minimize the need for slow intracrystalline diffusion [78–80], enhancing Li^+ uptake kinetics. On the contrary, aggregated morphologies sequester ion-exchange sites within the crystal interior, leading to slower and diffusion-limited adsorption [78–80].

These shape- and size-dependent characteristics are also similarly linked to adsorbent regeneration efficiency because regeneration involves the reverse ion-exchange process. The same structural features that enhance Li^+ uptake, namely, smaller crystal size and more open particle shape, are likewise expected to accelerate Li^+ release during regeneration by minimizing diffusion limitations and improving regenerant accessibility to ion-exchange sites [81]. This trend has already been reported in other metal ion-exchange applications in water treatment [48,82,83]. However, the specific influences of particle morphology (size and shape) on regeneration as well as Li^+ desorption kinetics remain largely vague, underscoring the need for targeted studies to unravel these effects.

3.4. Integration with Other Materials (Zeolite-Based Composite)

Integrating zeolites with other materials can be an effective approach for recovering Li^+ from various Li resources including geothermal water, brine, and salt lakes. Wisniewska et al. reported that natural and synthetic zeolites, combined with poly(acrylic acid) (PAA) polymers, resulted in enhanced Li selectivity from geothermal water in Poland [43]. The key idea is that PAA within zeolite–PAA hybrid adsorbents created a more favorable interface for capturing Li^+ through polymer–Li metal complexation, in addition to Li uptake via ion-exchange processes within the zeolite framework. It turned out that Li extraction is strongly dependent on the order of addition of PAA and Li^+ , where the way of adding the polymer layer controls the accessibility of exchange sites and diffusion pathways. When PAA is allowed to adsorb or Li^+ is pre-equilibrated before the second component is added, the resulting interfacial structure favors more efficient Li uptake by controlling both thermodynamic affinity and transport for Li in zeolite-based systems. Clinoptilolite–PAA composite provided the highest Li recovery from geothermal water, achieving approximately 50% Li removal from an initial concentration of about 10 mg L^{-1} .

Zeolite–hydrogel composite was investigated for the simultaneous extraction of Li and arsenic (As) from geothermal waters [46]. The composite was prepared by combining natural clinoptilolite zeolites with sodium alginate and chitosan, two biopolymer-based hydrogel materials. The rationale behind the composite design was to integrate the ion-

exchange capability of clinoptilolite with the adsorption properties and high-water affinity of alginate and chitosan hydrogels. The results showed that the composite performed poorly for direct Li extraction from untreated geothermal brine: it removed only ~5.5% of Li (with Li uptake of $\sim 0.09 \text{ mg g}^{-1}$). In contrast, the composite demonstrated promising As removal performance, reducing As concentrations by approximately 52%. The authors concluded that the composite's strong affinity for As but weak uptake of Li is attributable to the preferential binding of As to the carboxylic and amine groups in chitosan and alginate, whereas these groups do not effectively coordinate Li^+ . Additionally, high silica concentrations in geothermal water can foul zeolite surfaces and block micropores, thereby reducing Li^+ selectivity. To overcome low Li^+ selectivity barriers in complex geothermal brine, the authors suggested that future improvements include surface modification, pre-treatment of geothermal brine, incorporation of Li-selective functional groups, or modification of clinoptilolite zeolite.

Unlike zeolite-based Li recovery systems that rely on ion-exchange sites within zeolite pores, zeolites have also been used primarily as carriers or supporting materials that have no ion-exchange sites. Ding and coworkers illustrate this concept with salt lakes by anchoring crown ether (CE) ligands within nanofiber-containing zeolites, enabling CEs to provide Li^+ -selective binding functionality, while preserving the vacancies of epoxy groups in CE essential for Li^+ coordination [47]. Spectroscopic and computational analyses (e.g., Fourier transform infrared (FT-IR) spectroscopy, scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and density functional theory (DFT)) indicate that Li^+ undergoes dsp^3 hybridization, facilitating electron donation from CE-functionalized sites to coordinate with Li^+ and form stable complexes. The material exhibited rapid adsorption kinetics, reaching equilibrium within 2.5 h and conforming to a pseudo-second-order kinetic model. Adsorption behavior of the adsorbent followed the Langmuir isotherm, consistent with monolayer adsorption, with a maximum capacity of 8.6 mg g^{-1} . Overall, this work presents a promising strategy for designing selective and structurally tunable adsorbents for Li capture from complex brines.

Recently, composite Li adsorbents created by growing LiAl-LDH on a ZSM-5 zeolite support have been reported, producing a hierarchical structure designed to improve Li^+ selectivity, permeability, and structural stability in salt lake brines with a high Mg/Li ratio (i.e., 7.6) and Li^+ concentration of 388 mg L^{-1} [45]. The main takeaway is that the roles of ZSM-5 are providing (i) structural support to prevent collapse and aggregation of LiAl-LDH, (ii) enhanced diffusion of Li^+ to activate adsorption sites via hierarchical structures, and (iii) increased surface area to provide uniform LDH dispersion. In this work, ZSM-5 zeolites with MFI topology and SAR of 40 were prepared by a seed-assisted synthesis using siliceous MFI zeolites. Since the high SAR (i.e., 40) of ZSM-5 was used, its contribution to Li^+ capture was anticipated to be minimal. This composite achieved a Li adsorption capacity of $\sim 6.2 \text{ mg g}^{-1}$ for actual salt lake brine from Tibet. Kinetic analysis showed that adsorption followed the pseudo-second-order model, indicating that chemisorption is the dominant adsorption mechanism. More importantly, this adsorbent exhibited a $\text{Li}^+/\text{Mg}^{2+}$ separation factor ($\alpha_{\text{Li}/\text{Mg}}$) of 188.1, demonstrating strong Li selectivity. The material also maintained good recyclability during five repeated cycles of Li adsorption-desorption, amplifying its potential for practical Li extraction applications.

3.5. Operational Design Parameters

Operational parameters including temperature and solution pH have deep impacts on the efficiency of zeolite-based Li recovery by tuning both thermodynamics and mass-transfer kinetics. These design parameters define an optimal operational window, in which zeolite charge density, pore accessibility and Li^+ transport are simultaneously max-

imized to accomplish high capacity and selectivity of Li recovery. Further details on these effects are provided below.

3.5.1. Temperature Effect

Temperature markedly affects zeolite-driven Li adsorption through both thermodynamic and kinetic factors. In order for hydrated Li^+ ions to enter zeolite channels and reach ion-exchange sites, the hydrated Li^+ ions have to partially shed their hydration shell (with a diameter of $\sim 0.69\text{--}0.76$ nm) as they pass through size-restrictive pores for complete ion-exchange with resident cations (Table 5). In this respect, raising temperature generally weakens hydration, thereby promoting dehydration of the hydration shell, and also enables faster diffusion of ions, facilitating ion-exchange with extra-framework cations (e.g., Na^+ , K^+ , or Ca^{2+}) located in zeolite pores via favorable interactions between Li^+ and zeolites. Consistent with this temperature effect, Navarrete-Casas et al. also reported that elevating solution temperature from 10°C to 50°C resulted in higher Li^+ adsorption capacities for both 5A and 13X zeolites [58].

The magnitude and direction of temperature effect on Li^+ adsorption typically depend on the zeolite framework, exchangeable cation, zeolite dosage, and solution composition. Wang et al. evaluated NaA zeolite's ability to capture metal ions in the mixture of Co^{2+} and Li^+ (20 mmol L^{-1} each) for Li recovery from spent LiCoO_2 batteries [59]. The authors showed that the removal rate of Co^{2+} using NaA increased continuously from 59.1% to 96.9% and 99.0% by increasing solution temperature from 0°C to 60°C and 90°C . In contrast, Li^+ removal rate by NaA reached 5% at 90°C , while at temperatures of $\leq 60^\circ\text{C}$ the removal rate remained zero. These findings allowed the authors to accomplish selective separation of Li^+ and Co^{2+} from the spent batteries by keeping the adsorption at a solution temperature of 60°C . This suggests that although higher temperatures improve NaA's uptake capacity for both metal ions, the temperature-induced gains in ion-exchange overwhelmingly favor Co^{2+} , whose divalent charge and reduced hydration constraints enable rapid uptake of Co^{2+} over Li^+ .

Moreover, it was reported that a temperature-regulated approach was effective in separating multiple metal ions from waste $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ batteries using NaA zeolites [61]. The authors showed that both solution temperature and zeolite dosage strongly influenced selective metal uptake, with NaA zeolites exhibiting an ion-exchange preference of $\text{Mn}^{2+} > \text{Co}^{2+} > \text{Ni}^{2+} > \text{Li}^+$. By sequentially adding NaA in the leachates, Mn^{2+} was removed first at 20°C , followed by Co^{2+} at 20°C , and then Ni^{2+} at 60°C . Recovery selectivities reached $\sim 93\%$ for Mn, 94% for Co, and 99% for Ni, while more than 95% of Li remained in solution, leading to substantial Li enrichment for effective Li separation from battery leachates.

Recently, manipulating ion-exchange temperature enabled priority extraction of Li^+ and sequential recovery of divalent metals from retired $\text{LiNi}_x\text{Co}_y\text{Mn}_{1-x-y}\text{O}_2$ batteries using GIS zeolites (8-MR; pore dimensions of $0.31\text{ nm} \times 0.45\text{ nm}$ and $0.26\text{ nm} \times 0.49\text{ nm}$) (Table 3) [56]. This strategy reverses the typical ion-exchange preference of zeolites, in which divalent metals preferentially outcompete Li^+ . Small-pore GIS zeolites showed 95% recovery of Li^+ at 0°C , followed by 94% of Mn^{2+} at 40°C and 97% of Co^{2+} at 60°C , while 90% of Ni^{2+} remained in solution. The exceptional Li^+ selectivity is attributable to its 2.5-fold faster diffusion rate with respect to Mn^{2+} , Co^{2+} , and Ni^{2+} , as evidenced by ion-exchange kinetics and molecular dynamics simulations. This work also evaluated the recyclability of GIS zeolites over five Li^+ adsorption–desorption cycles (Table 6) [56]. The authors investigated the effect of Na^+ concentration on Li^+ desorption efficiency by varying Na^+ concentrations from 0.1 mol L^{-1} to 2.5 mol L^{-1} at 60°C . Complete Li^+ desorption was achieved at Na^+ concentrations of $\geq 0.5\text{ mol L}^{-1}$, corresponding to 100% ion-exchange between Li^+ and Na^+ . Before and after five cycles conducted at 0°C , Li^+ adsorption capacity of GIS zeolites re-

mained essentially unchanged, indicating excellent recyclability and ion-selective performance suitable for industrial applications.

Temperature-driven regeneration has also been demonstrated for zeolite-based composites, for instance, LiAl-LDH/ZSM-5 adsorbents in salt lake brine as reported by Fang and coworkers (Table 6) [45]. In this work, adsorption was conducted at 25 °C in salt lake water, whereas desorption at 60 °C using deionized water as optimal conditions was performed; however, the authors did not detail how optimal desorption conditions were determined. Over the five cyclic studies, Li⁺ uptake decreased slightly, retaining 91.9% of its initial adsorption capacity (i.e., from 6.42 mg g^{−1} to 5.90 mg g^{−1}). The 8.1% loss was attributed to partial degradation of LiAl-LDH active sites during repeated cyclic operation, suggesting the need to enhance long-term structural stability.

Table 6. Summary of Li recovery performance of zeolite-based materials with a focus on reusability.

Adsorbent	Li Adsorption Conditions	Li Desorption Conditions	Li Uptake Capacity after Cyclic Tests (mg g ^{−1})	Ref.
GIS	50 mL of battery leachate containing Co ²⁺ , Ni ²⁺ , Mn ²⁺ and Li ⁺ ; 4 mg L ^{−1} adsorbent; 0 °C	Na ⁺ concentrations of ≥0.5 mol L ^{−1} at 60 °C	>95% of Li ⁺ recovered (initial); Same performance after 5 cycles	[56]
LiAl-LDHs/ZSM-5 composite	Zeolite-to-Li ⁺ ratio of 2; 10 g L ^{−1} of adsorbent; 25 °C; pH of 7	Deionized water at 60 °C	6.42 (initial); 5.90 after 5 cycles	[45]
13X (powder)	100 mL of 500 mg L ^{−1} Li ⁺ solution; 1 g adsorbent; 40 °C; pH of 9	1 M NaCl or 1 M CH ₃ COONa solution	Desorption efficiencies of 94–100%; no reusability study	[44]
Nanofiber containing zeolite carrier (PAN CE@SiO ₂ /zeolite)	50 mL of 100 mg L ^{−1} Li ⁺ solution; 25 mg adsorbent, 25 °C; pH of 6	0.5 M HCl	8.6 (initial); 7.8 after 5 cycles	[47]

3.5.2. pH Effect

Solution pH strongly influences zeolite-driven Li recovery because it directly modulates ion-exchange environment, ion diffusion, and competition between metal cations. For zeolite-based Li recovery systems, each zeolite is characterized by point of zero charge (PZC), which helps describe surface charge behaviors of zeolites at a given solution pH [84]. PZC defines the pH at which the surface carries zero net charge, making the transition between positively and negatively charged surface states. For instance, PZC values of clinoptilolite and NaX were determined to be 9.2 and 10.2 [43], respectively, while NaA had that of 4.2 [60].

When solution pH is below the PZC of zeolites (typically at low-pH conditions), surface hydroxyl groups of (Si-OH and Al-OH) of zeolites become protonated and H⁺ competes with Li⁺ for negatively charged framework sites, decreasing the number of available exchange sites for Li and resulting in reduced Li uptake capacity. This effect is especially pronounced for low-SAR zeolites that possess high-cation exchange capacities for Li recovery [44,60]. However, a strongly acidic (e.g., pH < 2) environment causes dealumination of zeolites, losing ion-exchangeable sites for Li recovery [44,85].

At solution pH above the PZC of zeolites (typically at high-pH conditions), deprotonation increases negative charge density on the zeolite surface, thereby enhancing the electrostatic attraction of Li⁺ ions, facilitating their diffusion toward and into zeolite pores, and boosting Li⁺ adsorption on exchange sites within zeolites [43,52,84,86]. However, highly basic solutions (e.g., pH > 12) generate framework instability issues, i.e., desilication through hydrolysis of Si-O-Si bonds of the zeolite framework [85,87], as revealed by prior reports on Li recovery from geothermal brine using zeolite 13X [44,46].

Solution pH also regulates Li recovery by modulating competitive ion behavior. Although Li^+ retains a strongly bound hydration shell across a wide pH range, competing multivalent ions (e.g., Mg^{2+} and Ca^{2+}) undergo pH-dependent hydrolysis and partial de-hydration behavior. Under neutral to mildly alkaline conditions (i.e., pH 8–10), Mg^{2+} and Ca^{2+} ions begin forming hydrolyzed species or surface complexes [88], reducing their effective mobility and thereby making Li^+ exchange kinetically more favored, as evidenced by Wang et al. using SOD zeolites in the selective Li^+ extraction from low-quality brines [53].

Solution pH, when paired with suitable desorption agents, can significantly influence Li^+ release from Li-saturated zeolites. Zeolite 13X after Li^+ uptake was employed to assess the desorption behavior using NaCl, CH_3COONa , HCl, and CH_3COOH , enabling Li^+ removal through ion-exchange between Li^+ and Na^+ , and between Li^+ and H^+ (Table 6) [44]. Acidic solutions (i.e., either 0.1–1 M HCl or 0.1–1 M CH_3COOH) achieved 100% desorption, but caused detectable leaching of Al atoms from zeolites, raising concerns about framework stability. In contrast, either 1 M NaCl or 1 M CH_3COONa solution revealed high desorption efficiencies (94–100%), while maintaining structural stability. Although reusability was not evaluated in this work, the results clearly highlight the critical role of pH and regenerant selection in designing long-term zeolite durability for Li^+ adsorption–desorption. By contrast, acidic conditions with 0.5 M HCl were employed for regenerating nanofiber-containing zeolites with CE ligands for Li recovery from salt lake brines (Table 6) [47]. The hybrid adsorbent exhibited a Li uptake capacity of 7.8 mg g^{-1} after five adsorption–desorption cycles, compared to an initial capacity of 8.6 mg g^{-1} at optimal pH 6 conditions. The underlying cause of this performance decline was not discussed, the identity of the zeolite supports was not specified, and adsorbent stability was not evaluated. Nevertheless, the high degree of capacity retention shows promising reusability for Li extraction from salt lake brine.

4. Limitations and Opportunities for Future Research

Despite notable progress in the development of zeolite-based adsorbents for recovering Li from sustainable resources, several key limitations persist. These challenges simultaneously define promising directions for future investigation and technology development (Figure 6), as detailed below.

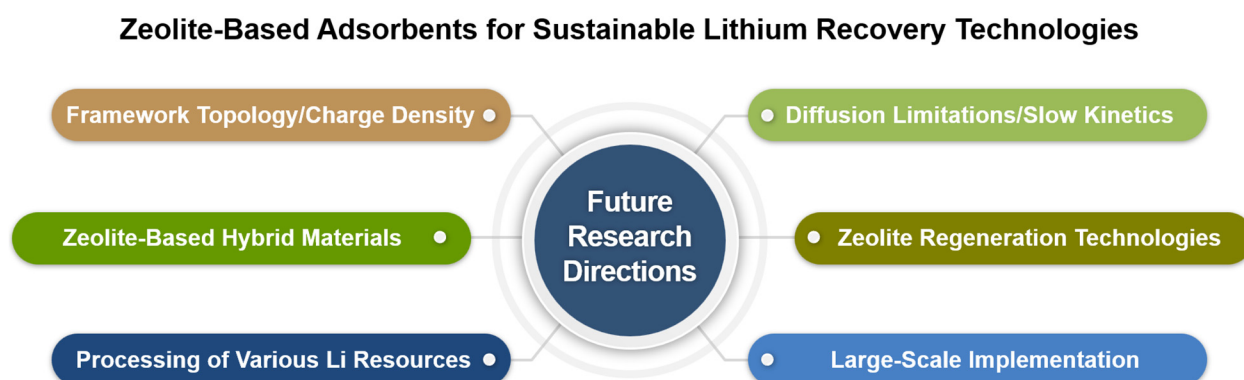


Figure 6. Future research directions focused on advancing and optimizing the design of zeolite-based adsorption processes for sustainable lithium recovery.

Zeolite framework topology and charge density are key players of Li adsorption capacity and selectivity, and its transport behavior. Yet, despite the existence of more than 240 distinct zeolite frameworks and the tunability of SAR and extra-framework cations [89], their impacts on Li recovery performance remain largely underexplored. Natural ze-

olites offer advantages of low cost and widespread availability [66], but their inherent heterogeneity (including variations in SAR, extra-framework cation composition, and framework topology, and the presence of impurity minerals) can substantially influence Li^+ adsorption performance. However, these effects remain poorly understood, and need to be elucidated to enable the effective use of natural zeolites in future Li recovery applications. For synthetic zeolites, zeolite framework topology and charge density can be rationally designed using synthetic approaches outlined in Section 2.2 (Figure 4). This strategic optimization of these structural and compositional variables would drastically improve Li^+ ion-exchange performance of zeolites. To advance this effort, integrating machine learning-driven screening with high-fidelity simulations [90,91] and experimental validation represents a promising route for rapidly identifying zeolite structures with favorable charge environments for Li extraction.

Diffusion limitations and slow kinetics should be addressed. Zeolite frameworks with micropore channels (<2 nm) can restrict ion transport and prolong equilibrium times. Diffusion limitations become particularly significant in larger zeolite crystals and pelletized adsorbents, where Li^+ ions must travel longer distances to access exchange sites. Future efforts can be directed toward exploring nano-sized zeolites, hierarchical zeolites with dual micro- and meso-pores (>2 nm), or zeolites with open architecture (e.g., zeolite nanosheets or layered zeolites) via controlled zeolite synthesis (Figure 4) to improve mass transport [69,78,79,87,92], while maintaining ion-exchange capability. In parallel, it is noteworthy that in real-world Li recovery systems, the use of finely divided particles complicates solid–liquid separation in batch processes, and fixed beds packed with very small particles suffer from excessive flow resistance, pressure-drop penalties, and diminished mechanical stability during continuous operation. Therefore, designing zeolite particle morphology (size and shape) should strike a balance between rapid ion transport and the practical requirements of system operation.

Designing zeolite-based hybrid materials could create synergistic effects for Li recovery beyond what zeolites can achieve alone. By integrating zeolites with complementary components such as metal oxides (including existing LIS materials), carbons, or polymer networks, hybrid adsorbents can simultaneously improve adsorption affinity, mass-transfer kinetics, mechanical robustness, and regeneration efficiency. Although these advantages have been demonstrated in the previous section, the design space for zeolite-based hybrid architecture is still in its infancy. This research gap offers a promising avenue for future research aimed at engineering interfacial interactions, composite architecture, and multi-scale porosity to maximize Li^+ selectivity, capacity, and cycling stability.

Zeolites are generally considered regenerable materials, according to extensive prior studies on zeolites in ion-exchange, catalysis and separation applications [64,67]. However, only a limited number of reports are available for Li adsorption–desorption performance over extended cycles. This scarcity of long-term cycling data highlights important research opportunities. Future research studies should focus on long-term cyclic testing (including standardized testing protocols), evaluation of structural stability, and identification of optimal Li^+ desorption conditions through operational parameters such as temperature, solution pH, and desorption agents (e.g., NaCl, and Na_2SO_4). It is also crucial to rigorously investigate extra-framework cation redistribution, framework degradation (e.g., leaching), fouling, or loss of active ion-exchange sites during repeated regeneration, particularly when processing real complex brines that contain organic matter, silica, and suspended solids. For such challenging feed streams, appropriate pretreatment steps can be integrated upstream of zeolite-based Li recovery to remove foulants and impurities. In this respect, techno-economic analysis (TEA) provides valuable insight into how regeneration, pretreatment, and long-term stability can be engineered to become economically viable at scale [93,94]. Moreover, lifecycle analysis (LCA) identifies where environmental

burdens occur (e.g., waste generation during adsorbent regeneration, pretreatment steps that minimize waste, and process configurations with the lowest environmental footprint), and how to effectively minimize these impacts [93,94]. Thus, developing cost-effective and environmentally benign regeneration strategies will be pivotal for translating zeolite-based Li recovery into practical industrial deployment.

Different Li sources pose distinct challenges for zeolite adsorbents to overcome. Specifically, salt lake brines contain high Li concentrations (200–7000 mg L⁻¹), but some of them are characterized by high Mg/Li molar ratios of > 200, making Li separation highly challenging [11,38,40,45]. Geothermal brines have moderate Li concentrations (10–300 mg L⁻¹) with elevated temperatures that enhance kinetics but introduce scaling from Ca²⁺ or Si species and volatile contaminants [12,20]. Oil- and gas-produced waters with low Li content (1–100 mg L⁻¹) present the most demanding conditions, owing to ultra-high salinity, hydrocarbon fouling, heavy metals, suspended solids, and variable compositions across reservoirs requiring site-specific pretreatment [95,96]. Battery leachates differ substantially from natural or geothermal brines, containing high concentrations of transition metals (Co²⁺, Ni²⁺, and Mn²⁺), Al³⁺, Fe³⁺, and residual organics that compete with Li⁺ for ion-exchange sites and may block zeolite pores [16,17]. Therefore, zeolite-based adsorbents should be engineered to withstand complex Li-bearing water matrices, reject multiple competing cations to achieve high Li selectivity over competing cations, and maintain pore accessibility in the presence of organic and inorganic foulants.

A significant gap persists between laboratory-scale batch adsorption studies and the process designs required for the large-scale implementation of zeolite-based Li recovery. Continuous-flow adsorption processes are generally preferred at large-scale operation in industry. Although zeolite-based adsorption in flow configurations has been widely studied, continuous-flow studies for zeolite-based Li recovery have not yet been reported, and thus the corresponding performance effects and scale-up challenges remain unresolved. This limited attention devoted to continuous-flow operation creates new opportunities to address critical scale-up challenges, including zeolite adsorbent shaping, pressure drop, mass transfer limitations, column design, regeneration strategies, and integration with existing Li recovery infrastructure and technologies (e.g., solvent extraction or membrane-based recovery). Beyond engineering considerations, successful large-scale implementation will ultimately depend on demonstrating both economic viability and environmental sustainability. Therefore, future research should incorporate comprehensive TEA and LCA to evaluate capital and operating costs, zeolite-based adsorbent lifetime and regeneration, chemical and energy consumption, waste generation, greenhouse gas emissions, and resource efficiency. Such system-level assessments will be essential for identifying economically competitive and environmentally sustainable process configurations, thereby accelerating the commercial deployment of zeolite-based Li recovery technologies.

5. Conclusions

With global Li demand rising exponentially, the development of Li recovery technologies capable of accessing non-conventional resources, including salt lakes, geothermal brines, seawater, spent battery leachates, and industrially produced water, has become increasingly urgent. Zeolite-based adsorption offers strong potential for these applications, owing to the exceptional thermal and chemical stability of zeolites, and their well-defined porous architectures, tunable framework charge density and particle morphology, compared with other LIS adsorbents. In this review, we aim to provide the first focused and comprehensive review of zeolite-based adsorbents for sustainable Li recovery, which is intended to catalyze future developments among researchers in academic and industrial research communities. We systematically analyze the progress of zeolite-based Li recovery from sustainable, non-traditional sources, and delineate the five guiding design

principles that govern Li uptake performance of zeolites: (i) framework charge density, (ii) framework topology and pore architecture, (iii) particle morphology, (iv) integration of zeolites with other materials, and (v) key operational design parameters, e.g., temperature and solution pH. These design principles provide a comprehensive platform for understanding the relationships between zeolite structure and properties, adsorption mechanisms, and Li recovery performance, ultimately delivering key guidance for the rational design of next-generation zeolite adsorbents. Although notable progress has been made, zeolite-based Li capture is still in early development, and multiple scientific and engineering challenges must be overcome. Specifically, over the next 3–5 years, research should focus on several key research priorities. First, highly Li-selective zeolites should be developed by precisely tuning framework composition, pore architecture, extra-framework cations, and surface chemistry to enhance Li adsorption capacity and Li/Mg selectivity across diverse, non-conventional Li-containing resources. Second, systematic investigations of long-term adsorption–desorption cycling, regeneration strategies, framework stability, and fouling mechanisms are needed to ensure operational durability and minimize lifecycle costs. Lastly, adsorption performance should be validated using real brines under continuous-flow operation to establish process reliability under industrially relevant conditions. In this context, TEA and LCA will be essential for evaluating adsorbent manufacturing cost, energy consumption, chemical usage, environmental footprint, and overall process scalability. Consequently, continued interdisciplinary research integrating zeolite chemistry, adsorption science and engineering, process design, and sustainability assessment will enable zeolite-based technologies to mature into scalable, resilient, economically viable, and sustainable solutions for next-generation Li recovery.

Author Contributions: Conceptualization, H.J.C.; Methodology, M.R.K. and H.J.C.; Formal Analysis, M.R.K. and H.J.C.; Investigation, M.R.K. and H.J.C.; Data Curation, M.R.K. and H.J.C.; Validation, M.R.K. and H.J.C.; Visualization, H.J.C.; Supervision, H.J.C.; Project Administration, H.J.C.; Funding Acquisition, H.J.C.; Writing—Original Draft Preparation, M.R.K. and H.J.C.; Writing—Review and Editing, H.J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the division of the vice president for research and the College of Engineering, Architecture and Technology at Oklahoma State University.

Institutional Review Board Statements: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this work are included in the article. No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xu, J.; Wei, X.; Han, J.; Qin, W. Synthesis and Optimisation Mechanism of Functionalised Adsorption Materials for Lithium-Ion Extraction from Salt Water: A Review. *Sep. Purif. Technol.* **2024**, *339*, 126237. <https://doi.org/10.1016/j.seppur.2023.126237>.
2. Yu, H.; Naidu, G.; Zhang, C.; Wang, C.; Razmjou, A.; Han, D.S.; He, T.; Shon, H. Metal-Based Adsorbents for Lithium Recovery from Aqueous Resources. *Desalination* **2022**, *539*, 115951. <https://doi.org/10.1016/j.desal.2022.115951>.
3. Hu, H.; Guo, X.; Yang, L.; Wu, Y.; Yang, G.; Luo, X. Adsorption Materials toward Highly-Efficient Lithium Extraction from Non-Conventional Lithium Sources. *Adv. Mater.* **2025**, *37*, 2506055. <https://doi.org/10.1002/adma.202506055>.
4. 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. <https://doi.org/10.1080/08827508.2022.2047041>.

5. Miatto, A.; Wolfram, P.; Reck, B.K.; Graedel, T.E. Uncertain Future of American Lithium: A Perspective until 2050. *Environ. Sci. Technol.* **2021**, *55*, 16184–16194. <https://doi.org/10.1021/acs.est.1c03562>.
6. Lithium Statistics and Information | U.S. Geological Survey. Available online: <https://www.usgs.gov/centers/national-minerals-information-center/lithium-statistics-and-information> (accessed on 21 June 2026).
7. 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.
8. Pan, S.-Y.; Haddad, A.Z.; Kumar, A.; Wang, S.-W. Brackish Water Desalination Using Reverse Osmosis and Capacitive Deionization at the Water-Energy Nexus. *Water Res.* **2020**, *183*, 116064.
9. Kumar, A.; Fukuda, H.; Hatton, T.A.; Lienhard, J.H. Lithium Recovery from Oil and Gas Produced Water: A Need for a Growing Energy Industry. *ACS Energy Lett.* **2019**, *4*, 1471–1474. <https://doi.org/10.1021/acsenergylett.9b00779>.
10. Munk, L.A.; Hynek, S.A.; Bradley, D.C.; Boutt, D.; Labay, K.; Jochens, H. *Lithium Brines: A Global Perspective*; Society of Economic Geologists: Littleton, CO, USA, 2016.
11. Yang, S.; Wang, Y.; Pan, H.; He, P.; Zhou, H. Lithium Extraction from Low-Quality Brines. *Nature* **2024**, *636*, 309–321. <https://doi.org/10.1038/s41586-024-08117-1>.
12. Stringfellow, W.T.; Dobson, P.F. Technology for the Recovery of Lithium from Geothermal Brines. *Energies* **2021**, *14*, 6805. <https://doi.org/10.3390/en14206805>.
13. Wu, F.; Shivakumar, K.R.; Konhauser, K.O.; Alessi, D.S. Lithium Resources and Novel Strategies for Their Extraction and Purification. *Npj Mater. Sustain.* **2025**, *3*, 30.
14. Kumar, A.; Naidu, G.; Fukuda, H.; Du, F.; Vigneswaran, S.; Drioli, E.; Lienhard, J.H. Metals Recovery from Seawater Desalination Brines: Technologies, Opportunities, and Challenges. *ACS Sustain. Chem. Eng.* **2021**, *9*, 7704–7712. <https://doi.org/10.1021/acssuschemeng.1c00785>.
15. Liu, C.; Lin, J.; Cao, H.; Zhang, Y.; Sun, Z. Recycling of Spent Lithium-Ion Batteries in View of Lithium Recovery: A Critical Review. *J. Clean. Prod.* **2019**, *228*, 801–813.
16. Krishnan, M.R.; Alsharaeh, E.H. Ion-Sieve Adsorbents for Lithium Recovery from Battery Leachates: Separation Performance and Process Limitations. *Sep. Purif. Technol.* **2026**, *394*, 137606.
17. Shi, H.; Zhang, J.; Ou, L. A Comprehensive Review on the Separation and Purification of Valuable Metals from the Leachate of Spent Lithium-Ion Batteries. *Sep. Purif. Technol.* **2025**, *360*, 130847.
18. Alera, A.C.; Benitez, J.P.; Fernandez, R.J.; Pascual, C.K.; Policarpio, F.; Lopez, E.C.R. Recent Advances in Lithium Extraction. *Eng. Proc.* **2024**, *67*, 52. <https://doi.org/10.3390/engproc2024067052>.
19. Mittal, H.; Shah, S.N.; Alsuwaidi, M.; Alfantazi, A. Lithium Recovery from Brines: A Comprehensive Review of Advanced Separation Technologies. *Precis. Chem.* **2026**, prechem.5c00264. <https://doi.org/10.1021/prechem.5c00264>.
20. Flexer, V.; Baspineiro, C.F.; Galli, C.I. Lithium Recovery from Brines: A Vital Raw Material for Green Energies with a Potential Environmental Impact in Its Mining and Processing. *Sci. Total Environ.* **2018**, *639*, 1188–1204. <https://doi.org/10.1016/j.scitotenv.2018.05.223>.
21. Sun, S.-Y.; Song, X.; Zhang, Q.-H.; Wang, J.; Yu, J.-G. Lithium Extraction/Insertion Process on Cubic Li-Mn-O Precursors with Different Li/Mn Ratio and Morphology. *Adsorption* **2011**, *17*, 881–887. <https://doi.org/10.1007/s10450-011-9356-0>.
22. Zhang, Q.-H.; Sun, S.; Li, S.; Jiang, H.; Yu, J.-G. Adsorption of Lithium Ions on Novel Nanocrystal MnO₂. *Chem. Eng. Sci.* **2007**, *62*, 4869–4874. <https://doi.org/10.1016/j.ces.2007.01.016>.
23. Liu, L.; Zhang, H.; Zhang, Y.; Cao, D.; Zhao, X. Lithium Extraction from Seawater by Manganese Oxide Ion Sieve MnO₂·0.5H₂O. *Colloids Surf. A Physicochem. Eng. Asp.* **2015**, *468*, 280–284. <https://doi.org/10.1016/j.colsurfa.2014.12.025>.
24. Ma, L.-W.; Chen, B.-Z.; Shi, X.-C.; Zhang, W.; Zhang, K. Stability and Li⁺ Extraction/Adsorption Properties of LiM_xMn_{2-x}O₄ (M = Ni, Al, Ti; 0 ≤ x ≤ 1) in Aqueous Solution. *Colloids Surf. A Physicochem. Eng. Asp.* **2010**, *369*, 88–94. <https://doi.org/10.1016/j.colsurfa.2010.08.016>.
25. Zheng, B.; Zeng, G.; Zhou, K.; Wu, L.; Zheng, Y. Stable Granular Li₄Mn₅O₁₂ Synthesized by Ammonia-Assisted Co-Precipitation: Achieving Minimal Mn Dissolution for Efficient Lithium Recovery from Low-Grade Brine. *J. Environ. Chem. Eng.* **2025**, *13*, 119129. <https://doi.org/10.1016/j.jece.2025.119129>.
26. Song, L.; Liu, M.; Nian, M.; Yang, G. Preparation of HMn₂O₄ Lithium-Ion Sieves with Low Manganese Dissolution Loss for Improved Cycling Stability. *RSC Adv.* **2024**, *14*, 19795–19805.
27. Ding, Y.; Nhung, N.T.H.; An, J.; Chen, H.; Liao, L.; He, C.; Wang, X.; Fujita, T. Manganese-Titanium Mixed Ion Sieves for the Selective Adsorption of Lithium Ions from an Artificial Salt Lake Brine. *Materials* **2023**, *16*, 4190. <https://doi.org/10.3390/ma16114190>.

28. Zhang, Q.-H.; Li, S.-P.; Sun, S.-Y.; Yin, X.-S.; Yu, J.-G. Lithium Selective Adsorption on Low-Dimensional Titania Nanoribbons. *Chem. Eng. Sci.* **2010**, *65*, 165–168. <https://doi.org/10.1016/j.ces.2009.06.001>.
29. Liu, J.; Zhang, Y.; Miao, Y.; Yang, Y.; Li, P. Alkaline Resins Enhancing Li^+/H^+ Ion Exchange for Lithium Recovery from Brines Using Granular Titanium-Type Lithium Ion-Sieves. *Ind. Eng. Chem. Res.* **2021**, *60*, 16457–16468. <https://doi.org/10.1021/acs.iecr.1c02361>.
30. Li, N.; Lu, D.; Zhang, J.; Wang, L. Yolk-Shell Structured Composite for Fast and Selective Lithium Ion Sieving. *J. Colloid Interface Sci.* **2018**, *520*, 33–40. <https://doi.org/10.1016/j.jcis.2018.02.031>.
31. Moazeni, M.; Hajipour, H.; Askari, M.; Nusheh, M. Hydrothermal Synthesis and Characterization of Titanium Dioxide Nanotubes as Novel Lithium Adsorbents. *Mater. Res. Bull.* **2015**, *61*, 70–75. <https://doi.org/10.1016/j.materresbull.2014.09.069>.
32. Liu, J.; Xu, N.-C.; Shi, D.-D.; Cao, Y.; Zhang, T.-Y.; Zhong, K.-P.; Zhao, Q.; Bian, S.-J. Preparation, Characterization, and Adsorption Performance of H_2TiO_3 Lithium Ion Sieves with Homogeneous Nanoparticles: Kinetics, Thermodynamics, and Mechanism Analysis. *ChemistrySelect* **2024**, *9*, e202402440. <https://doi.org/10.1002/slct.202402440>.
33. Xiong, S.; Lu, H.; Tang, K.; Yang, J.; Yang, C.; Shi, L.; Jiang, J.; Tang, A. First Granulation of $\text{H}_4\text{Ti}_5\text{O}_{12}$ Lithium-Ion Sieve Using Two Different Binders for Selective Lithium Extraction. *Ind. Eng. Chem. Res.* **2025**, *64*, 18904–18916. <https://doi.org/10.1021/acs.iecr.5c02340>.
34. Wang, Q.; Yang, X.; Li, C.; Zhao, C.; Huang, Y.; Qiu, S.; Qin, Y.; Shi, C. Titanium-Based Lithium Ion Sieve Adsorbent H_2TiO_3 with Enhanced Li^+ Adsorption Properties by Magnetic Fe Doping. *Sep. Purif. Technol.* **2024**, *346*, 127455. <https://doi.org/10.1016/j.seppur.2024.127455>.
35. Zhong, J.; Lin, S.; Yu, J. Li^+ Adsorption Performance and Mechanism Using Lithium/Aluminum Layered Double Hydroxides in Low Grade Brines. *Desalination* **2021**, *505*, 114983. <https://doi.org/10.1016/j.desal.2021.114983>.
36. Chen, J.; Lin, S.; Yu, J. High-Selective Cyclic Adsorption and Magnetic Recovery Performance of Magnetic Lithium-Aluminum Layered Double Hydroxides (MLDHs) in Extracting Li^+ from Ultrahigh Mg/Li Ratio Brines. *Sep. Purif. Technol.* **2021**, *255*, 117710. <https://doi.org/10.1016/j.seppur.2020.117710>.
37. Li, Y.; Tang, N.; Zhang, L.; Li, J. Fabrication of Fe-Doped Lithium-Aluminum-Layered Hydroxide Chloride with Enhanced Reusable Stability Inspired by Computational Theory and Its Application in Lithium Extraction. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *658*, 130641. <https://doi.org/10.1016/j.colsurfa.2022.130641>.
38. Zhang, L.; Zhang, T.; Zhao, Y.; Dong, G.; Lv, S.; Ma, S.; Song, S.; Quintana, M. Doping Engineering of Lithium-Aluminum Layered Double Hydroxides for High-Efficiency Lithium Extraction from Salt Lake Brines. *Nano Res.* **2024**, *17*, 1646–1654. <https://doi.org/10.1007/s12274-023-5950-1>.
39. Zhang, L.; Li, Y.; Qiao, X.; Li, R.; Li, T.; Cheng, P.; Zhang, J.; Tang, N. Carbonate-Intercalated Aluminum Layered Double Hydroxide for High-Capacity Lithium Extraction. *Desalination* **2025**, *615*, 119307. <https://doi.org/10.1016/j.desal.2025.119307>.
40. Zia, S.; Kashif, M.; Ge, H.; Zhao, K.; Guo, Y.; Deng, T. Advanced PDMS@Li/ZnAl-LDH Microspheres for Lithium Recovery from Qarhan Salt Lake Brine with High Mg/Li Disparity. *Desalination* **2025**, *615*, 119286. <https://doi.org/10.1016/j.desal.2025.119286>.
41. Grifasi, N.; Ziantoni, B.; Fino, D.; Piumetti, M. Fundamental Properties and Sustainable Applications of the Natural Zeolite Clinoptilolite. *Environ. Sci. Pollut. Res. Int.* **2025**, *32*, 27805–27840. <https://doi.org/10.1007/s11356-024-33656-5>.
42. Baile, P.; Fernández, E.; Vidal, L.; Canals, A. Zeolites and Zeolite-Based Materials in Extraction and Microextraction Techniques. *Analyst* **2019**, *144*, 366–387.
43. Wiśniewska, M.; Fijałkowska, G.; Ostolska, I.; Franus, W.; Nosal-Wiercińska, A.; Tomaszewska, B.; Goscianska, J.; Wójcik, G. Investigations of the Possibility of Lithium Acquisition from Geothermal Water Using Natural and Synthetic Zeolites Applying Poly(Acrylic Acid). *J. Clean. Prod.* **2018**, *195*, 821–830. <https://doi.org/10.1016/j.jclepro.2018.05.287>.
44. Reich, R.; Danisi, R.M.; Kluge, T.; Eiche, E.; Kolb, J. Structural and Compositional Variation of Zeolite 13X in Lithium Sorption Experiments Using Synthetic Solutions and Geothermal Brine. *Microporous Mesoporous Mater.* **2023**, *359*, 112623. <https://doi.org/10.1016/j.micromeso.2023.112623>.
45. Fang, D.; Suo, S.; Fu, D.; Liang, K.; Qiao, J.; Song, Z. An Aluminum-Based Adsorbent/Zeolite Molecular Sieve Composite for the Sorption of Lithium in the Salt Lake. *RSC Adv.* **2025**, *15*, 29089–29096. <https://doi.org/10.1039/D5RA05236J>.
46. Koza, M.; Mukti, M.; Tomaszewska, B. Zeolite-Hydrogel Composites for Lithium and Arsenic Extraction from Geothermal Waters. *Arch. Environ. Prot.* **2026**, *52*, 16–27.
47. Ding, T.; Zheng, M.; Peng, S.; Nie, Z.; Lin, Y.; Wu, Q. Recovery of Lithium Ions From Salt Lakes Using Nanofibers Containing Zeolite Carriers. *Front. Energy Res.* **2022**, *10*, 895681. <https://doi.org/10.3389/fenrg.2022.895681>.
48. Ofiera, L.M.; Kazner, C. Influence of Ammonium on the Adsorption and Desorption of Heavy Metals in Natural Zeolites. *Processes* **2025**, *13*, 2647. <https://doi.org/10.3390/pr13082647>.

49. Cho, H.J.; Xu, B. Enabling Selective Tandem Reactions via Catalyst Architecture Engineering. *Trends Chem.* **2020**, *2*, 929–941.
50. Vermeiren, W.; Gilson, J.P. Impact of Zeolites on the Petroleum and Petrochemical Industry. *Top. Catal.* **2009**, *52*, 1131–1161. <https://doi.org/10.1007/s11244-009-9271-8>.
51. Kumari, S.; Chowdhry, J.; Kumar, M.; Garg, M.C. Zeolites in Wastewater Treatment: A Comprehensive Review on Scientometric Analysis, Adsorption Mechanisms, and Future Prospects. *Environ. Res.* **2024**, *260*, 119782.
52. Hoyer, M.; Kummer, N.-A.; Merkel, B. Sorption of Lithium on Bentonite, Kaolin and Zeolite. *Geosciences* **2015**, *5*, 127–140. <https://doi.org/10.3390/geosciences5020127>.
53. Wang, J.; Hao, Y.; Li, J.; Yang, J. Precise Li^+ and Mg^{2+} Separation Enabled by Sodalite Ion Exchange Contribute to the Lithium Extraction from Low-Quality Brines. *J. Hazard. Mater.* **2025**, *498*, 139942. <https://doi.org/10.1016/j.jhazmat.2025.139942>.
54. Conte, N.; Gómez, J.M.; Díez, E.; Sáez, P.; Monago, J.I.; Espinosa, A.; Rodríguez, A. Sequential Separation of Cobalt and Lithium by Sorption: Sorbent Set Selection. *Sep. Purif. Technol.* **2022**, *303*, 122199. <https://doi.org/10.1016/j.seppur.2022.122199>.
55. Díez, E.; Redondo, C.; Gómez, J.M.; Miranda, R.; Rodríguez, A. Zeolite Adsorbents for Selective Removal of Co(II) and Li(I) from Aqueous Solutions. *Water* **2023**, *15*, 270. <https://doi.org/10.3390/w15020270>.
56. Wang, J.; Hao, Y.; Li, J.; Yang, J. Priority Extraction of Li^+ and Sequential Recovery of Divalent Metals from Retired $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ Batteries Using GIS Zeolite. *ACS Sustain. Chem. Eng.* **2025**, *13*, 6113–6120. <https://doi.org/10.1021/acssuschemeng.4c09995>.
57. Zhang, H.; Wang, N.; Li, T.; Zeng, L.; Kang, Q.; Tao, L.; Xu, F.; Yang, C.; Li, H.; Liu, C. Transformation of Small Pore Sized Zeolite from Universal Silicates and Its Potential for Lithium Extraction. *Silicon* **2025**, *17*, 3469–3480. <https://doi.org/10.1007/s12633-025-03423-3>.
58. Navarrete-Casas, R.; Navarrete-Guijosa, A.; Valenzuela-Calahorra, C.; López-González, J.D.; García-Rodríguez, A. Study of Lithium Ion Exchange by Two Synthetic Zeolites: Kinetics and Equilibrium. *J. Colloid Interface Sci.* **2007**, *306*, 345–353. <https://doi.org/10.1016/j.jcis.2006.10.002>.
59. Wang, J.; Huo, X.; Zhang, F.; Wang, L.; Wang, X.; Li, J.; Yang, J. Separation of Cobalt and Lithium from Spent LiCoO_2 Batteries Using Zeolite NaA and the Resulting Ion Exchange Product for N_2/O_2 Separation. *Sep. Purif. Technol.* **2023**, *313*, 123449. <https://doi.org/10.1016/j.seppur.2023.123449>.
60. Cheng, Q.; Wang, Y.; Liu, X.; Zhang, W.; Gao, P. Preferential Lithium Recovery and Temperature-Regulated Stepwise Desorption of Transition Metals from Simulated Spent NCM111 Leachate Using NaA Zeolite. *Separations* **2026**, *13*, 132. <https://doi.org/10.3390/separations13050132>.
61. Huo, X.; Wang, J.; Tang, X.; Li, J.; Yang, J. Stepwise Separation and Recovery of Metal Ions from Waste $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ Batteries Using a NaA Zeolite. *ACS Sustain. Resour. Manage.* **2024**, *1*, 970–977. <https://doi.org/10.1021/acssusresmgmt.4c00034>.
62. Cundy, C.S.; Cox, P.A. The Hydrothermal Synthesis of Zeolites: Precursors, Intermediates and Reaction Mechanism. *Microporous Mesoporous Mater.* **2005**, *82*, 1–78. <https://doi.org/10.1016/j.micromeso.2005.02.016>.
63. Database of Zeolite Structures. Available online: <https://www.iza-structure.org/databases/> (accessed on 21 June 2026).
64. Cejka, J.; Corma, A.; Zones, S. *Zeolites and Catalysis: Synthesis, Reactions and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
65. Wang, S.; Peng, Y. Natural Zeolites as Effective Adsorbents in Water and Wastewater Treatment. *Chem. Eng. J.* **2010**, *156*, 11–24. <https://doi.org/10.1016/j.cej.2009.10.029>.
66. Kuldeyev, E.; Seitzhanova, M.; Tanirbergenova, S.; Tazhu, K.; Doszhanov, E.; Mansurov, Z.; Azat, S.; Nurlybaev, R.; Berndtsson, R. Modifying Natural Zeolites to Improve Heavy Metal Adsorption. *Water* **2023**, *15*, 2215. <https://doi.org/10.3390/w15122215>.
67. Khaleque, A.; Alam, M.M.; Hoque, M.; Mondal, S.; Haider, J.B.; Xu, B.; Johir, M.A.H.; Karmakar, A.K.; Zhou, J.L.; Ahmed, M.B. Zeolite Synthesis from Low-Cost Materials and Environmental Applications: A Review. *Environ. Adv.* **2020**, *2*, 100019.
68. Iyoki, K.; Itabashi, K.; Okubo, T. Progress in Seed-Assisted Synthesis of Zeolites without Using Organic Structure-Directing Agents. *Microporous Mesoporous Mater.* **2014**, *189*, 22–30.
69. Liu, S.; Cheng, Z.; Li, B.; Zeng, H.; Liang, W.; Luo, Y.; Bai, Y.; Gao, H.; Pan, X.; Shu, X. Recent Advances in Biomass-Assisted Synthesis of Hierarchical Porous Zeolite. *Mater. Today Sustain.* **2024**, *27*, 100917.
70. Tansel, B. Significance of Thermodynamic and Physical Characteristics on Permeation of Ions during Membrane Separation: Hydrated Radius, Hydration Free Energy and Viscous Effects. *Sep. Purif. Technol.* **2012**, *86*, 119–126. <https://doi.org/10.1016/j.seppur.2011.10.033>.
71. Marcus, Y. Thermodynamics of Solvation of Ions. Part 5.—Gibbs Free Energy of Hydration at 298.15 K. *J. Chem. Soc. Faraday Trans.* **1991**, *87*, 2995–2999. <https://doi.org/10.1039/FT9918702995>.
72. Marcus, Y. Effect of Ions on the Structure of Water: Structure Making and Breaking. *Chem. Rev.* **2009**, *109*, 1346–1370. <https://doi.org/10.1021/cr8003828>.

73. Yang, Z.-H. The Size and Structure of Selected Hydrated Ions and Implications for Ion Channel Selectivity. *RSC Adv.* **2015**, *5*, 1213–1219.
74. Mountain, R.D. Solvation Structure of Ions in Water. *Int. J. Thermophys.* **2007**, *28*, 536–543. <https://doi.org/10.1007/s10765-007-0154-6>.
75. Shi, Y.; Beck, T.L. Absolute Ion Hydration Free Energy Scale and the Surface Potential of Water via Quantum Simulation. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 30151–30158. <https://doi.org/10.1073/pnas.2017214117>.
76. Mon, J.; Deng, Y.; Flury, M.; Harsh, J.B. Cesium Incorporation and Diffusion in Cancrinite, Sodalite, Zeolite, and Allophane. *Microporous Mesoporous Mater.* **2005**, *86*, 277–286. <https://doi.org/10.1016/j.micromeso.2005.07.030>.
77. Chukanov, N.V.; Vigasina, M.F.; Shendrik, R.Y.; Varlamov, D.A.; Pekov, I.V.; Zubkova, N.V. Nature and Isomorphism of Extra-Framework Components in Cancrinite- and Sodalite-Related Minerals: New Data. *Minerals* **2022**, *12*, 729. <https://doi.org/10.3390/min12060729>.
78. Jeon, M.Y.; Kim, D.; Kumar, P.; Lee, P.S.; Rangnekar, N.; Bai, P.; Shete, M.; Elyassi, B.; Lee, H.S.; Narasimharao, K. Ultra-Selective High-Flux Membranes from Directly Synthesized Zeolite Nanosheets. *Nature* **2017**, *543*, 690–694.
79. Roth, W.J.; Nachtigall, P.; Morris, R.E.; Čejka, J. Two-Dimensional Zeolites: Current Status and Perspectives. *Chem. Rev.* **2014**, *114*, 4807–4837. <https://doi.org/10.1021/cr400600f>.
80. Li, S.; Li, J.; Dong, M.; Fan, S.; Zhao, T.; Wang, J.; Fan, W. Strategies to Control Zeolite Particle Morphology. *Chem. Soc. Rev.* **2019**, *48*, 885–907.
81. Górka, A.; Bochenek, R.; Warchoń, J.; Kaczmarek, K.; Antos, D. Ion Exchange Kinetics in Removal of Small Ions. Effect of Salt Concentration on Inter- and Intraparticle Diffusion. *Chem. Eng. Sci.* **2008**, *63*, 637–650. <https://doi.org/10.1016/j.ces.2007.10.006>.
82. Nuić, I.; Trgo, M.; Vukojević Medvidović, N.; Ugrina, M. A Mass Transfer Analysis of Competitive Binding of Pb, Cd, and Zn from Binary Systems onto a Fixed Zeolite Bed. *Int. J. Environ. Res. Public Health* **2019**, *16*, 426. <https://doi.org/10.3390/ijerph16030426>.
83. Wen, D.; Ho, Y.-S.; Tang, X. Comparative Sorption Kinetic Studies of Ammonium onto Zeolite. *J. Hazard. Mater.* **2006**, *133*, 252–256. <https://doi.org/10.1016/j.jhazmat.2005.10.020>.
84. Kosmulski, M. *Surface Charging and Points of Zero Charge*; CRC Press: Boca Raton, FL, USA, 2009.
85. Silaghi, M.-C.; Chizallet, C.; Raybaud, P. Challenges on Molecular Aspects of Dealumination and Desilication of Zeolites. *Microporous Mesoporous Mater.* **2014**, *191*, 82–96.
86. Sprynskyy, M.; Buszewski, B.; Terzyk, A.P.; Namieśnik, J. Study of the Selection Mechanism of Heavy Metal (Pb²⁺, Cu²⁺, Ni²⁺, and Cd²⁺) Adsorption on Clinoptilolite. *J. Colloid Interface Sci.* **2006**, *304*, 21–28. <https://doi.org/10.1016/j.jcis.2006.07.068>.
87. Ancora, G.; Morari, F.; Brito, J.C.F.P.; Marchese, L.; Bisio, C.; Gianotti, E. Insights into the Role of Hierarchical Porosity in Zeolite Architectures for Selective Uptake of Metal Ions in Solution. *RSC Adv.* **2025**, *15*, 20092–20110. <https://doi.org/10.1039/D5RA03012A>.
88. Miliordos, E.; Xantheas, S.S. Unimolecular and Hydrolysis Channels for the Detachment of Water from Microsolvated Alkaline Earth Dication (Mg²⁺, Ca²⁺, Sr²⁺, Ba²⁺) Clusters. In *Thom H. Dunning, Jr.: A Festschrift from Theoretical Chemistry Accounts*; Wilson, A.K., Peterson, K.A., Woon, D.E., Eds.; Springer: Berlin, Heidelberg, 2015; pp. 329–340, ISBN 978-3-662-47051-0.
89. International Zeolite Association. Available online: <http://www.iza-online.org/> (accessed on 2 July 2026).
90. Sastre, G.; Daeyaert, F. *AI-Guided Design and Property Prediction for Zeolites and Nanoporous Materials*; John Wiley & Sons: Hoboken, NJ, USA, 2023.
91. Gandhi, A.; Hasan, M.F. Machine Learning for the Design and Discovery of Zeolites and Porous Crystalline Materials. *Curr. Opin. Chem. Eng.* **2022**, *35*, 100739.
92. Cho, H.J.; Kim, D.; Xu, B. Pore Size Engineering Enabled Selectivity Control in Tandem Catalytic Upgrading of Cyclopentanone on Zeolite-Encapsulated Pt Nanoparticles. *ACS Catal.* **2020**, *10*, 8850–8859. <https://doi.org/10.1021/acscatal.0c01542>.
93. Sharifian, S.; Nikfar, S.; Subasinghe, C.; Iranmanesh, Z.; Rezaee, M.; Vahidi, E. Conventional vs. Direct vs. Electrochemical Lithium Extraction: A Holistic TEA–LCA of Lithium Carbonate Production from Spodumene. *Green Chem.* **2026**, *28*, 1144–1157.
94. Huang, T.-Y.; Pérez-Cardona, J.R.; Zhao, F.; Sutherland, J.W.; Paranthaman, M.P. Life Cycle Assessment and Techno-Economic Assessment of Lithium Recovery from Geothermal Brine. *ACS Sustain. Chem. Eng.* **2021**, *9*, 6551–6560. <https://doi.org/10.1021/acssuschemeng.0c08733>.

95. Mackey, J.; Bain, D.J.; Lackey, G.; Gardiner, J.; Gulliver, D.; Kutchko, B. Estimates of Lithium Mass Yields from Produced Water Sourced from the Devonian-Aged Marcellus Shale. *Sci. Rep.* **2024**, *14*, 8813. <https://doi.org/10.1038/s41598-024-58887-x>.
96. Stringfellow, W.T.; Domen, J.K.; Camarillo, M.K.; Sandelin, W.L.; Borglin, S. Physical, Chemical, and Biological Characteristics of Compounds Used in Hydraulic Fracturing. *J. Hazard. Mater.* **2014**, *275*, 37–54. <https://doi.org/10.1016/j.jhazmat.2014.04.040>.

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