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PROGRESS AND INNOVATIONS IN LITHIUM EXTRACTION METHODS

Eshonqulov Uchqun Xudaynazarovich
Karshi State Technical University, PhD, Associate Professor
Email: uchqun.eshonqulov91@mail.ru

Komilov Botir Askarovich
Karshi State Technical University, Assistant
Email: b.komilov@kstu.uz

Abstract: The rapid growth in global lithium demand, fueled by its essential role in advanced batteries and nuclear technologies, requires more efficient and sustainable extraction strategies. Lithium is commonly obtained from brines, hard rocks, and low-grade mineral resources through techniques such as precipitation, ion exchange, adsorption, electrolysis, and solvent extraction. This review summarizes current extraction approaches and evaluates their effectiveness in addressing rising consumption needs. Special attention is given to adsorption systems employing lithium-selective materials, as well as membrane-based methods including nanofiltration and electrodialysis, which enable continuous and energy-saving recovery. Electrochemical technologies are also examined for their ability to support lithium intercalation processes, highlighting the importance of optimized electrode design. In addition, emerging solutions such as electrosorption and advanced pumping systems are discussed. Key operational challenges, including temperature variation, impurity interference, and feed concentration, are analyzed. The study identifies research priorities focused on cost-efficient materials and improved electrochemical recovery systems to ensure long-term, sustainable lithium production.

Keywords: lithium; extraction; leaching; adsorption; reaction-coupled separation technology

Introduction.

Earth materials constitute the fundamental resource base for industrial and technological development, providing raw inputs for energy, construction, electronics, and advanced manufacturing. Among these resources, lithium has gained exceptional importance due to its unique physicochemical and electrochemical characteristics, including low density, high energy capacity, and strong reactivity. It occurs in various geological settings, primarily in brine deposits, pegmatitic rocks, and low-grade ores, and does not exist freely in nature. The rapid expansion of battery technologies initially stimulated lithium demand, and its strategic relevance has further increased with applications in nuclear systems and high-performance materials.

In the twenty-first century, lithium has become a cornerstone of energy storage technologies, especially in lithium-ion batteries used in portable electronics, electric vehicles, and grid-scale storage systems. The global transition toward low-carbon energy solutions has intensified the need for stable and sustainable lithium supply chains. Market analyses indicate continuous growth in lithium consumption over the coming decades, highlighting concerns about resource limitations and long-term availability. Consequently, efficient extraction, processing, and resource management strategies are critical to ensuring economic and environmental sustainability.

Traditionally, lithium has been recovered from hard-rock ores and saline brines through evaporation, concentration, and refining processes. However, these conventional approaches often involve high energy consumption, significant water usage, and ecological impacts. To address these limitations, alternative techniques such as adsorption using lithium-selective sorbents, membrane-based separations, electrochemical recovery, and reaction-coupled separation technologies have been developed. Improving extraction efficiency, reducing environmental burdens, and enhancing resource utilization remain central objectives in advancing lithium production technologies.

Methods of Lithium Recovery

Lithium recovery from brine and other saline resources is achieved through several physicochemical and electrochemical approaches that aim to improve selectivity, efficiency, and environmental performance. One of the widely applied techniques is liquid–liquid extraction, which relies on differences in ion solubility and distribution between aqueous and organic phases. In this process, lithium ions are selectively transferred into an organic phase and later re-extracted into a purified aqueous solution, followed by evaporation and precipitation steps to obtain lithium compounds. Although effective, this method may face challenges when lithium exhibits similar chemical behavior to coexisting salts.

Adsorption-based methods employ lithium-selective sorbents capable of capturing Li^+ ions from complex brine matrices. The effectiveness of this approach depends on sorbent stability, selectivity, regeneration capacity, and resistance to competing ions such as magnesium and calcium. Membrane technologies, including electrodialysis and nanofiltration, offer continuous and energy-efficient separation by enabling controlled ion transport under electrical or pressure gradients. These systems are particularly advantageous for treating brines with high Mg/Li ratios and for reducing water consumption compared to conventional evaporation techniques.

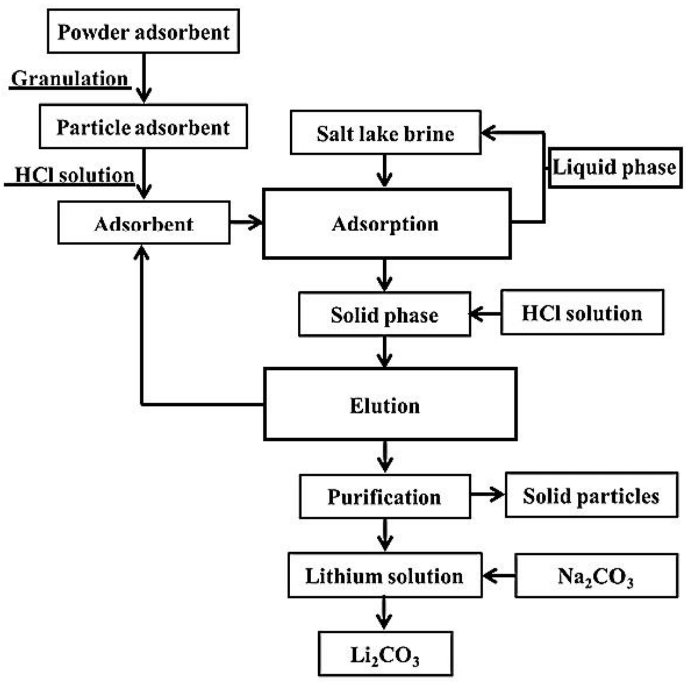

Figure 1. Technological flow diagram for lithium carbonate production from salt lake brine using the adsorption method.

Electrochemical recovery strategies utilize reversible lithium intercalation into electrode materials, allowing selective capture and release through controlled charging and discharging cycles. Additional innovations such as reaction-coupled separation, electrosorption, and ionic pump systems integrate chemical and electro-driven mechanisms to enhance lithium selectivity while minimizing reagent use and operational costs.

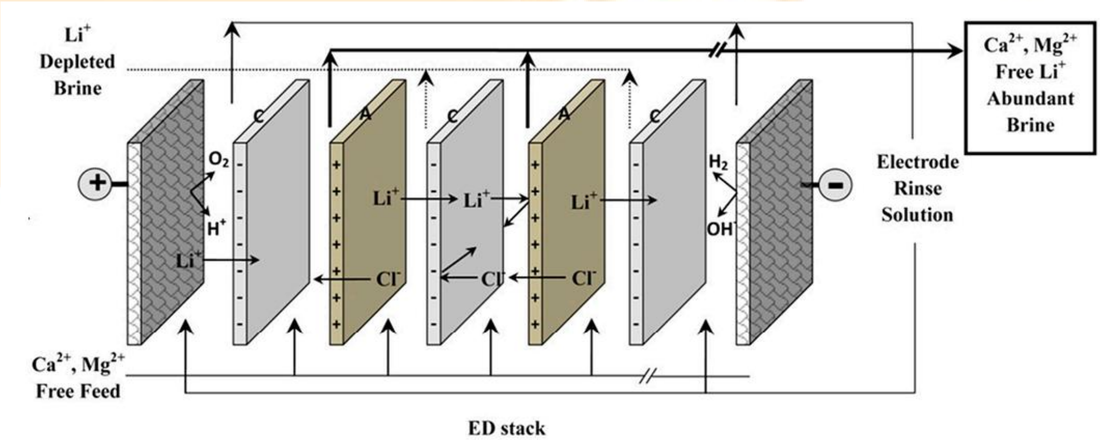

Figure 2. Schematic representation of an electrodialysis-based membrane system applied for lithium extraction.

Collectively, these emerging direct lithium extraction technologies represent promising alternatives to traditional evaporation-based production, supporting more sustainable and economically viable lithium supply chains.

Conclusion

The continuous growth in global demand for lithium, driven by the expansion of renewable energy systems and electric vehicles, necessitates the development of efficient, economically viable, and environmentally responsible extraction technologies. Traditional methods, while historically effective, are constrained by high resource consumption, long processing times, and environmental impacts. Emerging approaches such as Direct Lithium Extraction (DLE), advanced electrochemical systems, membrane-based separations, and reaction-coupled technologies demonstrate significant potential to enhance selectivity, reduce energy use, and minimize ecological footprints. Improvements in material science, process optimization, and system integration will be critical to achieving higher recovery efficiencies and operational stability. In addition, sustainable resource management, including lithium recovery from secondary sources such as spent batteries and industrial residues, will play an increasingly important role in ensuring long-term supply security. Ultimately, the future of lithium extraction will depend on the successful integration of technological innovation, environmental stewardship, and economic feasibility to support the global energy transition.

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