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Review

Sustainable lithium extraction from produced water: Integrating membrane pretreatment and next-generation adsorbents

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ABSTRACT

With the surging demand for lithium in energy storage and electric vehicles, lithium production has become increasingly crucial to modern society. While conventional Salt Lake brines remain a primary lithium source, produced water-a byproduct of oil and gas extraction-has emerged as a promising alternative due to its considerable extraction potential. In this review, we propose an efficient and sustainable process that leverages the strengths of membrane treatment and lithium adsorption. This process combines membrane treatment as an efficient pretreatment method for produced water with adsorption as a highly selective and effective approach for subsequent lithium extraction. The review first examines conventional membrane materials, such as polysulfone and ceramics, for pretreatment, alongside key classes of lithium adsorbents, including titanium-based, manganese-based, and aluminum-based materials. It then discusses advancements and modifications in these materials, emphasizing performance enhancements for lithium recovery. Emerging material optimization strategies, such as electrochemical coupling and the development of fibrous adsorbents, are also discussed, highlighting their potential to improve efficiency and scalability. A detailed process roadmap is presented, demonstrating the integration of membrane-based pretreatment with adsorbent-based lithium recovery and underscoring the strong industrial adaptability of this approach. By providing a comprehensive analysis of material performance and process optimization, this review offers valuable insights into scalable, efficient, and sustainable solutions for lithium extraction from produced water.

1. Introduction

Lithium is a key driver in the transition to a low-carbon economy. As countries strive to combat global climate change via pursuing carbon neutrality, they are implementing strategies to reduce greenhouse gas emissions, with a strong emphasis on developing renewable energy and electric vehicle (EV) industries (Baudino et al., 2022). The rapid growth of the EV market has driven an unprecedented surge in demand for lithium-ion batteries, underscoring their indispensable role in clean energy technologies (He et al., 2024). This rapid growth of lithium batteries underscores their crucial role in low-carbon transitions while pointing to surging lithium demand. However, global sustainability concerns are mounting due to lithium's limited supply and environmentally intensive extraction processes, making efficient recycling an urgent priority.

As shown in Fig. 1(a), lithium is primarily extracted from two major sources: brine deposits and hard rock ores such as spodumene. Among these resources, brines are particularly prominent due to their high lithium concentrations and simpler extraction processes (Carrasco, 2024). Lithium pyroxene, mainly mined in Australia, served as a major raw material through extraction and refining processes. These compounds are used across industries like battery production, casting molds, and air treatment systems, with lithium-ion batteries dominating demand for energy storage applications (Zhang et al., 2024). Expanding electric vehicle adoption and renewable energy technologies continue to fuel this demand. As shown in Fig. 1(b), as predicted in 2030, Chile, Australia, and China lead global lithium production and refining (IEA, 2024). However, post-2025 projections indicate mine supplies will fail to meet primary demand, necessitating expanded extraction capacities and alternative solutions like recycling to ensure sustainable supply security.

Lithium extraction from brines employs methods like ion exchange

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(Nishihama et al., 2011), electrochemical techniques (Zhang et al., 2021a), solvent extraction (Swain, 2016), membrane separation (Hou et al., 2021), and adsorption (Weibai and Jianming, 2020). Among these, the selective capture and concentration of Li^+ ions using specific adsorbent materials offers an efficient, environmentally friendly, and cost-effective approach. However, impurities in brines can degrade adsorbent performance through structural collapse or competitive capture, necessitating pretreatment (e.g., addressing salinity, pH, ionic composition) tailored to remove these impurities (Pramanik et al., 2020). Pretreatment method selection depends on brine physicochemical properties to optimize adsorption efficiency and mitigate interference (Fakhru'l-Razi et al., 2009).

Salt Lake brines have emerged as a key lithium extraction target due to their high salinity and lithium concentrations (Zhang et al., 2025a; Zhai et al., 2024), making them promising for scalable lithium recovery. However, surging global demand necessitates exploring alternative sources like geothermal brines, seawater, and oilfield produced water, the latter being hydrocarbon extraction byproducts containing salts, hydrocarbons, and treatment chemicals (Pan et al., 2025). Advanced sorption techniques with sustainable pretreatment could enhance lithium recovery from complex wastewater (Machado et al., 2023), potentially supplementing supplies while reducing environmental impacts from hydrocarbon operations. This dual-value approach supports both resource security and circular economy goals in energy storage sectors.

2. Produced water: sources and challenges

Produced water is co-extracted with hydrocarbons during oil and gas production (Neff et al., 2011). It primarily originates from three sources: (1) water produced during the oil and gas field development process (Nasiri and Jafari, 2017), (2) flowback and formation water generated during hydraulic fracturing (He et al., 2017), and (3) water used to depressurize and release gases from coal beds during coal bed methane extraction (Veil et al., 2004). In Fig. 2(a), taking hydraulic fracturing as an example, surface water is first extracted to create a base hydraulic fracturing fluid. This fluid is then mixed with additives at the well site and injected into production wells to move through target rock formations. After the fracturing process, the water that returns to the surface is collected and treated for either disposal or reuse (Clark and Veil, 2009). The volume of produced water is typically substantial, particularly in mature oil and gas fields, where it often far exceeds the volume of hydrocarbons produced. As the lifespan of a well increases, the volumetric ratio of produced water to hydrocarbons also rises, and in some cases, produced water can account for over 90 % of total output. As shown in Fig. 2(b), regional production data indicate that Asia and North America are the largest contributors, generating 42 % (4.6 billion m^3) and 28 % (3.0 billion m^3) of global produced water, respectively (Chauhan and Ghandat, 2016). This significant volume of produced water not only impacts the operational efficiency of oil and gas fields but also presents challenges in terms of environmental management and resource utilization.

Table 1 summarizes the composition and concentrations of various components found in produced water from different oil and gas fields or regions. The data clearly shows that produced water is rich in several metal ions, including Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, and Sr^{2+}. However, the concentration of Li^+ is relatively low compared to other metal ions, typically below 100 mg/L. Beyond metal ions, produced water contains significant amounts of oil-related substances, adding complexity to its treatment. Additionally, its high Chemical Oxygen Demand (COD) and Total Organic Carbon (TOC) levels indicate a substantial presence of organic pollutants. These organic compounds may stem from chemical additives used during the extraction process, residual oil and gas, naturally occurring organic materials within the formation

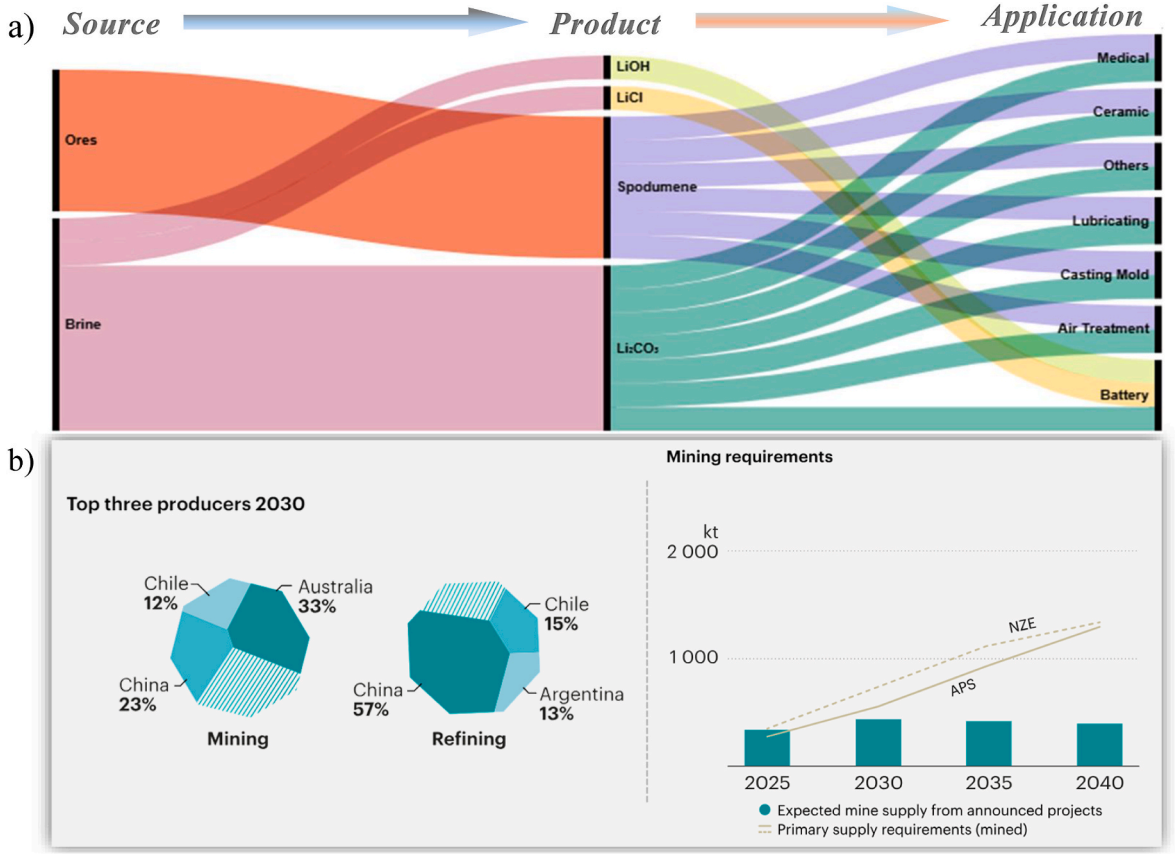

Fig. 1. (a) From source to end-use application of lithium metal; (b) Top three producers and future mining requirements (IEA, 2024).

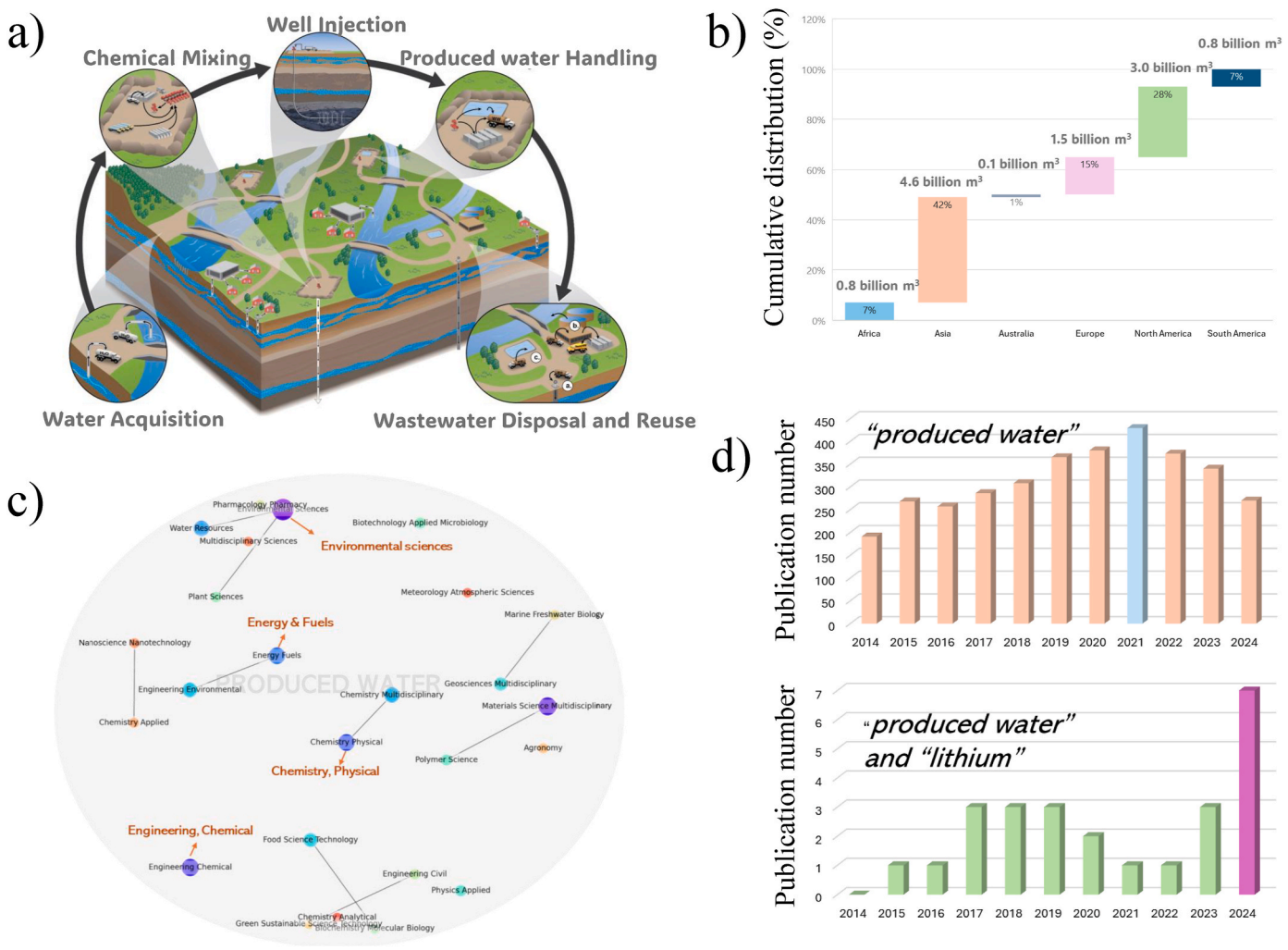

Fig. 2. (a) Produced water production cycle (source from U.S. Environmental Protection Agency. https://www.epa.gov/hfstudy/hydraulic-fracturing-water-cycle); (b) Distribution and volume of produced water across different countries; (c) Visualization of research topics related to produced water (Data Source-Scopus); (d) Publications related to "produced water" and "produced water & lithium" in the past decade (Data source-Web of Science).

Table 1
Produced water characteristics from various fields and locations.

Field/Location	Sr^{2+} (mg/L)	Li^{+} (mg/L)	Na^{+} (g/L)	K^{+} (g/L)	Ca^{2+} (g/L)	Mg^{2+} (g/L)	Oil (mg/L)	COD (mg/L)	TOC (mg/L)
Qianjiang Formation of the Jianghan Basin, China (Yu et al., 2023)	1.54–263.18	9.98–150	85.8	1.44	1.24	–	–	–	–
Shengli Oilfield, China (Lv et al., 2017)	68–72	–	5.46–5.84	0.001	0.356	–	96–112	270–320	45–71
Carboniferous Formation in west Poland (Engle et al., 2016)	2347	81	53	3.06	36	–	–	79	–
Japan (Chen, 2016)	–	–	–	–	–	–	–	964 ± 353	–
Swan Hills Formation, Alberta (Hitchon et al., 1993)	845	118	69.6	4.6	24.37		–	–	–
Smackover Formation, Kerlin Field, Columbia County, Arkansas, USA (Collins, 1974)	2980	445	71.4	8.34	45.7	–	–	–	–
Duvernay Formation, Alberta, Canada (Seip et al., 2021)	930	43	55	1.6	9.7	–	–	–	–
Montney Formation, Fox Creek area, Alberta, Canada (Wang et al., 2024)	1065	44.6	56.229	1.759	11.145	–	–	–	540
Marcellus Shale Formation, USA (Pan et al., 2024b)	3081	81.2	4.18	0.394	23.499	2.154	–	–	15–20

Note: "-" means no value can be obtained from literature.

(Maguire-Boyle and Barron, 2014), or microorganisms that are present in the subsurface environment. In addition, produced water often contains diverse microbial communities, including sulfate-reducing bacteria (SRB) and methanogenic archaea, which can influence water chemistry and contribute to biofouling and reservoir souring (Liu et al., 2015). The study of produced water holds great importance, not only in addressing the environmental pollution challenges associated with oil and gas extraction, but also in unlocking new opportunities for extracting valuable resources.

Produced water has become a critical focus in energy and environmental sectors, with interdisciplinary research spanning environmental science, energy and chemistry (Fig. 2(c)). Its substantial lithium content-

such as that found in the Smackover Formation in Arkansas, estimated at 750,000 metric tons (Kumar et al., 2019)-positions it as a promising alternative lithium resource. Fig. 2(d) illustrates exponential growth in produced water studies since 2010, though lithium recovery research remains nascent with only 7 dedicated publications in 2021. Key extraction challenges include: low lithium concentrations requiring enhanced selectivity and adsorption capacity; complex chemical matrices with competing ions and organics; technological limitations in extraction efficiency and cost-effectiveness. Adsorption-based direct lithium extraction (DLE) demonstrates distinct advantages: selective lithium capture through advanced adsorbents (Murphy and Haji, 2022); reduced energy consumption compared to conventional methods (Boroumand and Razmjou, 2024); operational simplicity and scalability for industrial deployment (Mojid et al., 2024). Current research prioritizes adsorbent optimization to address real-world operational challenges.

Effective pretreatment is crucial for lithium extraction from produced water's complex composition (Service, 2006). As illustrated in Fig. 3(a), primary methods include physical, chemical, biological, and advanced oxidation processes (AOPs) (Feng et al., 2017; Lai et al., 2009). Membrane technology dominates pretreatment (46 % of methods, Fig. 3(b)), offering selective organic/ion removal with minimal secondary pollution (Alzahrani and Mohammad, 2014), while AOPs face limitations due to high costs and toxic byproducts (Miklos et al., 2018). Integrating membrane pretreatment with adsorption creates a synergistic solution: membranes remove impurities to prepare cleaner feedwater, while adsorbents selectively capture lithium ions, enhancing overall recovery efficiency. This integrated approach requires dual material advancements: membranes needing enhanced selectivity, durability, and anti-fouling capabilities for harsh conditions (Ebrahimi et al., 2009); adsorbents requiring improved lithium selectivity, rapid kinetics, recyclability, and ion interference resistance (Zhao et al., 2022). Our review systematically analyzes these materials challenges through three lenses, examining pore engineering and surface modifications for targeted impurity removal in membrane optimization, evaluating conventional materials' limitations and emerging solutions like functionalized composites for adsorbent development, and proposing co-design principles for membrane-adsorbent compatibility. The analysis introduces two key innovations, coordinating membrane selectivity with adsorbent specificity and addressing long-term performance degradation mechanisms.

3. State-of-the-art material strategies

3.1. Advanced membrane architectures for selective pretreatment

Recent focus on produced water pretreatment addresses its complex composition, including oils, salts, heavy metals, organics, and drilling additives, to ensure efficient downstream lithium extraction. Membrane separation processes operate mainly through differences in concentration, temperature, electrical potential, or pressure (Al-Obaidani et al., 2008). Among these, pressure-driven processes are categorized based on the pore size of the membrane used, resulting in four primary types (Pendergast and Hoek, 2011): microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The main characteristics of pressure-driven membranes are presented in Fig. 4(a). The efficiency of membrane separation is typically evaluated by the oil rejection coefficient (R_o), which is defined as:

$$R_o = \frac{oil\ concentration\ in\ feed - oil\ concentration\ in\ permeate}{oil\ concentration\ in\ feed} \times 100 \quad (1)$$

The rejection coefficient in membrane filtration depends on contaminant size, operating conditions (temperature, pressure, pH, crossflow velocity), oil droplet capillary pressure, and membrane surface properties (tension, energy, charge, polarity), which govern fouling resistance and contaminant interactions (Hlavacek, 1995).

Another key parameter in membrane separation is permeate flux, which is defined as:

$$J = \frac{V_p}{At} \quad (2)$$

where J, V_p, and t are permeate flux, volume, and time, respectively, and A is membrane effective area.

3.1.1. Types of membrane materials

(1) Organic Membranes

Organic membranes are widely used for oil/water separation due to

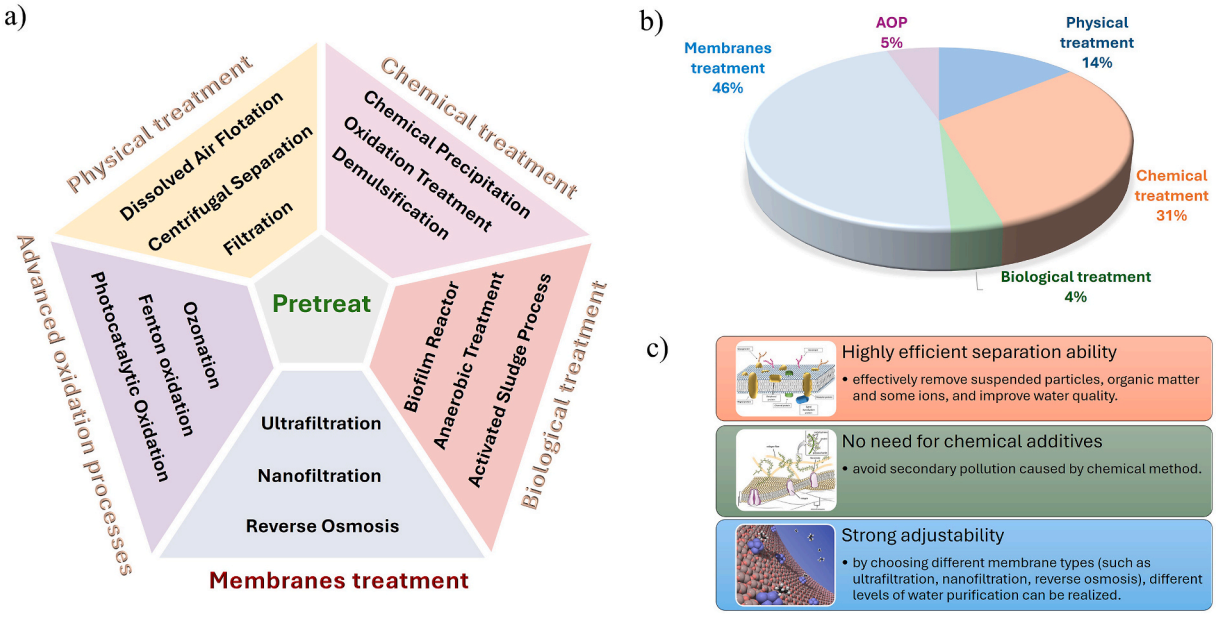

Fig. 3. (a) Main methods for produced water pretreatment; (b) Percentage of produced water pretreated by different pretreatment methods (Data source from Web of Science); (c) Advantages of using membrane treatment in produced water.

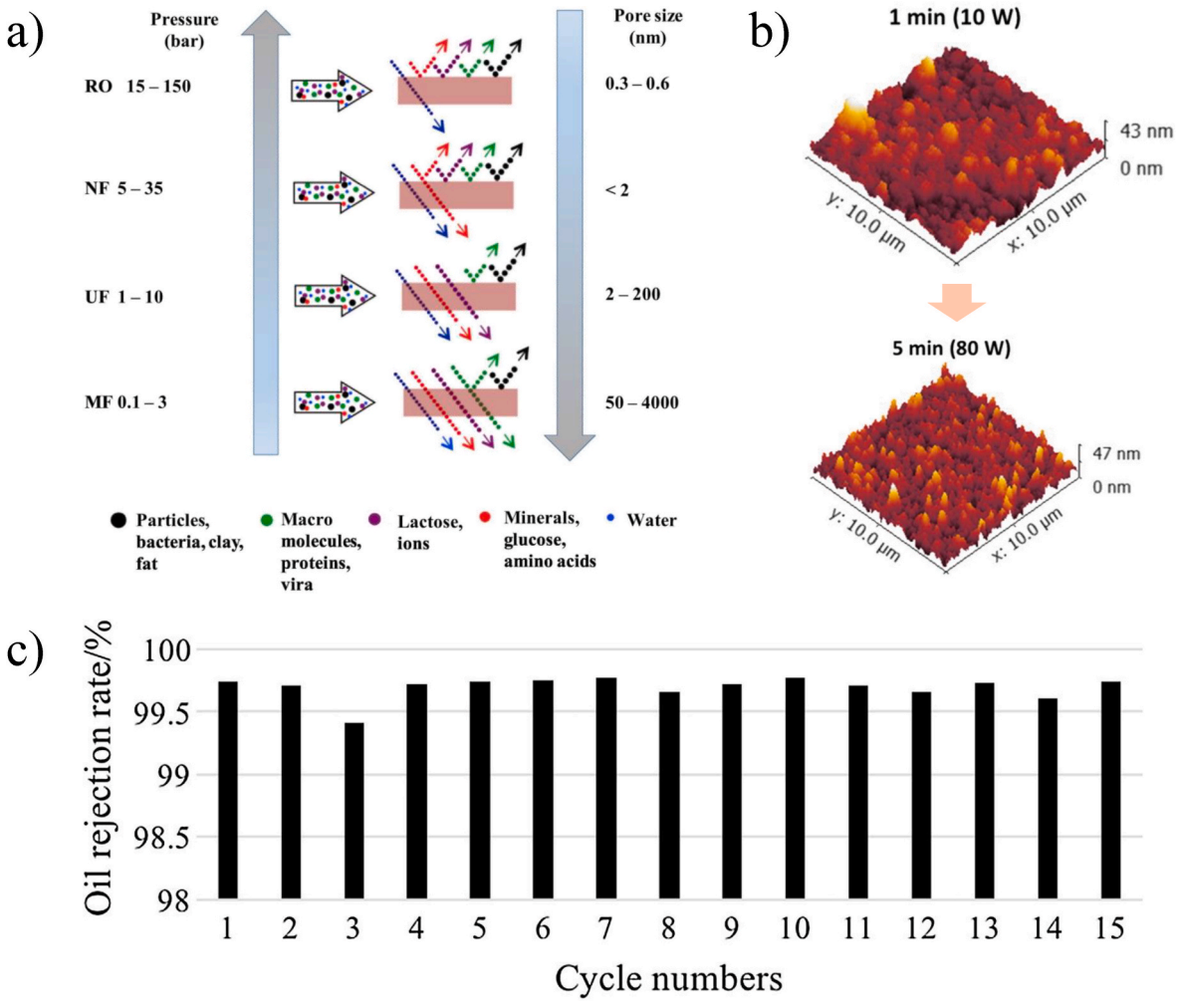

Fig. 4. (a) Membrane separation processes and separation characteristic (Tawalbeh et al., 2018); (b) AFM morphologies of the plasma-modified membranes (Reis et al., 2017); (c) Oil rejection rate of the Mobil Five (MFI) zeolite meshes (Liu et al., 2018).

their low cost and high efficiency. However, over time, oil and particulate accumulation within membrane pores can lead to a notable decline in separation performance (Peng and Tremblay, 2008). Materials like polysulfone (PSO), polyethersulfone (PES), polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), and cellulose acetate (CA) are commonly used for manufacturing MF and UF membranes (Yi et al., 2011). Polyvinylidene fluoride (PVDF) membranes modified with nano-sized TiO_2/Al_2O_3 were applied to the separation of oil/water emulsion. The enhanced hydrophilicity of these modified PVDF membranes resulted in higher relative flux (RF) and superior antifouling properties compared to unmodified PVDF membranes under identical operational conditions. Fouling can be significantly reduced by using hydrophilic membranes. This can be achieved either through chemical and/or physical modifications of the membrane surface or by incorporating hydrophilic additives into the polymer structure (Mansourizadeh and Javadi Azad, 2014). Interfacial polymerization, nanoparticle incorporation, and surface grafting are applied in modifying membrane hydrophilicity (Fan et al., 2014). Modified cellulose acetate membranes achieved a water flux of 271 m^2/s and 88 % oil rejection after 150 min, demonstrating improved hydrophilicity.

Interfacial polymerization is widely utilized for the fabrication of polyamide nanofiltration membranes (Qin et al., 2007). However, it is also applicable in the synthesis of polyurethanes, polysulfones, polycarbonates, and polyesters. This process occurs at the interface between an organic phase and an immiscible aqueous/organic solution (Chiang et al., 2009). Several key factors influencing the characteristics of the resulting membranes, such as thickness, porosity, pore size distribution, and thermal properties, include solvent properties, monomer types, concentrations of monomers in both the aqueous and organic phases, reaction time, and temperature (Zhang et al., 2013). Additionally, the incorporation of inorganic salts, carbon nanotubes, silica, and titanium dioxide nanoparticles into the aqueous phase can significantly enhance the solubility and diffusion rates of the monomers, thereby improving the overall performance of the membranes produced (Hu et al., 2012).

Nanoparticle incorporation involves embedding nanometer-sized particles within a polymeric membrane structure to improve membrane properties such as permeability, selectivity, and hydrophilicity. Commonly used nanoparticles include hydrous manganese oxide, graphene oxide, carbon nanotubes, and polymeric nanoparticles (Ao et al., 2017). Graphene oxide@electrospun cellulose nanofiber membrane demonstrated high efficiency in separating oil/water mixtures across a broad pH range and under high-salinity conditions, highlighting its potential for real-world applications in wastewater treatment. The interactions between the nanoparticles and the polymeric material largely determine the membrane's properties, which depend on the amount, size and type of nanoparticles used. Although nanoparticle incorporation is cost-effective and straightforward to implement (Kochkodan et al., 2014), it faces challenges such as nanoparticle aggregation and dissolution, which may impact membrane stability and performance.

Surface grafting can be initiated through various techniques, including ultraviolet (UV) irradiation, electron beam irradiation, plasma treatment, layer-by-layer modification, and Grignard or phosphoric acid

grafting (Ng et al., 2014). Ultraviolet irradiation is widely utilized due to its ease of operation (shown in Fig. 4(b)), cost-effectiveness, and rapid reaction rates, which can proceed with or without photoinitiators (Reis et al., 2017). Plasma grafting (Zou et al., 2011), in contrast, uses gas or vapor reactants at pressures below 100 Pa and a high frequency of approximately 13.66 Hz, allowing for modification in short treatment times. Electron beam irradiation (Cloete et al., 2017), employing high-energy beta radiation, generates free radicals that react with solution-phase monomers to enhance chemical modifications and promote cross-linking.

Despite advancements, organic membranes remain susceptible to performance fluctuations influenced by operating conditions such as temperature, transmembrane pressure, pH, and flow velocity. Variations in these factors can impact separation efficiency, membrane stability, and overall operational lifespan, highlighting the need for continuous optimization in membrane applications.

(2) Inorganic Membranes

Inorganic membranes (ceramic, metallic, etc.) for produced water treatment include ceramic types like alumina and zeolite, classified by pore size: macroporous (>50 nm) as support layer, mesoporous (2–50 nm) for nanofiltration, and microporous (<2 nm) for molecular sieving, while nonporous dense membranes rely on solution-diffusion mechanisms (Ismail et al., 2015). Ceramic membranes are synthesized through methods, such as chemical vapor deposition and slip casting (Wu et al., 2013). Apart from their geometric configuration, ceramic membranes undergo a three-step preparation process (Dong et al., 2000). Three steps for fabrication, suspension preparation, shaping, and sintering/calcination with controlled heating/cooling rates to manage organic additive decomposition.

A variety of ceramic membrane synthesis techniques have been developed, each offering distinct advantages and challenges, allowing for the customization of membrane properties to suit specific applications (Julbe et al., 2001). Among advanced fabrication techniques, the sol-gel process offers precise control over pore structure and composition, making it particularly suitable for developing both inert and catalytic membranes with highly pure thin-film coatings (Julbe et al., 2001). Additionally, chemical vapor deposition enables precise surface deposition through controlled thermal reactions, further enhancing membrane functionality and performance (Choy, 2003). Slip casting remains an economically efficient and widely used technique, particularly for fabricating tubular and hollow fiber membranes (Tiller and Tsai, 1986). Freeze casting and tape casting introduce novel structural hierarchies and smooth surface finishes but require careful handling due to mold corrosion, environmental hazards, and extended processing times (Athayde et al., 2016). For MF and UF, high-pressure pressing is advantageous for producing ceramic membranes designed, particularly in applications like oil/water separation (Liu et al., 2016). Lastly, atomic layer deposition stands out for its uniform film creation and scalability, offering exact control over film thickness even at low temperatures. Collectively, these techniques underscore the versatility and adaptability of ceramic membrane preparation, supporting advancements in membrane technology for filtration, catalysis, and separation processes. Clay, quartz sand, fly ash, and kaolin have been chosen as cost-effective raw materials for preparing membrane materials, specifically for the pretreatment of produced water (Ahmed et al., 2022).

(3) Oil/Water Separation

Organic membranes provide a cost-effective and highly efficient solution for oil/water separation. For instance, Kose et al. combined the fiber membrane separation with the breakdown of organic matter using biological treatment (Kose et al., 2012). A lab-scale system exhibited stable performance, maintaining a chemical oxygen demand removal efficiency of 80–85 %, significantly enhancing oil and grease removal from 60 % to 85 %, and achieving a hydrocarbon removal rate of 99 %. Despite these advantages, fouling remains a major challenge, as oil compounds tend to adhere strongly to the hydrophobic membrane surface, leading to performance degradation over time.

Ceramic membranes offer several advantages over organic membranes, primarily due to their homogeneous and narrow pore size distribution, high mechanical, chemical, and thermal stability, and reduced bonding with fouling substances on their surfaces. Ebrahimi et al. employed ceramic membranes for the treatment of oilfield produced water, achieving oil removal of up to 99 % and total organic hydrocarbon removal of up to 39 % (Ebrahimi et al., 2009). Alammar et al. (2020) synthesized graphene-based nanocomposite membranes for produced water treatment, achieving an oil removal efficiency of 99.9 % and a permeance of 91.3 L $m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$. Additionally, Ebrahimi et al. evaluated the separation efficiency of a process using ceramic membranes combined with microfiltration, simulated batch dissolved air flotation, and a multistage post-treatment step incorporating crossflow ultra- and nanofiltration (Ebrahimi et al., 2010). This approach resulted in oil removal of up to 99.5 % and TOC removal of 49 %.

The most used materials for ceramic membrane fabrication include silica, titania, alumina, and zirconia-based compounds (Liangxiong et al., 2003). Clay-based membranes have also been explored for purifying oily produced water, but they have been proven unsuitable for treating water with high total dissolved solids. Zeolite membranes, characterized by their three-dimensional, well-defined microporous structure, have shown promise for oil/water separation, exhibited in Fig. 4(c). Additionally, they present a favorable alternative for selectively removing specific ions from oilfield wastewater via RO. However, significant challenges primarily due to their selectivity limitations and mechanical fragility remain when using zeolite membranes for produced water pretreatment. While they have molecular sieving properties, achieving precise separation of complex contaminants, such as oil emulsions and dissolved salts, remains difficult. Besides, membrane fouling caused by organic matter, scaling, and particulate deposition reduces long-term stability and efficiency.

3.2. Adsorbents for direct lithium extraction from produced water

Adsorbents play a pivotal role in extracting lithium directly from produced water. As global demand for lithium accelerates, substantial research efforts have focused on developing highly efficient and selective adsorbent materials. Due to their low energy consumption, straightforward operation, and high lithium selectivity, adsorption technologies are increasingly recognized as a promising approach for lithium recovery from produced water (Chen et al., 2023). In this section, we delve into recent advances in lithium-specific adsorbents, emphasizing innovative materials and modification techniques with potential applications for improving lithium extraction efficiency in challenging produced water environments.

3.2.1. Titanium-based adsorbent

(1) Layered Structure and Fabrication

Ion-sieve adsorbents are a class of materials known for their highly selective adsorption properties. By precisely control of atomic-level vacancies and surface chemistry, these materials can effectively filter and capture target ions (Li et al., 2023). Due to their high selectivity, large adsorption capacity, and strong regeneration capabilities, they have become a focal point of research. Nanosized lithium titanium oxides (LTOs), particularly Li_2TiO_3 and $Li_4Ti_5O_{12}$, have demonstrated superior stability in lithium elution, making them kind of highly effective ion-sieve adsorbents (Lawagon et al., 2016). Several methods have been explored for synthesizing LTOs, including the solid-state reaction (Han et al., 2017), sol-gel method (Guo et al., 2016), hydrothermal method (Julien and Mauger, 2024), co-precipitation method (Li et al., 2019),

and molten salt method (Xue et al., 2018). The choice of synthesis method depends on the desired material properties and performance requirements. As illustrated in Fig. 5(a), the layered structure of Li_2TiO_3 consists of O atoms arranged in a cubic close-packed configuration, with Li and Ti atoms occupying the octahedral voids, resulting in a layered monoclinic structure (Chitrakar et al., 2014). In this structure, one layer is composed of Li atoms, while the other follows a $LiTi_2$ sequence. Through acid washing, lithium can be eluted, converting Li_2TiO_3 into H_2TiO_3. The resulting H_2TiO_3 exhibits the capability to selectively capture Li^+ ions.

(2) Lithium Adsorption from Produced Water

Extensive research has been conducted on the application of LTOs for lithium adsorption from produced water (Yao et al., 2024). These studies have achieved high lithium recovery rates by thoroughly examining both the properties of LTOs adsorbents and the characteristics of produced water. A key factor in this process is the precursor TiO_2, which significantly influences the adsorption performance and properties of LTOs (Qin et al., 2024). The crystal structure and particle size of TiO_2 directly influence LTOs' surface area, porosity, and adsorption efficiency. Tang et al. synthesized 88.35 % pure TiO_2 from low-grade titanium slag via alkaline roasting, yielding β-Li_2TiO_3 with stable cyclic capacity (23–24 mg/g) (Tang et al., 2015). Hossain et al. synthesized TiO_2 precursors from flocculated sludge derived from synthetic secondary effluent and dye wastewater. Their study confirmed the high lithium-selective adsorption capacity of these materials, as given in Fig. 5(b), highlighting their significant potential for industrial applications (Hossain et al., 2022). Furthermore, Li et al. systematically investigated the influence of different crystalline phases of TiO_2 on the wettability and performance of adsorbents (Li et al., 2020). As shown in Fig. 5(c), three titanium sources, amorphous, anatase, and rutile titanium dioxide, produced LTOs with varying wettability properties following the curing process. Among them, the HTO derived from anatase titanium dioxide (HTO-400) exhibited the highest lithium adsorption performance, reaching up to 34.2 mg/g, due to its superior hydrophilicity.

While LTOs show high selectivity and adsorption capacity for lithium recovery, practical challenges include interference from organic components and low lithium concentration in produced water. Jiang et al.

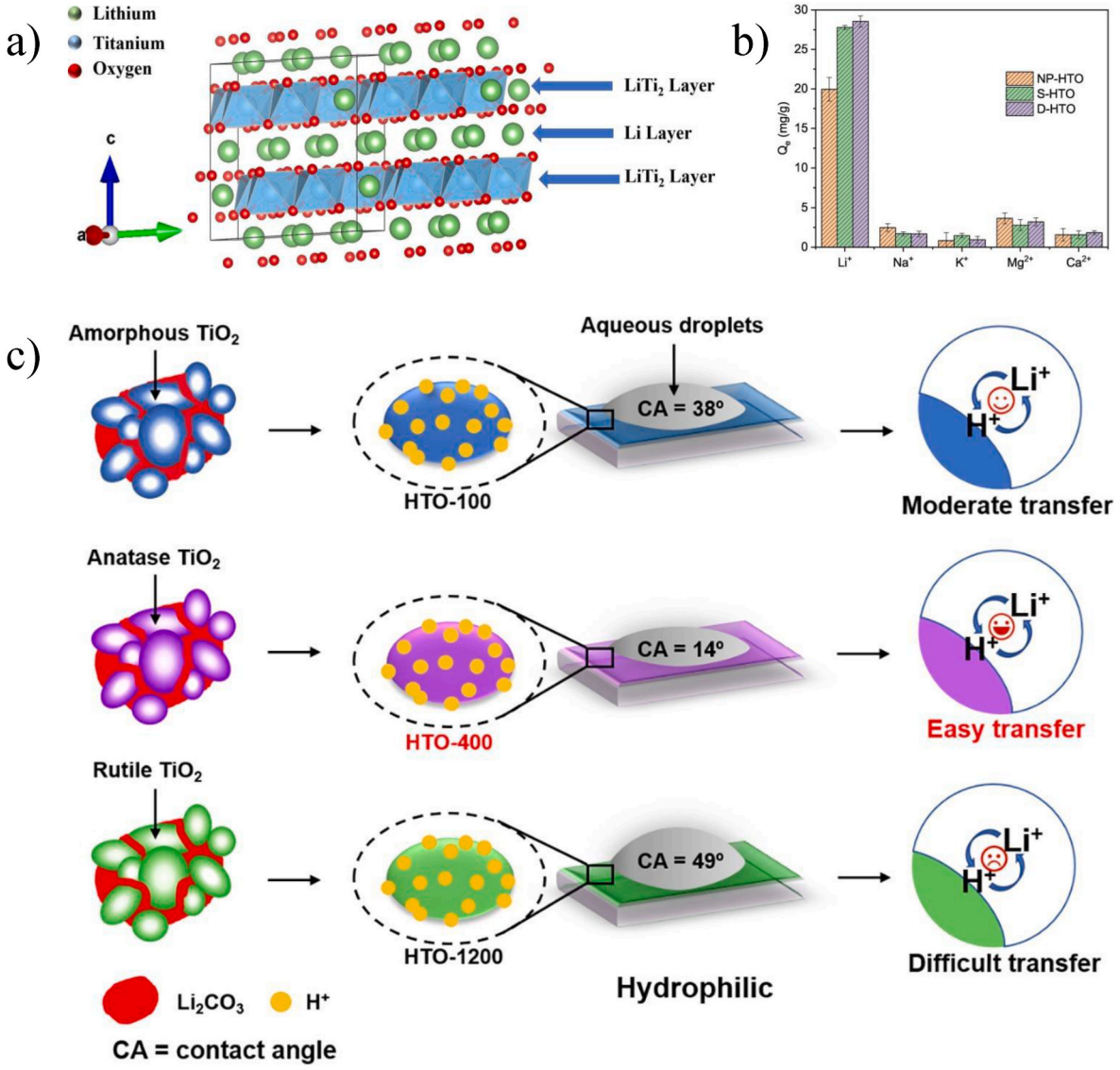

Fig. 5. (a) Li_2TiO_3 crystalline structure contains alternating layers of Li and $LiTi_2$ sequence (Li-O bonds are not shown for clarity)(Chitrakar et al., 2014); (b) Adsorption capacity of the synthesized HTOs in presence of the competing coexisting ions (Hossain et al., 2022); (c) Schematic illustrations of the wettability of HTO-x for Li adsorption (Li et al., 2020).

found that n-alkanes reduces H_2TiO_3 adsorption efficiency by lowering zeta potential and increasing particle size (Fig. 6(a)) (Jang and Chung, 2019a). Jang et al. also investigated the impact of organic compounds in produced water on lithium adsorption by LTOs. Their study found that low-molecular-weight organic compounds significantly inhibit lithium adsorption, highlighting the need for pretreatment strategies to mitigate these effects (Jang and Chung, 2019b). Another key challenge in LTO-based lithium recovery is the low lithium concentration in produced water, which limits adsorption efficiency. To address this, Zhang et al. prepared LTOs using the classical solid-state method (Fig. 6(b)), and the mechanism revealed Li^+ desorption rate and titanium dissolution loss rate influenced by the concentration of hydrochloric acid and some other factors. The optimized adsorbent demonstrated an initial lithium adsorption capacity of 20.14 mg/g in real produced water containing 100 ppm of Li^+, which offers valuable insights into the mechanism of LTOs and their potential for addressing the challenge of recovering lithium from produced water (Zhang et al., 2025b).

3.2.2. *Manganese-based adsorbent*

(1) Spinel-structure and Fabrication

Manganese based adsorbents (LMOs) are a class of materials primarily composed of manganese oxides, characterized by a high specific surface area and exceptional ion exchange capabilities. Their tunnel or layered structures enable highly selective adsorption of Li^+ ions, making them promising candidates for lithium recovery applications. Various methods for synthesizing LMOs have been documented in the literature, including solid-state reactions, hydrothermal/solvothermal processes, molten salt techniques, etc (Orooji et al., 2022; Tu and Cai, 2024). Among these, the solid-state reaction method is especially preferred due to its capability to yield LMOs materials with enhanced stability in both physical and chemical properties.

Currently, the precursors of LMOs can be classified into three categories based on their varying Li/Mn ratios and crystal structures: LiM_2O_4, $Li_4Mn_5O_{12}$, and $Li_2Mn_2O_5$. The crystal structure of these $Li_xMn_{3-x}O_4$ is determined by the stoichiometric ratio, applied pressure, and temperature in the solid-phase reaction, achieved by heating a mixture of manganese and lithium compounds (Yamaura et al., 2006). As illustrated in Fig. 7(a), using $Li_4Mn_5O_{12}$ as an example, the Li and Mn ions are positioned within two distinct types of interstitial sites: tetrahedral (A sites) and octahedral (B sites). In this structure, Li^+ ions occupy the tetrahedral A sites, while Mn ions (Mn^{3+}/Mn^{4+}) predominantly reside in the octahedral B sites, ensuring a balanced charge distribution within the crystal lattice (Darul et al., 2012). Fig. 7(b) illustrates the composite mechanism of spinel LMOs during Li^+ intercalation/deintercalation. The selectivity of spinel-type MnO_2 (λ-MnO_2) as an ion-sieve for Li^+ can be attributed to the specific ion exchange between Li^+ and H^+ (Liu et al., 2019). Consequently, the H^+ content within λ-MnO_2 is closely related to its adsorption capacity, directly influencing its ability to selectively adsorb Li^+ ions.

(2) Lithium Adsorption from Produced Water

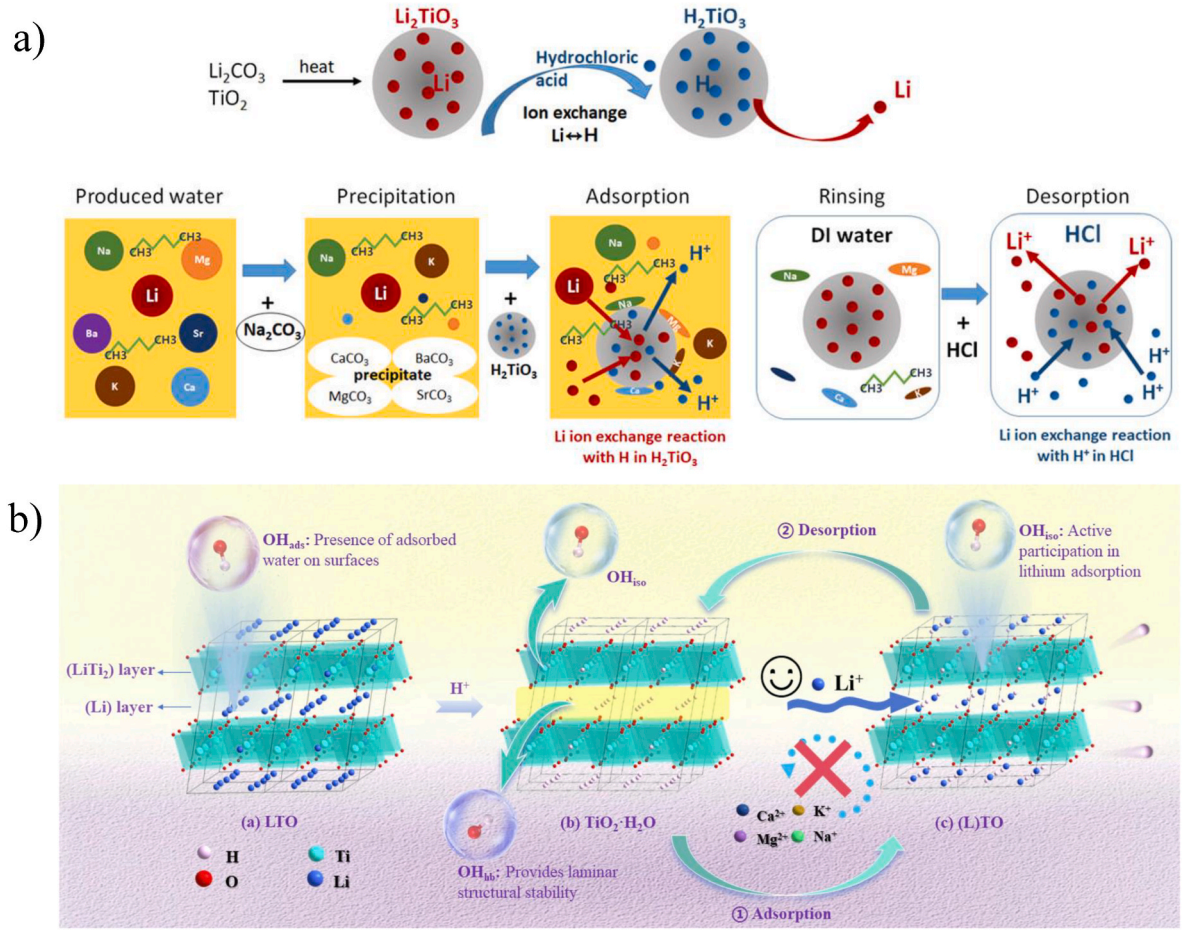

Fig. 6. (a) Graphic abstract of "*Influence of Alkanes on Lithium Adsorption and Desorption of a H_2TiO_3 Ion Sieve Adsorbent in Synthetic Shale Gas-Produced Water*" (Jang and Chung, 2019a); (b) Proposed formation and working mechanisms of as-prepared $TiO_2{\cdot}H_2O$ adsorbents by eluting the layered Li_2TiO_3 precursors by HCl (Li as blue ball, H as pink ball, O as red ball, Ti as green ball) (Zhang et al., 2025b).

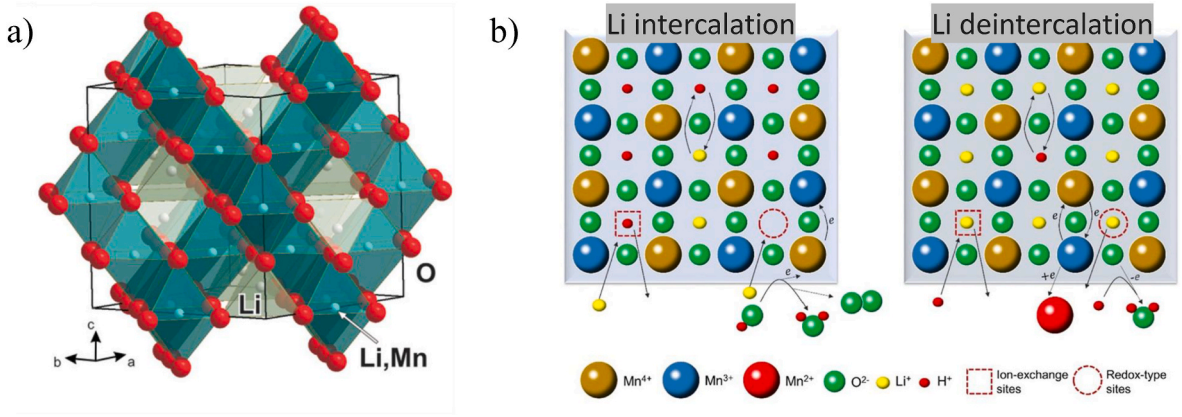

Fig. 7. (a) Crystal structure of spinel $Li_4Mn_5O_{12}$ (Yamaura et al., 2006); (b) Schematic representation of the Li intercalation and deintercalation mechanisms in spinel LMOs (Darul et al., 2012).

Alongside LTOs, LMOs are the second most widely used functional materials for extracting low-concentration lithium from produced water. However, LMOs have primarily been applied in the adsorption and recovery of lithium from Salt Lake brines, with their use in produced water remaining limited. This is largely due to the higher organic content and lower lithium concentrations found in produced water. Tian et al. synthesized LMOs materials through a solid-phase reaction, achieving a lithium adsorption capacity of up to 16.24 mg/g from shale gas flowback and produced water in the Sichuan Basin, China (Tian et al., 2022). Their study also demonstrated the material's excellent selectivity and recyclability. Besides, Qiu et al. explored lithium recovery from produced water using LMOs materials formed by two different granulation methods - extrusion and droplet (Qiu et al., 2024). By optimizing porosity, kinetics, and modeling, they achieved a lithium

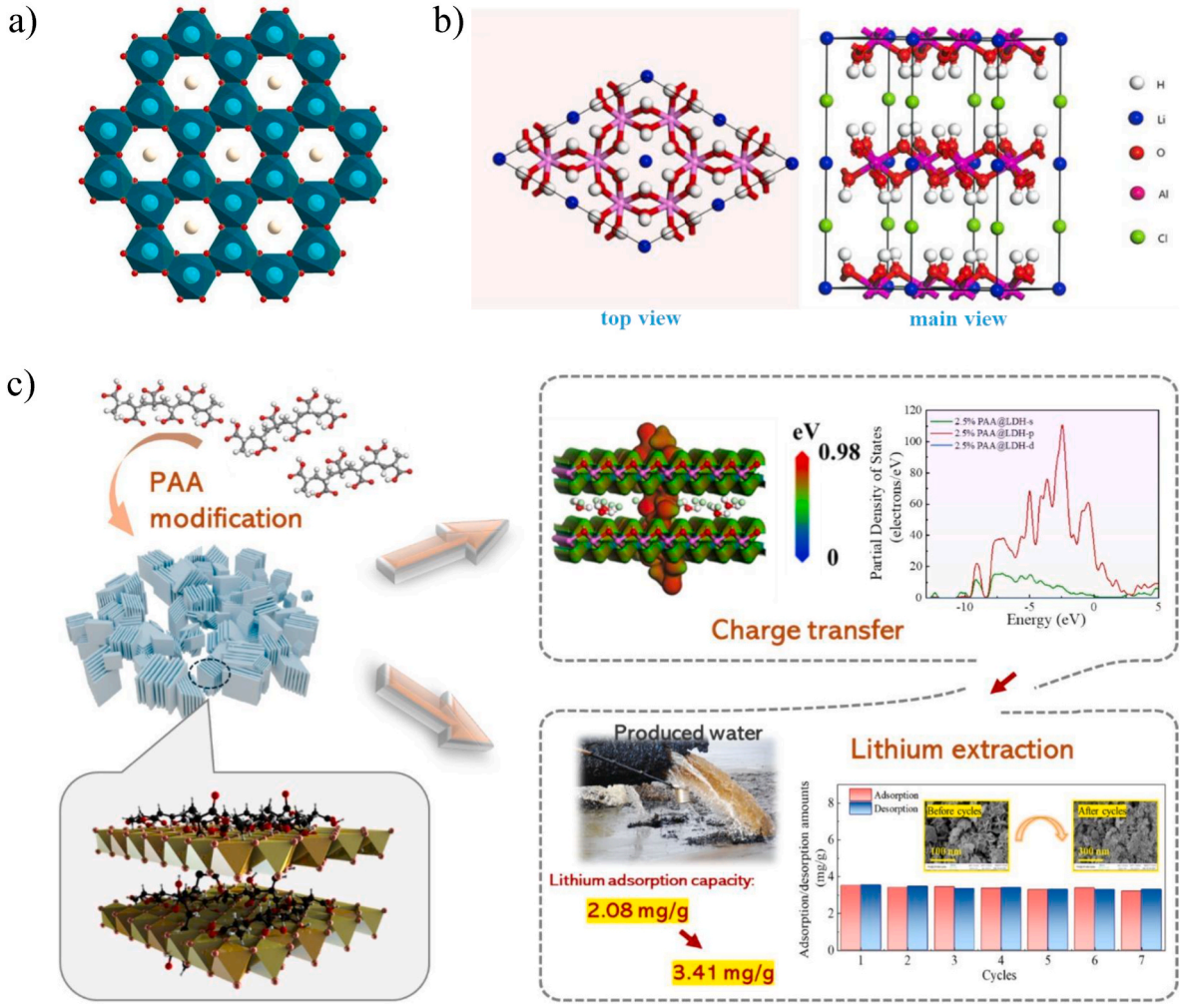

Fig. 8. (a–b) The atom structure and arrangement of Li/Al-LDH (Besserguenev et al., 1997; Zhang et al., 2024); (b) Graphic abstract of "*Charge transfer-driven enhanced lithium extraction using poly (acrylic) acid-modified layered double hydroxide*" (Pan et al., 2024a).

adsorption capacity of 17.30 mg/g after 20 cycles, further advancing the application of LMOs in lithium extraction from produced water.

3.2.3. Aluminum-based adsorbent

Aluminum-based adsorbents are a class of materials that leverage the porous or layered structures of aluminum compounds and are widely employed for the removal of metal ions and organic pollutants (Du et al., 2014). Lithium-aluminum layered double hydroxide (Li/Al-LDH) stands out due to its unique layered structure, which is synthesized by embedding Li^+ ions into the octahedral vacancies of $Al(OH)_3$ layers (Chen et al., 2021). This configuration results in exceptional ion-exchange capabilities and highly selective adsorption properties (Pan et al., 2022). Li/Al-LDH can be synthesized using various methods, including co-precipitation, hydrothermal, and mechanical synthesis (Pavel et al., 2021), with the choice of method depending largely on the desired material properties and morphology. As shown in Fig. 8(a) and (b), the hexagonal layered structure of Li/Al-LDHs is formed through the intercalation of lithium salts into the vacant octahedral sites within the $Al(OH)_3$ layers (Kozlova). In this configuration, Al^{3+} ions occupy two-thirds of the octahedral vacancies within the close-packed oxygen layers, while Li^+ ions (~0.68 Å) are intercalated into the remaining unoccupied vacancies, which have a radius of approximately 0.70 Å. The resulting $[LiAl_2(OH)_6]^+$ layers are stabilized by hydrogen bonding, electrostatic interactions, and van der Waals forces, providing structural integrity and stability (Besserguenev et al., 1997; Zhang et al., 2024).

To date, limited research has focused on the application of Li/Al-LDH for the adsorption of low-concentration Li^+ in produced water. Notably, Pan et al. investigated Li/Al-LDH materials with varying Li/Al molar ratios, applying them to shale gas produced water (Pan et al., 2024b). Their study demonstrated that a two-dimensional layered Li/Al-LDH synthesized at a Li/Al molar ratio of 0.6 exhibited superior physical and chemical properties, with Li^+ showing higher selectivity over competing ions such as Na^+, K^+, and Ca^{2+}. Furthermore, the adsorption performance of the material remained stable over five cycles. Despite these favorable properties, the adsorption capacity of Li/Al-LDH in produced water containing 80 mg/L of Li^+ was approximately 2.0 mg/g, indicating limited efficiency as a high-performance adsorbent for low lithium concentrations. To address this limitation, the research team modified Li/Al-LDH with polyacrylic acid (PAA), significantly enhancing its adsorption performance. As shown in Fig. 8(c), the optimized PAA@LDH exhibited an increased Li^+ adsorption capacity from 2.08 mg/g to 3.41 mg/g, along with notably improved adsorption kinetics (Pan et al., 2024a). This study provides valuable insights into the potential of Li/Al-LDH for extracting lithium from low-concentration produced water, demonstrating a promising approach for improving adsorption efficiency under challenging conditions.

3.2.4. A comparative evaluation of various adsorbents

Different types of adsorbents exhibit distinct advantages and limitations in lithium recovery from produced water. As shown in Table 2, LTOs offer high Li^+ selectivity due to their ion-sieve effect, but their performance is highly dependent on maintaining an alkaline environment, with potential risks of Ti dissolution loss. LMOs, utilizing ion exchange, provide high adsorption capacity and broader pH adaptability, yet they are susceptible to structural degradation in the presence of multivalent ions, requiring periodic deep regeneration. Li/Al-LDHs, leveraging a memory effect, are cost-effective and structurally stable under neutral to mild alkaline conditions but exhibit lower selectivity in high Mg^{2+} environments and are prone to performance deterioration under extreme pH and organic interference. Given these differences, the selection of an appropriate adsorbent should consider factors such as water composition, pH adaptability, selectivity, adsorption capacity and kinetics, and long-term stability to ensure efficient and sustainable lithium recovery. To overcome existing limitations, further optimization of adsorbent materials is crucial to enhance selectivity, improve structural stability, and extend recyclability, ultimately contributing to the development of more efficient and economically viable lithium extraction technologies from produced water.

Table 2
Comparative analysis of lithium adsorbents.

Criteria	LTOs	LMOs	Li/Al-LDH
Li^+ Adsorption Capacity	High (20–50 mg/g), optimized at pH 10-12	High (15–40 mg/g), optimized at pH 3–7	Moderate (2–10 mg/g), optimized at 6-9
Li^+ Selectivity	High, particularly in Na^+/K^+-rich environments	High, but sensitive to Mg^{2+}/Ca^{2+}	Moderate, less effective in high Mg^{2+} environments
Adsorption Mechanism	Ion sieve effect	Ion exchange	Memory effect (vacancy size matching Li^+)
pH Adaptability	Requires strong alkaline conditions	Wide pH range (pH 2–8)	Better in neutral to weakly alkaline conditions
Regeneration Performance	Good, but potential Ti dissolution loss	Good, but structural degradation occurs	Good with minimal structural degradation
Advantages	High adsorption capacity and selectivity	Wider pH adaptability	Low cost, easy operation
Application Risks in Produced Water	A strictly alkaline environment must be maintained, acidic conditions can cause dissolution. Practical applications require integration with pH-adjusting equipment.	Multivalent ions (Mg^{2+}/Ca^{2+}) can cause structural degradation, requiring periodic deep regeneration.	Fails under extreme pH conditions, exhibits rapid performance degradation after cycling, easily affected by organic compounds.

3.3. Adsorbent optimization and upgrading

The optimization of lithium adsorption materials serves to enhance their practical efficiency in applications such as lithium extraction from produced water, while also improving selectivity, regeneration capabilities, and environmental sustainability. This section provides a comprehensive analysis of the upgraded adsorbents utilized for lithium extraction from produced water.

3.3.1. Improvement in crystal structure

Ji et al. optimized the synthesis of Li_2TiO_3 by fine-tuning roasting temperature, reaction duration, and composition using a solid-phase reaction (Ji et al., 2017). In a novel approach, they treated the precursor with $Na_2S_2O_8$ as the elution solution, resulting in the formation of monoclinic spinel structure metatitanic acid lithium (Li_2TiO_3) with high selectivity. According to their findings, the amount of dissolved titanium loss stabilized after the first 120 min and decreased to 27.39 mg/g after three cycles when using a reaction temperature of 850 °C for 5 h with a heating rate of 4 °C/min. This innovative approach significantly improves the selectivity and stability of Li_2TiO_3 in lithium extraction, offering valuable insights into optimizing material synthesis for enhanced performance.

Doping technology has been a prominent research focus in recent years, as it can enhance the crystal structure and surface chemistry of adsorbents by incorporating external elements or ions. This modification improves selectivity, adsorption capacity, and stability for Li^+, enabling more efficient lithium extraction from produced water. To reduce manganese loss during desorption step using acid and enhance the lithium adsorption capacity of $H_{1.33}Mn_{1.67}O_4$ in shale gas wastewater, Li et al. utilized solid-phase synthesis to dope the $Li_{1.33}R_xMn_{1.67-x}O_4$ (R means the doped elements, including Fe, Ni, and Al) precursor, which was obtained through high-temperature calcination followed by

leaching under acidic conditions (Li et al., 2024). The resulting doping HMO-R materials exhibited significantly improved performance. The equilibrium adsorption capacities of the three doped adsorbents, namely $Li_{1.33}Fe_xMn_{1.67-x}O_4$, $Li_{1.33}Ni_xMn_{1.67-x}O_4$, and $Li_{1.33}Al_xMn_{1.67-x}O_4$, were 20.7 mg/g, 20.7 mg/g, and 29.0 mg/g, respectively, which are substantially higher than those of undoped materials (13.7 mg/g). Furthermore, the manganese dissolution loss during recycling was reduced by 30 %, demonstrating the positive impact of Fe, Ni, and Al doping on material modification and performance. These advancements make lithium adsorption materials more effective and reliable for extraction processes, particularly in challenging environments.

3.3.2. *Morphology and surface functional changes*

Granulation techniques offer significant benefits by enhancing the mechanical strength, improving flowability, and increasing mass transfer efficiency of materials. Yoo et al. developed high-porosity HTO particles using carboxymethyl cellulose nanofibers (CMCNFs) as binders (CMCNF@HTOs) and assessed their lithium adsorption performance (Yoo et al., 2024). Their study demonstrated that, under optimal conditions, using a 10:1 ratio of 5 wt% CMCNFs solution to HTO powder by weight, the resulting particles exhibited mechanical stability exceeding 93.48 % and porosity over 51.22 %. Additionally, the new material achieved a maximum lithium adsorption capacity of 34.72 mg/g, only slightly lower than the 41.49 mg/g observed for pure HTO powder, representing a reduction of just 6.77 mg/g. Similarly, Zhang et al. employed block copolymer poly (ethylene-co-vinyl alcohol) (EVAL) as a binder to synthesize HTO particles (Zhang et al., 2023). As illustrated in Fig. 9(a), the process involved dispersing HTO powder into a DMAC solution containing a specific concentration of EVAL, followed by injecting the mixture into deionized water to form stable porous spheres with enhanced mechanical strength and efficient adsorption performance. These newly developed EVAL-HTO porous spheres exhibited a lithium adsorption capacity of 11.8 mg/g and excellent Li^+ selectivity in real-world systems, underscoring their potential for practical lithium

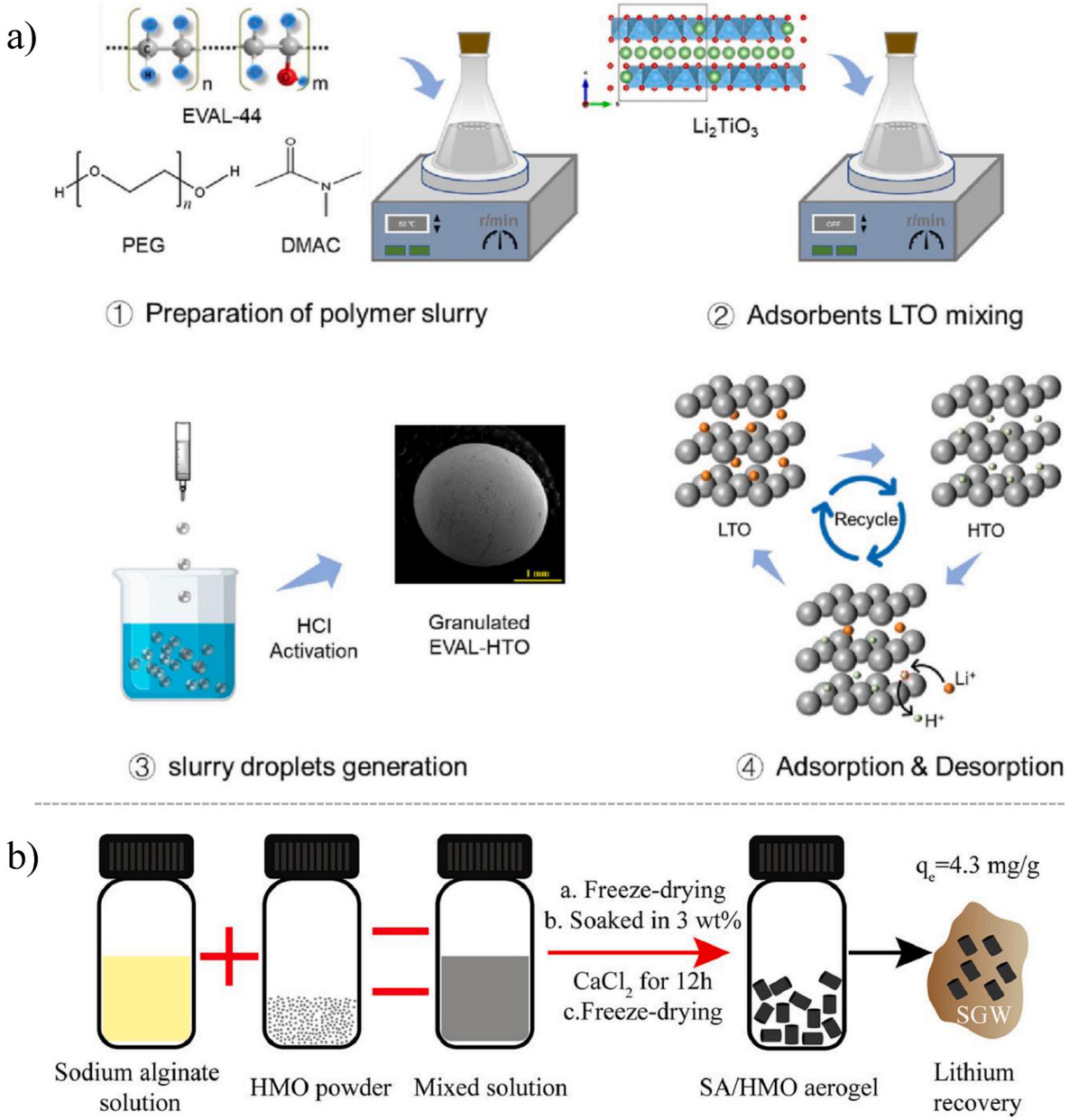

Fig. 9. (a) Schematic diagram for preparation, adsorption/desorption of Li^+ of porous EVAL-HTO spheres (Zhang et al., 2023); (b) Graphic abstract of "*Efficient Lithium Extraction from Shale Gas Wastewater Using Sodium Alginate/$H_{1.33}Mn_{1.67}O_4$ Composite Granular Adsorbents*" (Tian et al., 2023).

extraction applications. Additionally, Tian et al. utilized a similar granulation technique to fabricate $H_{1.33}Mn_{1.67}O_4$ granular adsorbents (Tian et al., 2023). They employed Ca^{2+} to crosslink the natural polymer sodium alginate (SA) and successfully synthesized sodium alginate/-manganese oxide (SA/HMO) composite granular adsorbents through a crosslinking method, as depicted in Fig. 9(b). These composite granules were then applied in a fixed-bed system for the continuous adsorption and recovery of lithium ions from shale gas produced water, demonstrating the effectiveness of the granulation approach in real-world lithium extraction applications.

Targeted optimization of lithium adsorption materials can be achieved by modifying their physical and chemical properties, such as morphology and surface functional groups. Xiao et al. successfully synthesized super hydrophilic spinel-type lithium-ion sieves ($H_4T_5O_{12}$, HTO-IV) using a dual-surfactant system consisting of CTAB and F127 (Xiao et al., 2024). This approach precisely tailored the surface morphology and wettability of the precursor materials, resulting in ultra-thin nanosheets with enhanced superhydrophilicity. The resulting HTO-IV lithium-ion sieve exhibited excellent surface hydrophilicity and a well-defined hierarchical mesoporous structure. It achieved a lithium adsorption rate exceeding 85 %, with a maximum adsorption capacity of 57.90 mg/g. In addition, Liu et al. designed a novel H_2TiO_3 lithium-ion sieve with a hollow structure and a large surface area of 111.57 m^2/g, utilizing TiO_2 hollow spheres as the precursor (Liu et al., 2024). This innovative structure demonstrated a high adsorption capacity of 47.0 mg/g while significantly reducing the dissolution loss of Ti^{4+} ions. These advancements not only improve lithium adsorption efficiency but also ensure greater material durability, making them highly viable for large-scale lithium recovery applications. By tailoring surface structure and properties, these modifications significantly improve adsorption capacity, selectivity, and stability, making the materials more effective in complex extraction environments.

4. Emerging materials prospect

4.1. Advanced membrane material

Organic membranes provide a cost-effective and efficient approach for oil/water separation. However, over time, oil and particulates can accumulate within their pores, significantly reducing their separation efficiency. Inorganic membranes, on the other hand, face limitations such as low permeability, performance degradation, sensitivity to flow variations, limited predictability of membrane lifespan, and relatively high production costs. In the pursuit of effective oil/water separation technologies, both organic and inorganic membranes hold promising potential for further development. With the ongoing optimization of membrane materials, configurations, and synthesis techniques, both types of membranes are poised to offer increasingly viable solutions for complex separations in industrial and environmental applications. A hybrid membrane bio-system has been proposed for removing organic constituents (99 %) and total dissolved solids (94 %), serving as an effective pretreatment step with minimal membrane fouling (Riley et al., 2016). Membrane fouling, limited pilot- and full-scale experience, and high energy consumption are key challenges in applying membranes for produced water treatment. Addressing these challenges requires further research into advanced membrane materials, systematic analysis of organic compounds, and energy generation from salinity gradients, which offer promising approaches to mitigate these issues.

4.2. Innovative strategies for advancing lithium adsorbents

(1) External Driving Force Addition

One of the key challenges in the adsorption and recovery of lithium from produced water is the low ionic driving force due to the low lithium concentration. The adsorption performance of most metal-based lithium adsorbents is highly dependent on the initial concentration of lithium, making it essential to introduce an external driving force to either the material or the produced water itself to enhance the efficiency of lithium-ion capture (Mojid et al., 2024). Electrochemical adsorption is a highly promising method that has garnered significant research attention. By applying an external electric field, ion migration is facilitated, enabling selective capture of Li^+ ions by the adsorbent material at the electrode (Wang et al., 2022). Through imparting conductivity to traditional adsorbents and utilizing them as electrode materials, this approach effectively supports the recovery of low-concentration lithium.

The application of an electric field not only accelerates the mass transfer rate of Li^+ ions but also works synergistically with the selectivity of the adsorbent material, enabling more targeted ion adsorption. By carefully designing the structure or surface functionalities of the electrode material, Li^+ ions can be preferentially captured, while interference from other ions, such as Na^+ and Mg^{2+}, is significantly reduced. This selective mechanism arises from the electrochemical properties of the material and the charge and size characteristics of lithium ions. Furthermore, in the absence of an electric field, Li^+ ions must overcome a high energy barrier to approach and be adsorbed onto the material's surface. The electric interactively lowers this energy barrier, making it easier for Li^+ ions to interact with the adsorbent material, thereby improving the adsorption capacity and overall performance of the system (Feng et al.).

(2) Mass Transfer Enhancement

Enhancing mass transfer in adsorbent materials is critical for efficient lithium recovery from low-concentration produced water. Accelerating Li^+ ion migration to adsorbent surface reduced diffusion resistance, boosting adsorption kinetics and capacity. Two advanced strategies show promise: spinning techniques (e.g., electrospinning/wet spinning) and hollow-structured materials. Electrospinning utilize and s electrostatic forces, where a high-voltage electric field stretches a polymer solution or melts into nanometer- or micrometer-scale fibers (Zhang et al., 2021b). On the other hand, wet spinning involves forming fibers through a chemical coagulation process in which a polymer solution is extruded into a coagulation bath (Guan et al., 2024). Researchers can modify and upgrade traditional lithium adsorbent materials using these spinning techniques to optimize their structure and functionality.

Materials with hollow structures share similar advantages in enhancing mass transfer (Purwajanti et al., 2016). Their unique design, which includes both internal cavities and external surfaces, leads to a substantial increase in specific surface area, exposing more active sites for ion exchange and adsorption. Additionally, the outer shell of hollow-structured materials typically offers good mechanical strength, ensuring structural stability during adsorption and desorption processes, especially when dealing with complex produced water (Alias et al., 2019). This durability helps prevent material degradation from repeated use.

(3) Bio-based Materials Functionalization

Bio-based materials (e.g., cellulose, chitosan, lignin) enhance lithium adsorbents through hierarchical porosity, tunable surface chemistry, and renewable nature (Bedian et al., 2017). Functionalization with these materials enhances adsorbent performance through three synergistic mechanisms: expanded specific surface area and improved active site dispersion for intensified Li^+ ion capture, particularly in hypersaline produced water; mechanical reinforcement and chemical stabilization via biomolecular crosslinking networks (Lee et al., 2022); selective lithium recognition enabled by targeted functional groups. The inherent biodegradability of bio-based components further reduces environmental footprint while enabling cost-effective adsorbent regeneration.

It is also important to highlight that while chemical modifications

have proven promising in optimizing lithium adsorbent performance, their associated drawbacks warrant systematic consideration to ensure balanced technological evaluation. The electrochemical enhancement approach, though effective in improving lithium selectivity and adsorption kinetics, raises concerns regarding increased energy demands and progressive material deterioration during prolonged operation. Bio-functionalization using sustainable biomaterials presents an eco-friendly pathway for efficiency enhancement yet concurrently introduces vulnerabilities in mechanical robustness under extreme operational conditions. Furthermore, the strategic incorporation of functional groups through chemical modification may inadvertently induce three critical secondary effects: (1) compromised long-term structural integrity, (2) increased susceptibility to pore occlusion phenomena, and (3) potential environmental contamination of these modified constituents. These inherent challenges and trade-offs highlight the necessity of simultaneously optimizing durability, recyclability, and sustainability in next-generation lithium adsorbents.

5. Lithium recovery process

By combining the strengths of advanced membrane and adsorbent materials, the integration of membrane pretreatment technology with adsorption-based lithium recovery presents a highly promising approach for produced water treatment. As illustrated in Fig. 10, produced water from mining operations is first subjected to coarse filtration to remove larger particulates and impurities. Although various physical methods can be used, membrane processes provide a promising approach for effectively targeting specific contaminants, such as organic impurities and oils in the produced water. The choice of membrane material at this stage is critical to ensuring effective removal and pretreatment performance. The pretreated produced water is then passed through an adsorption column packed with selective lithium adsorbents. These adsorbents enable the selective capture of Li^+ ions, where the efficiency of the adsorption process largely depends on the properties of the selected adsorbent materials. Additionally, the regenerability of these absorbents plays a vital role in ensuring the sustainability of the overall process. After adsorption, the treated water is discharged for reuse or disposal, while the lithium concentrate solution is collected for further processing into battery-grade lithium carbonate.

6. Future prospects of combining advanced membrane and adsorption materials

This integrated system combines advanced membrane treatment with adsorption materials, creating significant synergistic advantages for lithium recovery. The combination of these technologies ensures robust operational stability by facilitating phased removal of diverse contaminants, thereby mitigating performance fluctuations caused by variations in water quality.

From an environmental perspective, this hybrid process reduces ecological impacts by replacing solvent-based extraction (high VOC emissions) with membrane filtration (92 % oil/organics removal) (Marchese et al., 2000), eliminating the need for solvent-based liquid--liquid extraction processes, which are associated with high volatile organic compound (VOC) emissions (Clark et al., 2017). Additionally, adsorption-based lithium recovery reduces the reliance on large-scale evaporation ponds and minimizes the consumption of significant chemical reagents, thereby lowering environment impact (Jafarinejad and Esfahani, 2021). Lithium adsorbents maintain over 81 % of their adsorption capacity after several cycles, highlighting their potential for waste reduction and long-term reuse (Kaczorowska, 2024). Despite energy-intensive nanofiltration membrane (20 %–30 % higher energy vs. polymeric, offset 50 % longer lifesapn) and spent adsorbent disposal challenges, closed-loop regeneration systems could enhance sustainability (Politano et al., 2024).

From an economic perspective, this approach offers notable advantages. By integrating membrane filtration with adsorption recovery, the process significantly reduces reliance on chemical reagents, lowering operational costs associated with pH adjustment and chemical separation. The modular nature of membrane-adsorption technology allows for process scalability, enabling flexible deployment across various geological conditions and water compositions. Furthermore, this method has the potential to require lower energy requirements compared to precipitation-based lithium extraction, which could enhance its cost-effectiveness and industrial feasibility. The adaptability of membrane and adsorption materials to diverse produced water sources enhances its practicality, making it a promising candidate for widespread application in lithium extraction.

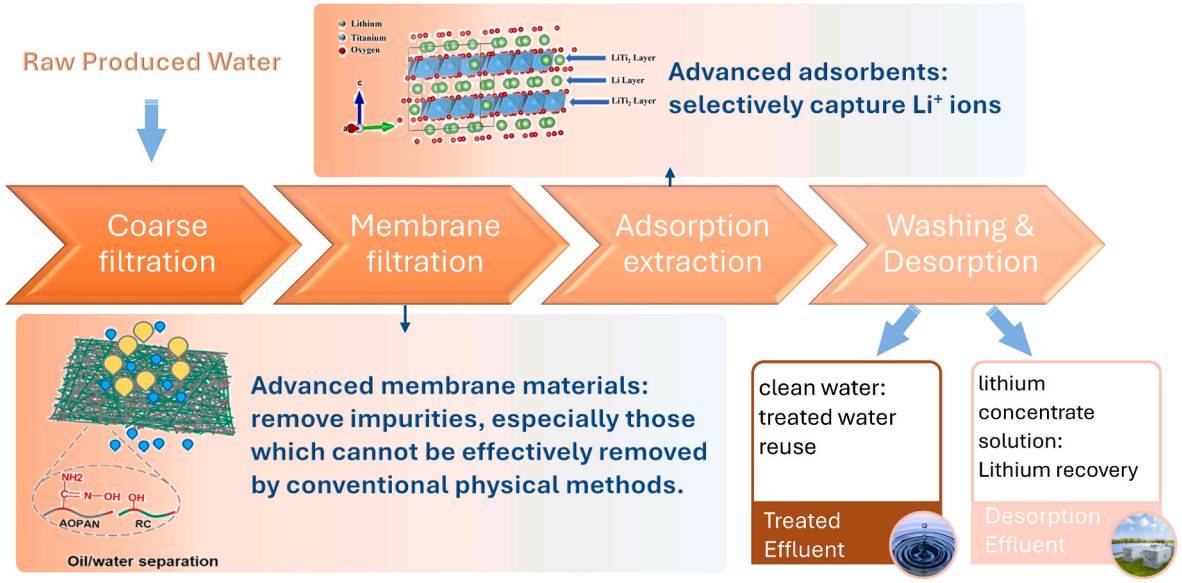

Fig. 10. A Schematic diagram illustrating the systematic process for lithium extraction from produced water through membrane material pretreatment combined with adsorption material recovery.

7. Conclusions

7.1. Summary of key findings

This review evaluates produced water's viability as a lithium source, proposing a membrane-adsorption hybrid process to enhance extraction efficiency and sustainability. The review first examines the pretreatment stage of produced water using advanced membrane materials, analyzing the effectiveness of various membranes, including PSO, PES, zeolite, and ceramic membranes, in removing impurities. Furthermore, we propose strategies to optimize membrane materials for pretreatment applications, including the integration of biofilm technology to extend membrane lifespan and improve stability, thereby enhancing the overall performance and economic viability of the process.

This review examines the performance of three conventional lithium adsorbents-LTOs, LMOs, and Li/Al-LDH-in lithium extraction from produced water. Research has primarily focused on LTOs due to their high lithium adsorption capacity and customizable structure. LMOs have also gained attention for their robust structural stability in complex produced water environments. However, both LTOs and LMOs face challenges, including dissolution losses of Ti and Mn during use, and their desorption processes require large amounts of acid, which constrains their viability for large-scale industrial applications. In contrast, Li/Al-LDH has seen limited application, largely due to the low lithium concentrations and complex organic content in produced water.

To further advance lithium extraction from produced water, we propose several innovative material strategies, focusing on improving efficiency and advancing material design.

1. Applying an external driving force (e.g., an electric field) to enhance adsorption efficiency, particularly in low-lithium-concentration environments.
2. Reducing the size of adsorbents by developing fibrous structures, which accelerate Li^+ mass transfer and improve adsorption kinetics.
3. Integrating bio-based materials, which provide porous architectures and abundant functional groups, enhancing both selectivity and adsorption capacity.

Compared with existing lithium extraction methods, this membrane-adsorption hybrid approach offers several distinct advantages.

1. Higher lithium recovery efficiency: This approach enhances lithium extraction rates by integrating selective impurity removal with targeted lithium capture.
2. Reduced chemical usage and waste production: This method significantly minimizes the need for acids and bases, leading to lower secondary waste generation.
3. Greater process stability and adaptability: This method is more flexible and can be applied across diverse produced water compositions and operating environments.
4. Economic feasibility and industrial scalability: By improving membrane longevity and enhancing adsorbent regeneration, this process helps lower operational costs, making it a viable and cost-effective solution for large-scale lithium recovery.

7.2. Future directions and call to action

Amid rising global lithium demand, this work presents an integrated membrane-adsorbent process to enable eco-efficient extraction from produced water. Future priorities include:

1. Pretreatment optimization: We encourage the exploration of novel membrane materials, such as biofilm-integrated systems, to better handle organic contaminants. Tailoring pretreatment strategies to the unique chemical composition of produced water will be crucial to enhancing downstream lithium adsorption recovery.
2. Materials development: Researchers should focus on engineering materials resistant to organic fouling and structural degradation. Exploring hybrid materials that integrate bio-based and inorganic components may yield promising results.
3. Innovative extraction techniques: Beyond conventional methods, new approaches like coupled electrochemical-adsorption systems and size-reduction technologies (e.g., fibrous adsorbents) should be further developed to enhance Li^+ ion transfer and capture efficiency in low-concentration environments. These techniques have the potential to overcome existing limitations and enable more efficient large-scale lithium adsorption.
4. Large-scale implementation and sustainable practices: Future work should prioritize energy-efficient and cost-effective methods that minimize environmental impact, align with industry standards, and promote sustainable practices. Additionally, developing robust life cycle assessments for lithium extraction processes will support informed decision-making and responsible resource management.

CRediT authorship contribution statement

Yanan Pan: Writing – original draft. **Weiquan Zhan:** Writing – review & editing, Writing – original draft. **Wencai Zhang:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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