



Experimental Study on the Separation of Lithium and Imidazolium Ions Using a Cation Exchange Membrane

Jingyi Xue⁺, Xiang Meng⁺, Runci Wang, Zhongwei Yuan *^D and Weifang Zheng *

Department of Radiochemistry, China Institute of Atomic Energy, Beijing 102413, China; xuejingyi0925@163.com (J.X.); mengxiang199603@163.com (X.M.); wangrunci@163.com (R.W.) * Correspondence: yuanzw99@163.com (Z.Y.); zhengwfcn@163.com (W.Z.)

⁺ These authors contributed equally to this work.

Abstract: The separation of Li⁺ and [Bmim]⁺(1-Butyl-3-methylimidazolium) using a cation exchange membrane in an electric field is studied in this work. The effects of the type of cation exchange membrane, current density, total cation concentration, temperature, and anion types on the separation efficiency are investigated. The results indicate that it is feasible to achieve the efficient separation of Li⁺ and [Bmim]⁺ using the selectivity of cation exchange membranes under an electric field. The CIMS membrane (a type of cation exchange membrane produced by ASTOM Corporation) shows obvious selectivity of Li⁺ from [Bmim]⁺. When the current density is 5 mA/cm² and the feed concentrations of Li⁺ and [Bmim]⁺ are 0.3 mol/L and 0.2 mol/L, respectively, the selective transport coefficient of CIMS can reach 5.9 in the first 120 min of the process. The separation efficiency can be effectively improved by reducing the current density and increasing the total cation concentration. Decreasing the feed temperature can slightly improve the separation efficiency. Changing the type of anion in the feed from chloride to acetate has no detectable effect on the separation.

Keywords: lithium ions; imidazolium cations; cation exchange membrane



Citation: Xue, J.; Meng, X.; Wang, R.; Yuan, Z.; Zheng, W. Experimental Study on the Separation of Lithium and Imidazolium Ions Using a Cation Exchange Membrane. *Separations* **2024**, *11*, 123. https://doi.org/10.3390/ separations11040123

Academic Editor: Sascha Nowak

Received: 25 March 2024 Revised: 12 April 2024 Accepted: 16 April 2024 Published: 19 April 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).

1. Introduction

Lithium mainly exists in lithium ores, salt-lake brine and seawater. After years of development, lithium ore resources are on the verge of depletion. Therefore, obtaining lithium resources from salt-lake brine, geothermal brine, seawater and lithium-containing industrial wastewater is of strategic importance [1–5].

Lithium-ion batteries are widely used in electronic products, large-scale energy storage, military applications, aerospace and other fields due to the advantages of their high specific energy, long life cycle and no memory effect [6–8]. Currently, the organic electrolytes used in lithium-ion batteries are flammable and explosive, posing a major safety hazard at high power densities [9–12]. Ionic liquids (ILs), with high ionic conductivity, low viscosity, excellent thermal stability, negligible vapor pressure, and a wide electrochemical window [13–15], are expected to solve the safety problems of lithium-ion batteries and improve their electrochemical performance [16–18]. In addition, ILs can also broaden the operating voltage of the battery [19] and increase its temperature range. However, ILs are expensive due to their high production costs, resulting in a high threshold for their application [20–22]. On the other hand, a large amount of waste liquid containing a low concentration of ionic liquids is generated, which needs to be properly disposed of prior to discharge. Otherwise, the potential toxicity of ionic liquids and their low natural degradation property will increase the risk of environmental pollution [23–25].

Currently, the separation and recovery of lithium ions mainly focus on the separation of Li⁺ from divalent cations such as Mg^{2+} , Ca^{2+} , Co^{2+} , Ni^{2+} , Mn^{2+} , and Fe^{2+} [26–31], and there are also some reports on the separation of Li⁺ from Na⁺ and K⁺ [32–34]. [Bmim]⁺(1-Butyl-3-methylimidazolium) is an ionic liquid cation with promising applications in high-voltage

electrolytes for lithium-ion batteries, but there are few reports on the separation of Li⁺ and [Bmim]⁺ cations. Because these cations have the same charge properties and charge numbers, the separation between these monovalent cations is difficult. The research on the separation of Li⁺ and [Bmim]⁺ cation can provide technical support for the recovery of new high-efficiency lithium-ion batteries using ionic liquid as an electrolyte in the future, and can also provide reference for the separation of other monovalent cations.

Considering the size and structural differences between Li⁺ and [Bmim]⁺ cations, there exists a competitive migration phenomenon when they pass through the cation exchange membrane. Driven by an electric field, this work explores a green separation method of Li⁺ and [Bmim]⁺ cations without the addition of external reagents.

2. Experimental Section

2.1. Equipment and Methods

The membrane module was the core part of the electrodialysis equipment, and its structure is shown in Figure 1, including a feed chamber, a lithium-ion product chamber, a lithium chloride circulation chamber, and electrode chamber. The feed was 150 mL of LiCl and [Bmim]Cl, and after the experiment, a separated [Bmim]Cl solution was obtained. A volume of 150 mL of deionized water was added to the lithium-ion product chamber, and after the experiment, a separated LiCl solution was obtained. The purpose of the two lithium chloride circulation chambers was to prevent the separated [Bmim]Cl and LiCl from mixing with the anolyte and catholyte. A volume of 150 mL of 0.1 mol/L LiCl solution was circulated in these chambers. Two electrode chambers were connected to share the same solution (150 mL 0.1 mol/L LiNO₃) to maintain the pH value. The effective area of each ion exchange membrane in the device was 50 cm². The solution was circulated via peristaltic pumps. The anode and cathode were made from ruthenium-coated titanium and titanium, respectively. The separation unit was powered by a constant-current DC power supply (omitted from the figure).



Figure 1. Schematic diagram of the experimental device and membrane stack: 1—feed chamber; 2—lithium-ion product chamber; 3—lithium chloride circulation chamber; 4—electrode chamber; 5—pump; 6—membrane stack; 7—DC power supply.

The selective transport coefficient $T_{[Bmim]^+}^{Li^+}$ was used to evaluate the separation efficiency of the membrane, which could be calculated as follows:

$$T^{\text{Li}^{+}}_{[\text{Bmim}]^{+}} = \frac{\Delta Q_{t}(\text{Li}^{+}) / \Delta Q_{t}([\text{Bmim}]^{+})}{Q_{0}(\text{Li}^{+}) / Q_{0}([\text{Bmim}]^{+})}$$

where:

 $\Delta Q_t(Li^+)$ is the decrease in the concentration of Li⁺ in the feed chamber in each period, mol; $\Delta Q_t([Bmim]^+)$ is the decrease in the concentration of $[Bmim]^+$ in the feed chamber in each period, mol;

 $Q_0(Li^+)$ is the initial amount of Li^+ in the feed chamber in each period, mol;

 $Q_0([Bmim]^+)$ is the initial amount of $[Bmim]^+$ in the feed chamber in each period, mol.

2.2. Reagents and Materials

Lithium chloride and 1-butyl-3-methylimidazole chloride were purchased from Macklin. Four types of cation exchange membranes were studied. These were commercial cation exchange membranes, namely N-117 (Jiangsu Thinkre Membrane Materials Co., Ltd., Huai'an, China), CMB, CMX and CIMS (Astom Corportation, Tokyo, Japan), the properties of which are listed in Table 1.

embranes

Membrane Type	Resistance (Ω·cm ²)	Bursting Strength (MPa)	Thickness (mm)	Temperature (°C)	pН	Ion Exchange Capacity (meq/g)
N-117		\geq 28 (Tensile strength)	0.175			
CMB	4.5	≥ 0.40	0.21	≤ 40	0~14	2.7~2.8
CMX	3.0	≥ 0.40	0.17	≤ 40	0~10	1.5~1.8
CIMS	1.8	≥ 0.10	0.15	≤ 40	0~10	2.0~2.5

2.3. Analytical Methods

2.3.1. The Concentration of [Bmim]+

The concentration of $[Bmim]^+$ was determined by means of UV spectrophotometry (Cary 3500 UV-Vis, Agilent Technologies Inc., Santa Clara, CA, USA). The maximum absorption wavelength of $[Bmim]^+$ was 211 nm. We weighed out several grams of [Bmim]Cl, then dissolved it in 500 mL of deionized water. Then, we diluted this to obtain solutions with concentrations of 10, 20, 30, 40, and 50 mg/L, respectively. The standard curve was obtained from these solutions, as shown in Figure 2. The standard curve equation is y = 0.095 + 3.981x, $r^2 = 0.999$.



Figure 2. Standard curve of the [Bmim]Cl aqueous solution.

2.3.2. The Concentration of Li⁺

The concentration of Li⁺ was analyzed via ICP-OES (iCAP 7000, Thermo Fisher Scientific Inc., Waltham, MA, USA). The analysis method was the standard curve method, which is mainly suitable for samples with coexisting components that do not interfere with each other. A 1 mol/L lithium chloride solution was diluted to obtain solutions with concentrations of 2, 4, 6, 8, and 10 mg/L, respectively. The standard curve was obtained from these solutions, as shown in Figure 3. The standard curve equation is y = 824 + 12087x, $r^2 = 0.999$.



Figure 3. Standard curve of the LiCl aqueous solution.

3. Results and Discussion

3.1. Comparison of Cation Exchange Membranes

The current density was set to 5 mA/cm², and the feed concentrations of Li⁺ and [Bmim]⁺ were 0.3 mol/L and 0.2 mol/L, respectively. The separation performances of the selected membranes for Li⁺ and [Bmim]⁺ were compared. The results are shown in Figure 4. All four of the tested membranes showed selective transport of Li⁺ from [Bmim]⁺, and the CIMS showed the best performance, with a selective transport coefficient of up to 5.9 in the first 120 min. The selectivity performance of N-117 and CMX was not satisfactory, with the selection transport coefficients in the first 120 min being 1.53 and 1.60, respectively. The transport coefficient of CMB in the first 120 min was 2.02.



Figure 4. Effect of cation exchange membrane on the selective transport coefficients.

3.2. The Effect of Current Density

Since the CIMS showed the best separation performance, the experiments were carried out using the CIMS in all subsequent studies. We set the concentrations of Li⁺ and [Bmim]⁺ to 0.3 and 0.2 mol/L, respectively. Constant current densities of 5, 10, and 20 mA/cm² were applied to investigate the influence of current density on the process. The changes in Li⁺ and [Bmim]⁺ concentrations over time are shown in Figure 5. It can be seen that the rate of decrease of the [Bmim]⁺ concentration increased gradually, while the rate of decrease of the Li⁺ concentration slowed down gradually. In the initial stage of the process, due to the membrane's selectivity, Li⁺ preferentially undergoes transmembrane transport. As the process progresses, the Li⁺ content in the solution gradually decreases, and the total amount of cations migrated is fixed during the constant current process. More [Bmim]⁺ ions replace Li⁺ ions for transmembrane migration, resulting in this phenomenon.



Figure 5. Changes in Li⁺ (a) and [Bmim]⁺ (b) concentration over time.

Different current densities result in different separation times for the same solution. It is more convenient to study the effect of current density on the separation process under the same electric quantity passing through the membrane. As the current efficiency approaches 100%, the electric quantities were obtained by multiplying the current density by time, and the calculation method for selective transport coefficients is shown in Section 2.1. The selective transport coefficients of Li⁺ and [Bmim]⁺ with the electric quantity are shown in Figure 6. It can be seen that when the current density is 5 mA/cm², the selective transport coefficient is the highest, and Li⁺ is more likely to pass through the membrane. The selective transport coefficient decreases significantly with the increase in current density, which is due to the fact that the major factors affecting the ED process are different under different current densities. According to Kohel Urano [35], the transport coefficient is controlled by the diffusion rates through the ion exchange membrane when current density is low (state determined by diffusion through membrane), and the transport coefficient becomes proportional to the mobilities of ions in the boundary layer because of concentration polarization when the current density increases (state determined by diffusion in solution).



Figure 6. Effect of current density on selective transport coefficients of Li⁺ and [Bmim]⁺.

3.3. The Effect of Total Cation Concentration

Section 3.2 shows that among the applied current densities of 5, 10, and 20 mA/cm², the best performance was obtained at 5 mA/cm^2 . Thus, all the subsequent experiments were carried out at a current density of 5 mA/cm^2 .

The concentration ratio of $\text{Li}^+/[\text{Bmim}]^+$ was fixed at 3:2. In order to investigate the effect of total cation concentration, its values were set to 0.25 mol/L, 0.5 mol/L, and 1.5 mol/L, respectively. The changes in Li⁺ and [Bmim]⁺ concentrations over time are shown in Figure 7. Similar to the experimental phenomenon of current density mentioned earlier, under all three conditions, there was a trend of a gradual increase in the [Bmim]⁺ concentration reduction rate and a gradual slowing down of the Li⁺ concentration reduction rate. The total cation concentration is different, but the selective transport coefficient with the same percentage of ions passing through the membrane can indicate the separation efficiency. The variation of selective transport coefficients with the percentage of ions passing through the membrane is shown in Figure 8. It can be seen from Figure 8 that selective transport coefficients increase with the increase in the total cation concentration. When the total concentration of Li⁺ and [Bmim]⁺ is 0.25 mol/L, 0.5 mol/L and 1.5 mol/L, the maximum selective transport coefficients are 3.98, 5.90 and 6.63, respectively.



Figure 7. Changes in Li⁺ (a) and [Bmim]⁺ (b) concentration over time.



Figure 8. Effect of total cation concentration on the selective transport coefficients of Li⁺ and [Bmim]⁺.

We firstly need to discuss the separation mechanism of Li+ and [Bmim]+ in order to explain the above phenomenon. Because Li⁺ and [Bmim]⁺ have the same charge numbers, the ionic radius of Li⁺ is 0.071 nm [36] and the size of [Bmim]⁺ is approximately 0.5 nm \times 0.6 nm \times 1.0 nm [37], and the spatial scale difference between these two is significant. Thus, we believe that the electrostatic barrier effect is not important, while the sieving effect is the major cause of the selectivity of Li⁺ and [Bmim]⁺. When the total concentration of Li⁺ and [Bmim]⁺ increases, the sieving effect is still in effect though the loss of the charge-exclusion ability, so the selective transport coefficient will not decrease. Moreover, an increase in total concentration (with the same ratio of Li⁺ and [Bmim]⁺) leads to a higher concentration in the solution and the boundary layer, causing lower resistance and shifting kinetic control from the boundary layer to the membrane in a similar way as for a decrease in current density, as discussed in Section 3.2.

3.4. The Effect of Temperature

With the concentrations of Li⁺ and $[Bmim]^+$ at 0.3 and 0.2 mol/L, at a current density of 5 mA/cm², the effect of feed temperature on the process is shown in Figure 9. It can be seen that compared to feed temperatures of 20 and 35 °C, when the material liquid temperature is set to 5 °C, the selective transport coefficients are slightly higher. However, the improvement in the separation efficiency caused by reducing the temperature is limited. The reason for this may be that the swelling degree of the membrane increases with the increase in the feed temperature, leading to an increase in the membrane pore size. Therefore, Li⁺ and $[Bmim]^+$ in the solution are both more likely to undergo transmembrane transport.



Figure 9. Effect of temperature on the selective transport coefficients of Li⁺ and [Bmim]⁺.

This phenomenon is very similar to Zhao's report [38], which investigated the selective transport coefficients of $Li^+-M^{n+}(M^{n+}: Na^+, Mg^{2+}, Ca^{2+})$ in the electrodialysis process with a temperature ranging from 10 °C to 30 °C and found that the selective transport coefficient displayed little variation caused by temperature. The swelling degree of the membrane increases with the feed temperature [39], while the number of hydrated ions decreases with feed temperature [40]. The above two factors result in the separation coefficient being almost independent of temperature.

3.5. The Effect of Anion Types

With the concentrations of Li⁺ and $[Bmim]^+$ at 0.3 and 0.2 mol/L, at a current density of 5 mA/cm², the effect of anion type on separation efficiency was investigated by changing the anions from Cl⁻ to CH₃COO⁻ (acetate). The change in the selective transport coefficients with time is negligible, as shown in Figure 10. Changing the chloride ions in the system to acetate ions has almost no effect on the separation efficiency. Acetate and chloride ions do not complex with imidazole cations, and the two ionic liquids dissociate completely in the aqueous solution. Therefore, changing the chloride ions in the system to acetate ions has almost no effect on the separation efficiency.



Figure 10. Effect of anion types on the selective transport coefficients of Li⁺ and [Bmim]⁺.

Through the above studies, it can be seen that by using CIMS as the separation membrane, setting the current density to 5 mA/cm^2 and using a higher concentration of feed, better separation performance can be obtained.

4. Conclusions

This research work demonstrated that it is feasible to utilize the selectivity of cation exchange membranes to realize the efficient separation of Li⁺ and [Bmim]⁺ ions under the driving effect of an electric field. The results show that the CIMS membrane showed the best selectivity for Li⁺ and [Bmim]⁺. Reducing the current density and increasing the total ion concentration are beneficial measures for the separation process. Compared with 10 and 20 mA/cm², a lower current density of 5 mA/cm² provides better separation performance for Li⁺ and [Bmim]⁺, with selective transport coefficients up to 5.9 under test conditions. When the total concentration of Li⁺ and [Bmim]⁺ is 1.5 mol/L, the maximum selective transport coefficient is 6.63. In addition to these results, compared to 20 and 35 °C, when the feed temperature was set to 5 °C, the selective transport coefficients increased slightly. In addition, changing the chloride ions in the system to acetate ions has almost no detectable effect on the separation efficiency.

Funding: This work was funded by Youth Fund of Department of Radiochemistry, China Institute of Atomic Energy.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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

References

- 1. Su, H.; Zhu, Z.; Wang, L.; Qi, T. Research progress in extraction and recovery of lithium from hard-rock ores. CIESC J. 2019, 70, 10–23.
- Shang, X.; Meng, Y.; Zhang, Q.; Yang, H. Lithium Extraction and Strategic Application of Lithium-rich Minerals. *Conserv. Util. Min. Res.* 2019, 39, 152–158.
- 3. Qin, X.; Gao, X.; He, Y.; Xing, H.; Zhang, R. Recent advances in lithium extraction from salt lake brine using Ti-based ion sieve absorbent. *J. Salt Lake Res.* 2023, *31*, 91–101.
- 4. Zhu, H.; Bai, Y.; Zu, L.; Bi, H.; Wen, J. Separation of Metal and Cathode Materials from Waste Lithium Iron Phosphate Battery by Electrostatic Process. *Separations* **2023**, *10*, 220. [CrossRef]
- Wang, K.; Zhang, G.; Luo, M. Recovery of Valuable Metals from Cathode—Anode Mixed Materials of Spent Lithium-Ion Batteries Using Organic Acids. Separations 2022, 9, 259. [CrossRef]
- 6. Chen, G.; Sun, X.; Zhang, X.; Wang, K.; Ma, Y. Progress of high-power lithium-ion batteries. Progress of high-power lithium-ion batteries. *CJEE* **2022**, *44*, 612–624.
- 7. Luo, G. Application of High Performance Li ion Battery. Yunnan Chem. Technol. 2021, 48, 105–107.
- 8. Smart, M.; Ratnakumar, B.; Whitcanack, L.; Chin, K.; Surampudi, S.; Byers, J.; Gitzendanner, R.; Puglia, F. Lithium-ion batteries for aerospace. *IEEE Aerosp. Electron. Syst. Mag.* 2004, 19, 18–25. [CrossRef]
- 9. Golozar, M.; Paolella, A.; Demers, H.; Bessette, S.; Lagacé, M.; Bouchard, P.; Guerfi, A.; Gauvin, R.; Zaghib, K. In situ observation of solid electrolyte interphase evolution in a lithium metal battery. *Commun. Chem.* **2019**, *2*, 131. [CrossRef]
- Eliana, Q.; Piercarlo, M. Electrolytes for solid-state lithium rechargeable batteries: Recent advances and perspectives. *Chem. Soc. Rev.* 2011, 40, 2525–2540.
- 11. Jin, Y.; Xue, Z.; Jiang, X.; Lu, N. Research Progress of Safety Protection of Lithium-ion Energy Storage Power Station. J. Zhengzhou Univ. Nat. Sci. Ed. 2023, 55, 1–13.
- 12. Wang, Q.; Ping, P.; Zhao, X. Thermal Runaway Caused Fire and Explosion of Lithium Ion Battery. *J. Power Sources* **2012**, 208, 210–224. [CrossRef]
- 13. Garcia, B.; Lavallée, S.; Perron, G.; Michot, C.; Armand, M. Room temperature molten salts as lithium battery electrolyte. *Electrochim. Acta* **2004**, *49*, 4583–4588. [CrossRef]
- Cheng, H.; Nie, X.; Shen, Y. Performance of Piperidine Ionic Liquid Based Mixed Electrolyte in Li/LiCoO₂ Cell. J. Electrochem. 2017, 23, 59–63.
- 15. Yang, S.; Zhao, D.; Zhao, Y.; Zhai, J. Research progress of ionic liquid in lithium-ion batteries electrolyte. *Chin. J. Power Sources* **2016**, *40*, 912–914.
- Liu, K.; Wang, Z.; Shi, L.; Jungsuttiwong, S.; Yuan, S. Ionic liquids for high performance lithium metal batteries. *J. Energy Chem.* 2021, 59, 320–333. [CrossRef]
- Ahmed, F.; Rahman, M.M.; Sutradhar, S.C.; Lopa, N.S.; Ryu, T.; Yoon, S.; Choi, I.; Kim, J.; Jin, Y.; Kim, W. Synthesis of an imidazolium functionalized imide based electrolyte salt and its electrochemical performance enhancement with additives in li-ion batteries. J. Ind. Eng. Chem. 2019, 78, 178–185. [CrossRef]
- Papović, S.; Cvjetićanin, N.; Gadžurić, S.; Bešter-Rogač, M.; Vraneš, M. Physicochemical and Electrochemical Characterisation of Imidazolium Based IL + GBL Mixtures as Electrolytes for Lithium-Ion Batteries. *Phys. Chem. Chem. Phys.* 2017, 19, 28139–28152. [CrossRef]
- 19. De Anastro, A.F.; Lago, N.; Berlanga, C.; Galcerán, M.; Hilder, M.; Forsyth, M.; Mecerreyes, D. Poly(ionic liquid) iongel membranes for all solid-state rechargeable sodium battery. *J. Membr. Sci.* **2019**, *582*, 435–441. [CrossRef]
- Liu, Y.; Hedin, N.; Jia, L.; Nie, Y. Studies on reaction kinetics and phase changes during the synthesis of ionic liquids using an in-situ low field MRI spectrometer. *Chin. J. Chem. Eng.* 2020, 20, 807–821.
- 21. Wang, M.; Zhang, L.; Yang, M.; Hu, W. Synthesis and Preparation of [NH₂ e-mim][BF₄]. J. Wuhan Polytech. Univ. 2014, 2, 41–45.
- 22. Liu, H.; Wei, X.; Li, J.; Li, T.; Wang, F. Review of Ionic Liquids Recycling. J. Cell. Sci. Technol. 2013, 21, 63–69.
- 23. Docherty, K.M.; Kulpa, C.F., Jr. Toxicity and antimicrobial activity of imidazolium and pyridinium ionic liquids. *Green Chem.* **2005**, *7*, 185–189. [CrossRef]
- 24. Horowitz, A.I.; Wang, Y.; Panzer, M.J. Reclamation and reuse of ionic liquids from silica-based ionogels using spontaneous water-driven separation. *Green Chem.* **2013**, *15*, 3414–3420. [CrossRef]
- 25. Viboud, S.; Papaiconomou, N.; Cortesi, A.; Chatel, G.; Draye, M.; Fontvieille, D. Correlating the structure and composition of ionic liquids with their toxicity on Vibrio fischeri: A systematic study. *J. Hazard. Mater.* **2012**, 215–216, 40–48. [CrossRef] [PubMed]

- Miao, S.; Shi, L.; Song, Z.; She, J.; Chen, X.; Wu, C.; Lu, X. Preparation of nanofiltration membranes with dually charged separation layer for Mg²⁺/Li⁺ separation. *Membr. Sci. Technol.* 2023, 43, 37–43.
- Luo, Q.; Dong, M.; Li, J.; Liu, Z.; Wu, Z.; Ye, X.; Huang, X.; Wang, X. Research Progress of Lithium Separation from Salt Lake Brine by adsorption method. Research Progress of Lithium Separation from Salt Lake Brine by adsorption method. *J. Salt Lake Res.* 2023, *31*, 106–117.
- 28. Li, X.; Mo, W.; Qing, W.; Shao, S.; Li, J. Membrane-based technologies for lithium recovery from water lithium resources: A review. J. Membr. Sci. 2019, 591, 117317. [CrossRef]
- 29. Zhang, J.; Cheng, Z.; Qin, X.; Gao, X.; Wang, M.; Xiang, X. Recent advances in lithium extraction from salt lake brine using coupled and tandem technologies. *Desalination* **2023**, *547*, 116225. [CrossRef]
- Li, H.; Li, L.; Li, W. Lithium Extraction from Salt Lake Brine with High Mass Ratio of Mg/Li Using TBP-DIBK Extraction System. Separations 2023, 10, 24. [CrossRef]
- Liu, Y.; Zhu, R.; Srinivasakannan, C.; Li, T.; Li, S.; Yin, S.; Zhang, L. Application of Nanofiltration Membrane Based on Metal-Organic Frameworks (MOFs) in the Separation of Magnesium and Lithium from Salt Lakes. *Separations* 2022, 9, 344. [CrossRef]
- Zhang, X.; Zhang, J.; Su, H.; Qi, T.; Wang, L. Recovery of Lithium from Lithium Sulfate Precipitation Mother Liquor. *Rare Met.* 2022, 46, 67–77.
- 33. Qin, Y.; Shi, C.; Wang, X.; Song, G.; Li, H.; Zhang, J. Study on scrubbing process of lithium extraction from brine in ionic liquid system. *Inorg. Sal. Ind.* 2020, *52*, 55–58+106.
- Xin, W.; Fu, J.; Qian, Y.; Fu, L.; Kong, X.-Y.; Ben, T.; Jiang, L.; Wen, L. Biomimetic KcsA channels with ultra-selective K⁺ transport for monovalent ion sieving. *Nat. Commun.* 2022, 13, 1701. [CrossRef] [PubMed]
- Urano, K.; Kawabata, M.; Yamada, N.; Masaki, Y. Selectivity of ion transport in desalination by electrodialysis. *Ind. Eng. Chem.* Process Des. Dev. 1980, 19, 59–64. [CrossRef]
- 36. Hayamizu, K.; Chiba, Y.; Haishi, T. Dynamic ionic radius of alkali metal ions in aqueous solution: A pulsed-field gradient NMR study. *RSC Adv.* **2021**, *11*, 20252–20257. [CrossRef] [PubMed]
- Kanj, A.B.; Verma, R.; Liu, M.; Helfferich, J.; Wenzel, W.; Heinke, L. Bunching and immobilization of ionic liquids in nanoporous metal–organic framework. *Nano Lett.* 2019, 19, 2114–2120. [CrossRef] [PubMed]
- Zhao, L.-M.; Chen, Q.-B.; Ji, Z.-Y.; Liu, J.; Zhao, Y.-Y.; Guo, X.-F.; Yuan, J.-S. Separating and recovering lithium from brines using selective-electrodialysis: Sensitivity to temperature. *Chem. Eng. Res. Des.* 2018, 140, 116–127. [CrossRef]
- 39. Roy, Y.; Warsinger, D.M. Effect of temperature on ion transport in nanofiltration membranes: Diffusion, convection and electromigration. *Desalination* **2017**, *420*, 241–257. [CrossRef]
- 40. Yamaguchi, T.; Ohzono, H.; Yamagami, M.; Yamanaka, K.; Yoshida, K.; Wakita, H. Ion hydration in aqueous solutions of lithium chloride, nickel chloride, and caesium chloride in ambient to supercritical water. *J. Mol. Liq.* **2010**, *153*, 2–8. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.