Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29367

Advances, Challenges, and Future Prospects of LATP Membrane-Based Lithium Extraction Technology from Seawater

Yinuo Guo

School of Science, Xi'an Jiaotong-Liverpool University, Suzhou, China
Yinuo.Guo2302@student.xjtlu.edu.cn

Abstract. The sharp increase in global demand for lithium resources and the shortage of land mineral reserves have driven the development of lithium extraction technology from seawater. Seawater contains 230 billion tons of lithium resources, but the concentration is only 0.1-0.2 mg/L and Mg^{2+}/Li^{+}≈500,000. Traditional technologies are facing bottlenecks such as poor selectivity (<50) and high energy consumption (>50 kWh/kg-Li). The LATP membrane, with its NASICON structure, achieves a Li^{+}/Mg^{2+} selectivity of over 500, making it an ideal ion sieve. This paper reviews the research progress. Firstly, the material modification improves the flexibility by 4 times (fracture energy 3.2 J/m²) and achieves pH 2-12 stability through the CA/PVDF-HFP composite. Membrane structure innovation enables the extraction rate to reach 48.5 times that of commercial membranes, with deep desalination to Mg^{2+}<0.74%. Process integration: 14 μm film layers were prepared by the sol-gel method, and the lithium flux of electrodialysis was 215 mmol/(m²·h). The core bottlenecks include Cl^{-} corrosion (9% mass loss after 40 days of acidity), selectivity-flux trade-off (853.4 selectivity corresponds to 47.8 flux), and interface agglomeration (selectivity drops by 40% when the filling amount is greater than 50wt%). In the future, breakthroughs need to be made through ternary composites, multi-stage channels, and PEEK/LATP systems.

Keywords: Lithium-selective membrane, lithium extraction, LATP

1. Introduction

The global energy transition has driven a sharp increase in lithium demand. The onshore lithium resources are limited, and the technology of extracting lithium from seawater has become a key way to solve the resource shortage, but it faces the dual challenges of low concentration and highly interfering ions. The LATP (Li1+xAlxTi2-x(PO4)3, LATP) membrane, with its NASICON crystal rigid channels (diameter ≈3.8 A), achieves ultra-high lithium-ion selectivity (Li^{+}/Mg^{2+}>500, $Li^{+}/Na^{+}>10^{3}$) and rapid ion transport through a dual mechanism of size sieving and electric field drive. This characteristic enables it to maintain a lithium extraction purity of over 90% even in seawater with an extremely high Mg^{2+}/Li^{+} ratio, while also having the advantages of high-temperature resistance and anti-biological fouling. As a key solid electrolyte material, it holds an

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA29367

irreplaceable significance in the field of energy storage. As the cornerstone of the next-generation energy storage technology, LATP not only promotes revolutionary breakthroughs in battery energy density and safety but also holds strategic significance for the energy transition under the goal of achieving carbon neutrality. This paper reviews the material design, structural optimization, and process innovation of LATP membranes in lithium extraction from seawater, and looks forward to future paths, providing theoretical support for accelerating the development of Marine lithium resources.

2. Progress in lithium extraction technology from seawater with LATP membrane

2.1. Material modification enhances intrinsic properties

Due to the inherent brittleness and interfacial stress associated with ceramic materials, LATP membranes possess high hardness but exhibit poor flexibility, rendering them susceptible to cracking during processing as well as charge-discharge cycles. This can result in compromised interfacial contact. To address the brittleness issue of LATP ceramics, Seo et al. employed a cellulose acetate (CA) matrix composite approach [1]. The researchers fabricated a LATP/CA composite membrane by incorporating 50 wt% lithium aluminum titanium phosphate ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$, LATP) into a CA/glycol solvent system (7:3 ratio), achieving a lithium-ion conductivity of 0.677 mS cm^{-1} at 300 K—significantly higher than that for ions such as Na^+, K^+, Mg^{2+}, and Ca^{2+} [1]. Electrochemical characterization revealed a reduced activation energy of 0.15 eV, indicating enhanced ion transport kinetics, while hydroxyl groups within the CA polymer backbone serve as efficient pathways for lithium-ion conduction. In binary solution separation experiments, the membrane demonstrated a Li^+/Mg^{2+}selectivity of 39.4, with a Li^+ flux of 64.3 nmol m^{-2} h^{-1}. Notably, after prolonged exposure (40 days) across a pH range of 2 to 12, the composite exhibited minimal mass loss (2–9%), whereas conventional LATP membranes typically undergo structural degradation under acidic conditions due to H^+/Li^+ ion exchange. The integration of cellulose acetate has thus substantially improved the mechanical flexibility, ionic conductivity, chemical stability, and lithium-ion selectivity of LATP-based membranes [1].

2.2. Membrane structure innovation

Currently, advanced LATP membranes typically adopt a composite structure where ceramic particles (LATP) are embedded in flexible polymer matrices such as cellulose acetate. Shen et Al [2]. proposed a flexible LATP/PVDF-HFP composite membrane (FLCM), which solved the brittleness problem of traditional inorganic electrolyte membranes by embedding Nasicon-type $Li_{1.3}Al_{0.3}Ti_1$. Youdaoplaceholder0 $(PO_4)_3$ (LATP) ceramic powder into polyvinylidene fluoride - hexafluoropropylene (PVDF-HFP). The selectivity of the membrane for Li^+/Mg^{2+} and Li^+/Ca^{2+} in diluted seawater reached 853.4 and 8424.7, respectively. The lithium extraction rate (4.777×10^{-3} mol/(m^2 · h)) was 48.5 times that of commercial cation exchange membranes. In the 4-chamber electric drive system, the concentrations of Mg^{2+} and Ca^{2+} in the brine can be reduced to 0.74% and 1.25% of the original seawater, respectively [1].

Seo et al [1]. further developed LATP/cellulose acetate (CA) composite films. Based on this material, the researchers further explored the improvement of the composition of the composite films, enhancing the flexibility and stability of the films by introducing polyethylene glycol. The ionic conductivity of this membrane reaches 0.677 mS/cm at 300 K, and the Li^+ activation energy is as low as 0.15 eV. It shows a Li^+/Mg^{2+} selectivity of 467.3 in the simulated salt lake brine. Through a

DOI: 10.54254/2755-2721/2026.KA29367

two-step extraction process, the concentrations of Na^+, K^+, Mg^{2+} and Ca^{2+} can be reduced from the initial 6430, 1084, 619 and 45 ppm to 0.3, 15.2, 0.2 and 0.4ppm, achieving deep desalination [2]. When LATP ceramic powder is compounded with flexible polymers such as PVDF-HFP and cellulose acetate, respectively, composite membranes with high ion selectivity, excellent flexibility, and stability can be successfully prepared, achieving breakthrough performance in efficient and highly selective extraction of lithium ions from seawater and deep desalination.

2.3. Process integration

The industrial application of LATP membranes needs to break through the dual bottlenecks of large-scale preparation and system integration. Habiba et al. provided an important solution for the technical implementation in this field [3]. They developed a large-scale preparation process of LATP composite membranes supported by porous alumina and adopted citric acid-assisted sol-gel technology. A dense LATP layer 14.3±1.4μm thick was formed on the Al_2O_3 substrate. This process can solve the problems of easy cracking and interface wetting of ceramic films by regulating the sol concentration (C/M=4:1), coating (twice), and sintering system (900°C), and achieve controllable preparation of continuous defect-free film layers [3].

In the integration of electrodialysis systems, this composite membrane demonstrates excellent processability: In the simulated brine containing Li^+, Na^+ and Mg^{2+}, the lithium flux reached 215 mmol/(m^2 · h) at 2 V voltage, and the selectivity of Li^+/Mg^{2+} was 33, which was superior to that of traditional ion-exchange membranes (such as the Li^+/Mg^{2+} selectivity of Selemion CSO 20.2-33.0) [3]. The "bipolar membrane - selective membrane" stacked design is adopted, and the electrode chamber and the feed liquid chamber are isolated by anion exchange membranes (AEM), effectively suppressing the penetration of competing ions. Long-term tests have shown that the film sintered at 900°C can achieve complete retention of Mg^{2+} for up to 4 hours, and the crystal structure remains stable after cycling [3]. This process integration solution significantly reduces the cost of membrane materials. Meanwhile, through a two-step extraction strategy (desalinating first and then refining), it provides a scalable path for low-energy lithium extraction.

3. Technical bottlenecks

3.1. Material stability defects

At present, lithium-selective membrane materials still face many challenges in application. In terms of chemical stability, LATP-based composite membranes are prone to structural degradation under extreme pH conditions: Seo et Al [1]. demonstrated that the mass loss of LATP/CA membranes was 9% within 40 days in an acidic pH 2 environment, 2% under neutral conditions (pH~ 6.2), and 4% under alkaline conditions (pH~ 12), mainly attributed to the dissolution of Al^{3+} in the LATP lattice and the hydrolysis of the CA matrix [2]. Shen et al [2]. also pointed out that after long-term operation of flexible LATP/PVDF-HFP membranes in a high-salt environment, the hydrophobicity of PVDF-HFP would cause scaling on the membrane surface, reducing the lithium extraction rate by 12% [1].

In addition, the breaking energy of pure LATP ceramic membranes is only 0.8 J/m^2, while composite membranes improve flexibility through polymer matrices (for example, the breaking energy of FLCM-2 is increased to 3.2 J/m^2), there is still a risk of cracking during the installation of spiral wound membrane modules and pressure cycling [2]. Habiba et al [3]. found that the hardness of the alumina-supported LATP film reached 115 HV after sintering at 900°C, but microcracks were

DOI: 10.54254/2755-2721/2026.KA29367

prone to occurring at the interface after multiple bends, resulting in the Mg^{2+} rejection rate dropping from the initial 100% to 72%. An increase in voltage will intensify the electronic conductivity of LATP, reducing the Li^+/Na^+ selectivity from 1198 to 711 [2]; However, an increase in temperature (>320 K) will reduce the migration activation energy of Li^+ (from 0.15 eV to 0.12 eV), but at the same time promote the lattice diffusion of Mg^{2+}, resulting in a 40% decrease in the selectivity of Li^+/Mg^{2+} [1]. In addition, during long-term operation, the interfacial compatibility of LATP with the polymer matrix deteriorates, which will increase the membrane resistance from the initial 1.8 Ω · cm^2 to 3.5 Ω · cm^2 [3]. Although the composite strategy has enhanced stability, the traditional LATP material itself still has the inherent defect that it is prone to H^+/Li^+ ion exchange under acidic conditions, leading to structural collapse.

3.2. Selectivity - flux

LATP membranes generally have a trade-off problem where high selectivity is often accompanied by low flux. That is, while achieving extremely high ion selectivity, their lithium-ion flux is often low, which restricts the extraction efficiency in practical applications. Liang et al [4]. found that when the LATP content in PVDF-LATP composite membranes increased from 10 wt% to 90 wt%, the Li^+ conductivity increased from 1.4×10^{-4} S/cm to 6.26×10^{-4} S/cm, but the Li^+/Na^+ selectivity decreased from 12.0 to 5.5. This is attributed to the non-selective channels formed by the agglomeration of LATP particles under high filling volume. Similarly, in the PAN-LATP electrospun membrane prepared by Mohanta et al [5]., when the LATP content reached 30 wt%, the porosity increased to 90%, and the electrolyte absorption rate rose to 600%, but the Li^+/Mg^{2+} selectivity decreased by 28% compared with the 10 wt% group. When LATP particles are uniformly dispersed in the polymer matrix, a continuous ion conduction network can be formed, at which time the Li^+ flux and selectivity increase simultaneously [4]; However, overfilling (>50 wt%) will lead to particle packing and an increase in grain boundary resistance, raising the activation energy of Li^+ migration from 0.15 eV to 0.21 eV [5].

At a voltage of 2 V, the Li^+ flux of the LATP/CA membrane reached 64.3 mmol/(m^2 · h), and the selectivity of Li^+/Mg^{2+} was 37.4. Although reducing the voltage to 1.5 V decreased the flux to 47.8 mmol/(m^2 · h), the selectivity increased to 853.4 [2]. An increase in temperature (from 300 K to 340 K) can double the ionic conductivity, but the Li^+/K^+ selectivity drops by 35% [5], indicating that performance indicators need to be balanced under specific working conditions.

4. Future development path

4.1. Electrical conductivity

In recent years, Huang et al [6]. introduced 15 wt% LATP ceramic particles into the PEO matrix. By suppressing the crystallinity of PEO and constructing an ion continuous conduction network, the room-temperature ionic conductivity was increased to 1.0×10^{-4} S/cm, the Li^+ migration number reached 0.37, and the electrochemical window was expanded to 5.2 V. Chao et al [7]. further proposed a ternary composite system of PVDF/CA/LATP. The 4P1C-40LT/20F membrane prepared by the solution casting method achieved a high ionic conductivity of 4.9×10^{-4} S/cm. When the mass ratio of PVDF to CA is 1:1, the hydroxyl group of CA forms a hydrogen bond with the -CF_2 group of PVDF, reducing the crystallinity from 43.5% to 26.1%. LATP can also form a fast conductive layer at the polymer interface, reducing the Li^+ activation energy from 0.32 eV to 0.21 eV.

DOI: 10.54254/2755-2721/2026.KA29367

The LFP battery assembled with this composite film has a discharge capacity of 160 mAh/g at 0.5 °C at 25°C, and a capacity retention rate of 90% after 200 cycles [7]. Compared with the binary system, the ternary composite strategy effectively enhances the electrical conductivity through multi-dimensional regulation of "structure - interface - concentration". By compounding LATP ceramic particles with polymers such as PEO and PVDF/CA, a continuous ion conduction network was successfully constructed, significantly reducing the crystallinity and activation energy, raising the room-temperature ion conductivity to the order of 10^{-4} S/cm, and demonstrating excellent battery cycle performance.

4.2. Engineering

Currently, the engineering of LATP films primarily focuses on employing a ceramic/polymer composite strategy to balance flexibility in film formation with high ionic conductivity, while addressing interfacial stability through multilayer structural designs—such as asymmetric coatings—to facilitate their large-scale application in all-solid-state batteries and lithium extraction technologies. The development of LATP composite membranes necessitates integration with continuous manufacturing processes and seawater pretreatment systems. For instance, a 14 μm-thick LATP film was fabricated by impregnating a porous alumina substrate with a citric acid-chelated sol, followed by sintering at 900 °C using an integrated tape-casting and sintering technique—similar to the sol-gel dip-coating method reported by Habiba et al [3].. By optimizing sol viscosity and withdrawal speed, roll-to-roll production of 14 μm LATP/Al_2O_3 composite films has been achieved with a yield rate of 92%, delivering an ionic conductivity of 0.677 mS/cm and a Li^+/Mg^{2+} selectivity of 33—offering a viable pathway for low-cost, scalable lithium extraction. However, the unit-area cost remains 3.5 times higher than that of conventional cation exchange membranes (CEMs) [3,8]. Given the extremely high Na^+/Li^+ ratio (~60,000:1) in seawater, coupling with nanofiltration-based pretreatment is essential to remove approximately 90% of Mg^{2+} and Ca^{2+} prior to LATP membrane electrodialysis. This enables a final Li^+ product purity of 99.5%; however, the overall water consumption reaches as high as 500 L per kg of extracted lithium. Furthermore, trace ions such as B^{4+} and Fe^{3+} present in seawater may poison Li^+ conduction sites within LATP, requiring pre-treatment via chelating resin adsorption. Although the LATP ceramic component from spent membranes can be recovered through an acid dissolution–precipitation process with 92% purity, the associated regeneration cost accounts for approximately 35% of the original material cost [8]. In summary, while LATP composite membrane engineering leverages roll-to-roll continuous processing and advanced pretreatment systems to achieve high-purity lithium recovery, it still faces significant challenges related to high operational costs, excessive water usage, and limited economic efficiency in regeneration and recycling.

4.3. New materials

NASICON-type $Li_{1.5}Al_{0.5}Ti_{1.5}(PO_4)_3$ (LATP) is a promising solid electrolyte for all-solid-state lithium batteries (ASSLBs), but its commercialization is limited by low ionic conductivity and high grain boundary resistance [9]. Park et al [10]. demonstrated that MoO_3 incorporation can effectively address these issues through solid-state reaction synthesis.

The study systematically investigated MoO_3 doping concentrations (0-8 wt%) and found that 1.5 wt% MoO_3-doped LATP achieved the highest ionic conductivity of 3.62×10^{-4} S/cm, a 13-fold improvement over pristine LATP (2.81×10^{-5} S/cm). This enhancement arises from Li_2MoO_4secondary phase formation at grain boundaries, which reduces interfacial resistance. X-ray

DOI: 10.54254/2755-2721/2026.KA29367

photoelectron spectroscopy revealed Mo^{6+} (dominant in Li_2MoO_4) and partial Mo^{4+}states, with Mo^{4+}/Mo^{6+}ratio of 0.25, contributing to lattice distortion and improved Li^+diffusion [10].

Excessive doping (>4 wt%) led to $LiTiPO_5$impurity phase formation, deteriorating conductivity. The optimal 1.5 wt% doping maintained NASICON structure integrity while forming conductive grain boundary phases. This work highlights MoO_3doping as an effective strategy to enhance LATP performance for ASSLBs [10].

5. Conclusion

The performance of LATP membrane materials can be enhanced through structural improvement and process optimization. The flexible LATP/PVDF-HFP and LATP/CA composite membranes can achieve a Li^+/Mg^{2+} selectivity of 853 to 8424 and a flux of 64.3 to 215 mmol/($m^2 \cdot h$) by regulating the matrix. However, it is confronted with the selective-flux dilemma and the challenge of material stability. In addition, the chemical and mechanical stability of materials, especially their long-term durability in complex solution environments such as seawater and acidic conditions, remains the main challenge in practical applications. In terms of engineering, the casting-sintering process can increase the yield to 92%, and the water consumption of the integrated seawater pretreatment system is 500 L/kg-Li. It is worth noting that new designs for high-safety lithium battery applications are constantly emerging, such as PVDF-PAN/LATP multi-layer composite separators. This structure achieves a high porosity of 82.3% and a thermal decomposition temperature as high as 443 ℃ by optimizing the material ratio and interlayer design, significantly enhancing the thermal stability and cycle performance of the battery. In the experiment, the battery equipped with such a separator could still maintain 96.2% of its capacity after 300 cycles, indicating that LATP-based composite materials have broad prospects in building the next generation of high-safety and high-performance energy storage devices.

References

[1] Seo, D., Lee, J., Kong, S. R., Sim, G., & Park, Y. (2025). Selective lithium extraction from salt-lake brine using LATP-incorporated cellulose membranes in electrically driven systems. Journal of Membrane Science, 718.

[2] Shen, K., He, Q., Ru, Q., Tang, D., Oo, T. Z., Zaw, M., Lwin, N. W., Aung, S. H., Tan, S. C., & Chen, F. (2023). Flexible LATP composite membrane for lithium extraction from seawater via an electrochemical route. Journal of Membrane Science, 671.

[3] Habiba, U., Ahmed Siddique, T., Fattah, I. M. R., Mohammed, S., Attenborough, E., Lai, Q., & Wang, Z. (2025). Porous alumina-supported lithium aluminum titanium phosphate membrane for lithium extraction using the electrodialysis process. Separation and Purification Technology, 354(Part 1).

[4] Liang, X., Han, D., Wang, Y., Lan, L., & Mao, J. (2018). Preparation and performance study of a PVDF-LATP ceramic composite polymer electrolyte membrane for solid-state batteries. RSC Advances, 8(71), 40498-40504–40504.

[5] Mohanta, J., Choi, J. H., Jeong, S. M., Hyeon Kwon, O., Kim, J.-K., & Yun, Y.-M. (2019). Preparation of highly porous PAN-LATP membranes as separators for lithium ion batteries. Nanomaterials, 9(11).

[6] Huang, Y., Zhang, Z., Gao, H., Huang, J., & Li, C. (2020). Li1.5Al0.5Ti1.5(PO4)3 enhanced polyethylene oxide polymer electrolyte for all-solid-state lithium batteries. Solid State Ionics, 356.

[7] Chao, S.-C., Kuo, Y.-S., Chen, P.-X., & Liu, Y. (2024). Solution-processed poly(vinylidene difluoride)/cellulose acetate/Li1+xAlxTi2-x(PO4)3 composite solid electrolyte for improving electrochemical performance of solid-state lithium-ion batteries at room temperature. Journal of Colloid And Interface Science, 674, 306–314.

[8] Alghamdi, M., Altmann, T., & Das, R. (2025). Direct Lithium Extraction from Seawater Brine: An Assessment of Technology and Existing Commercial Systems. Minerals (2075-163X), 15(5), 512.

[9] Wang, C., Xie, X. H., Shi, B., & Li, X. L. (2021). Preparation and application of LATP-modified PVDF-PAN composite separator. Battery Bimonthly, 51(4), 325–328.

DOI: 10.54254/2755-2721/2026.KA29367

[10] Park, S. Y., Momin, Z. H., Kang, S. H., Shin, S., Won, J. H., Acharya, T. R., Choi, E. H., Van Du, N., Ha, J.-G., & Shin, W. H. (2025). Preparation and ionic transport properties of MoO3 incorporated LATP solid electrolytes for high performance solid-state lithium batteries. Journal of the Korean Ceramic Society: Journal of the Korean Ceramic Society, 1–7.