Chapter 05

Rethinking homo economicus
ISBN: 978-9915-704-23-4
DOI: 10.62486/978-9915-704-23-4.Ch05
Pages: 65-98

©2026 The authors. This is an open access article distributed under the terms of the Creative Commons Attribution (CC BY) 4.0 License.

Lithium, Modern Technological Approaches to Extraction, Efficiency Issues, and Directions for Innovative Development

Litio, enfoques tecnológicos modernos para la extracción, problemas de eficiencia y direcciones para el desarrollo innovador

Bakhodir Abdullayev[1] ✉

[1]University of Economics and Pedagogy.

ABSTRACT

As there has been rapid development in the electronics of cars, hybrids, and electric cars, there has been an emergent demand for Lithium and its compounds, like the carbonate form, Lithium hydroxide, as well as mineral concentrates that consume 80 % of the world's requirement. The requirement for Lithium is also set to increase by 60 % in the next few years, with continuous use in electric cars. The need here is to have rapid discovery and rapid exploration techniques that are effective and efficient in discovery and geological exploration. Mineral mapping can be done quickly, and data on how much there is and its location within the ore and fossil mineral reserves can be gained with the use of hyperspectral imaging. The Lithium resource deposits in the Salt Water areas include 70-80 % of the whole deposits that are superior in quality to be processed to produce Lithium. In this case, there has been research that combines the industrial extraction process of Lithium from water resources. Lithium-ion battery recycling processes also increase Lithium extraction, but with novel approaches. Lithium present in geothermal resources is more limited in comparison to the Lithium found in the brines; further, not all techniques are practical and useful. The processes that are followed to extract Lithium from such fluids are either by evaporation techniques, solvent extraction processes, membrane processes, nanofiltration processes, or adsorption processes. The most preferred use that has minimal energy requirements and that are risk-free and environment-friendly processes include highly functional and highly active selective adsorbents.

Keywords: Lithium Demand; Electric Vehicles; Geological Exploration; Hyperspectral Imaging; Lithium Brines; Lithium Extraction; Lithium Recovery; Adsorption Processes; Selective Adsorbents; Lithium-Ion Battery Recycling; Geothermal Resources; Solvent Extraction; Membrane Processes; Nanofiltration.

RESUMEN

Dado el rápido desarrollo de la electrónica de automóviles, híbridos y eléctricos, ha surgido una creciente demanda de litio y sus compuestos, como el carbonato y el hidróxido de litio, así como de concentrados minerales que consumen el 80 % de la demanda mundial. Se prevé que la demanda de litio aumente un 60 % en los próximos años, con su uso continuo en automóviles eléctricos. Es necesario contar con técnicas de descubrimiento y exploración rápidas que sean eficaces y eficientes en el descubrimiento y la exploración geológica. El mapeo de minerales se puede realizar rápidamente, y mediante imágenes hiperespectrales se pueden obtener datos sobre la cantidad y su ubicación dentro de las reservas de mineral y minerales fósiles. Los depósitos de litio en las zonas de agua salada incluyen entre el 70 % y el 80 % de los depósitos totales con una calidad superior para su procesamiento. En este caso, se han realizado investigaciones que combinan el proceso de extracción industrial de litio a partir de recursos hídricos. Los procesos de reciclaje de baterías de iones de litio también incrementan la extracción de litio, pero con enfoques novedosos. El litio presente en los recursos geotérmicos es más limitado en comparación con el litio presente en las salmueras; además, no todas las técnicas son prácticas y útiles. Los procesos que se siguen para extraer litio de estos fluidos incluyen técnicas de evaporación, extracción por solventes, procesos de membrana, nanofiltración o adsorción. El uso más preferido, con mínimos requerimientos energéticos, libre de riesgos y respetuoso con el medio ambiente, incluye adsorbentes selectivos altamente funcionales y activos.

Palabras clave: Demanda de Litio; Vehículos Eléctricos; Exploración Geológica; Imágenes Hiperespectrales; Salmueras de Litio; Extracción de Litio; Recuperación de Litio; Procesos de Adsorción; Adsorbentes Selectivos; Reciclaje de Baterías de Iones de Litio; Recursos Geotérmicos; Extracción por Solventes; Procesos de Membrana; Nanofiltración.

INTRODUCTION

Lithium was discovered in 1817 by the Swedish chemist Johan August Arfvedsson. He identified lithium during the analysis of the mineral petalite ($LiAlSi4O10$). Arfvedsson found a new, previously unknown element in this mineral, but he was unable to isolate lithium as a separate element. Then, in 1821, Sir Humphry Davy and William Brand isolated lithium in metallic form by electrolysis. Since then, lithium has been studied in various fields, and its important physicochemical properties have been studied.(1)

Lithium is the third element in the periodic table, after hydrogen and helium. It is the lightest alkali metal, with an atomic mass of 6,939 g/mol and a density of 0,534 g/cm3. Lithium has a high electrode potential (3,045 V) and the highest specific heat of all solid elements.(2,3) Lithium compounds are of great importance in various industries. Lithium and its compounds are used not only in the production of glass, ceramics, refrigerators, and batteries, but also in increasing the resistance of plastic lubricants to extreme temperatures, in the production of aluminium, in the creation of catalysts for the pharmaceutical and rubber industries, and in air purification and drying systems.(4,5,6,7)

Lithium has been revealed to be one of the most sought-after elements in the 21st century. This is because it has been playing a critical role in bringing about a sustainable transition towards low-carbon energy systems across the world. Lithium is used extensively because it possesses outstanding electrochemical characteristics.(8) This makes it a principal element in the fabrication of rechargeable lithium-ion batteries for various uses, such as automobiles and home energy storage. Due to this high demand for lithium across the world, it is playing a prominent role in the current "green technology revolution".(9,10)

Traditional processes for lithium isolation from mineral deposits (e.g., spodumene and petalite) and brines (salt-lake, geothermal, and oil-field waters) are plagued with a variety of technological issues.(2) These involve high energy demands, relatively high losses of lithium during processing, and overall strong ecological effects due to the chemicals used. Thus, attention to efficient, inexpensive, and ecologically compatible technologies for lithium separation by means of membrane separation, solvent extraction, sorption, and electrochemical processes is one of the principal areas now investigated.(6,9)

Recent developments have been focused on improving selectivity for separation over other coexisting ion species (Na^+, K^+, Mg^{2+}, Ca^{2+}), improving material performance, and lowering overall process costs.[10] Of particular interest here are nanostructured adsorbents, membrane materials modified with functional groups, and combined approaches where multiple physicochemical separation concepts are used synchronously for efficient separation even in ultra-dilute Li-containing liquids.[11]

Apart from technological progress, it is clear that a sustainable, innovative future for the lithium sector relies on implementing digital technologies and a closed-loop recycling system with a focus on waste and resource conservation. From this point, it is imperative to conduct a thorough evaluation of available mining technologies, efficiency bottlenecks, and innovative alternatives to build a sustainable technological foundation for lithium.[12]

Therefore, it is expected that even better results can be achieved by systematically studying existing technologies for obtaining lithium and its compounds and introducing the use of artificial intelligence in this important technological field.

The global lithium compound economy, trends in demand, production, and sustainable use

Lithium is one of the rare elements; its amount in the Earth's crust is 0,007 %.[7] Lithium sources are divided into two main types: liquid and solid. Liquid types include seawater, salt lakes, geothermal waters, and solid types include recycled raw materials such as mineral deposits and lithium-ion batteries, and waste from the electronics industry (figure 1).[13]

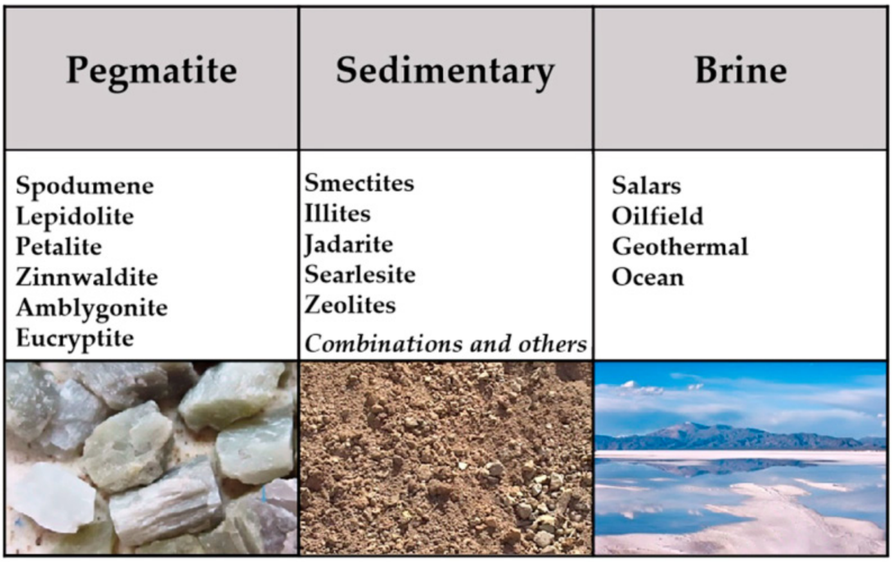

Figure 1. General classification of lithium-containing raw materials[13]

The world's lithium reserves are estimated at 14-15 million tons.[11] The main deposits of minerals containing lithium compounds are located in Chile, China, Canada, Russia, Serbia, Congo, and Afghanistan. Lithium does not occur in free form in nature and is present in more than 150 minerals, as well as clays.[12]

A large amount of lithium is concentrated in sea and ocean waters, salt lake waters, and geothermal waters, which account for 70-80 % of world resources. However, the technology for industrial production of lithium from sea and ocean waters has not been developed, since the concentration of lithium in them is low (0,1-0,2 ppm), although the total amount is approximately 2600 billion tons.[13,14,15,16]

The amount of lithium in geothermal waters ranges from 1 to 100 ppm. However, the high concentration of other metals in such waters complicates the extraction and processing of lithium. Salt Lake waters are rich in lithium, with concentrations in the hundreds or thousands of ppm. However, the high concentration of magnesium makes these solutions difficult to process. The high concentration of alkali and alkaline earth elements in salt lake waters creates problems in the extraction of lithium.[17,18]

Currently, the main lithium-based products are lithium carbonate, mineral concentrates, and lithium hydroxide, which account for 80 % of the world market.[19] Lithium carbonate is obtained by processing spodumene ores and brine solutions.[20]

Spodumene is the first raw material for industrial production. This mineral is found in a rock called pegmatite. Its lithium content is 1-4 %, and its recovery during processing is increased to 60-70 %. In addition to spodumene, lithium carbonate can also be obtained from other minerals in pegmatite rocks. Such rocks contain up to 6 % lithium and are called amblygonite, lepidolite, nepidalite, netallite, or synwaldite.[21,22,23]

As a result of the depletion of lithium ores, there is a need to use aqueous solutions to extract lithium on an industrial scale. Sources of aqueous lithium include brines, geothermal waters, sea and ocean waters.[23]

Despite the low concentration of lithium in aqueous solutions, this direction is considered promising due to its widespread distribution and ease of processing. There is extensive scientific and technical literature on various methods for extracting lithium from aqueous solutions. These methods are developing environmentally friendly, highly selective, economically viable, and technically simple production of lithium compounds. Today, lithium production is carried out mainly through the extraction of hard rocks in Australia and the processing of brines in Chile. These countries account for the majority of the world's lithium reserves (table 1).[24]

Table 1. World lithium reserves and their distribution by country[24]

Rankings	Country name	Amount of lithium (tons)	Percentage of total
1	Chile	9 300 000	33,6
2	Australia	6 200 000	22,4
3	Argentina	3 600 000	13,0
4	China	3 000 000	10,8
5	United States	1 100 000	4,0
6	Canada	930 000	3,4
7	Brazil	390 000	1,4
8	Zimbabwe	310 000	1,1
9	Portugal	60 000	0,2
	Other	2 800 000	10,1
Total amount in the world		27 690 000	100

From 2017 to the present, the global lithium production volume has been approximately 43 000 tons, and the total global lithium reserves are approximately 28 million tons.(25)

Data on the areas of application of lithium are presented in figure 2, from which it can be seen that batteries constitute a significant portion of the use of lithium and its compounds.(25)

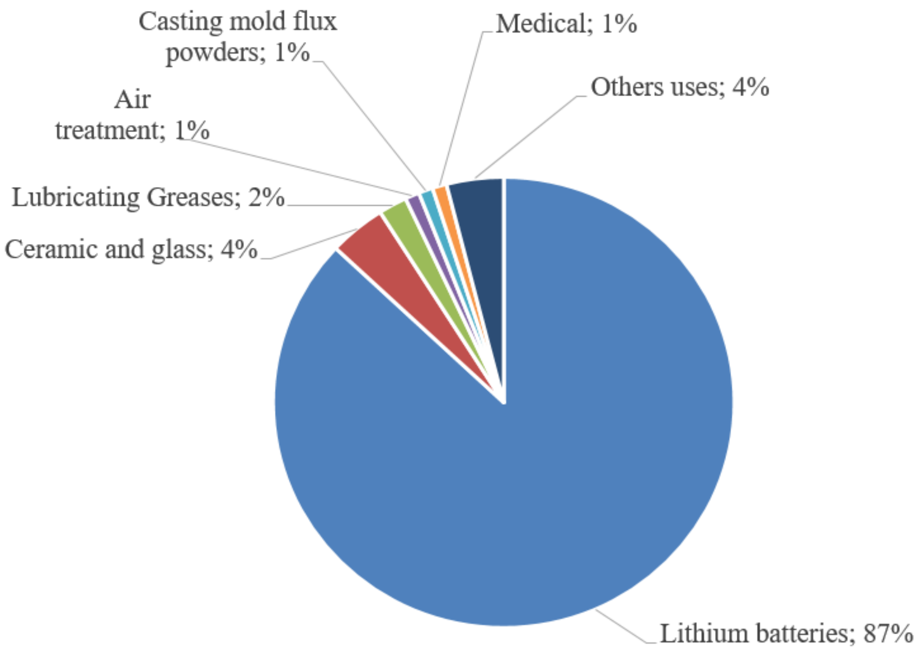

Figure 2. The main fields of application of lithium and its compounds(25)

Many elements can replace lithium. In the production of glass and ceramics, sodium or potassium fluxes can be used, and in the production of batteries, calcium, magnesium, mercury, or spirit can be used. However, batteries based on these elements are rarely used due to their low energy capacity.(26,27)

Lithium is considered the basis for the development of safe green energy in the 21st century, has a high energy storage capacity, and is important as a future replacement for hydrocarbon fuel sources. In this regard, the development of technologies for obtaining lithium carbonate from local raw materials is of great practical importance.(28)

The sector with the highest growth potential for lithium is batteries, with lithium battery production growing by more than 20 % per year since 2000.(29) Lithium-ion batteries (LIBs) can be single-use or rechargeable, and are classified as primary or secondary batteries. Secondary lithium batteries are more in demand in personal electronics than lithium-free ones. The development of geopolitical movements to reduce greenhouse gas emissions has led to an increase in demand for lithium.(30) Member states of the European Union have set ambitious emission reduction targets and are planning to shift their economies away from fossil fuels and towards renewable energy sources (solar, wind, etc.). While lithium-ion batteries retain their advantage in energy storage, secondary lithium-ion batteries will be an important factor in the transition of vehicles from fossil fuels and in solving the problems of continuity of solar and wind energy.(31)

As a result of the growing use of batteries, the demand for lithium is increasing by 8-11 % per year. According to the data, by 2100, the annual demand for lithium in the world market will be 20 mln. reaches tons.(24,25,32,33,34,35,36,37)

According to the 2017 U.S. Geological Survey's Mineral Resources Report, global lithium resources are estimated at 40 million tons. According to the 2018 report, global lithium resources have increased to approximately 53 million tons. The identification of new sources is the result of the activities of geological exploration groups seeking to take advantage of the growing demand for lithium and its rising price. Although the price of lithium resources currently exceeds the price of lithium, not all lithium resources are equally suitable for their extraction. The most economically attractive lithium sources are mined first, and only after technological innovations reduce the cost of extraction are more difficult lithium sources exploited. At the same time, bridging the gap between demand and supply will depend on refining, the development of new sources, and the substitution of materials.(24,25,38,39,40,41,42,43,44,45,46)

In 2009, the U.S. Department of Energy allocated $9,5 million to support the construction of a lithium-ion automotive battery recycling plant in the United States for the recycling of lithium metal and lithium-ion batteries.(47,48,49,50) It is estimated that by 2050, the recycling rate of lithium will reach 25 % worldwide.(51,52)

Today, the low level of global production of lithium and its compounds is slowing the development of the ever-growing complex lithium-ion battery (LIB) industry.(53)

Table 2. New projects for lithium extraction from liquid and solid raw materials

Country name	Company name	Project name	Raw material type	Annual production (t)
Argentina	OOO «Galaxy Resources»	Sal de Vide	Continental brines	25 000
Australia	Altura	Pilgangoora	Pegmatite	19 000
Argentina	Lithium Americas	Cauchari-Olaroz	Continental brines	20 000
Australia	Reed Resources	Mount Marlon	Pegmatite	25 000
Argentina	Rodonia	Salar de Diablillos	Continental brines	15 000
Argentina	Orocobre	Olaroz lithium plant	Continental brines	17 500
Bolivia	Comibol	Salar de Uyuni	Continental brines	30 000
Canada	Nemanska Lithium Inc.	James Bay	Pegmatite	47 000
Chile	Albermarle	La Negra	Continental brines	20 000
Finland	Kliber Oy	Ostrobothnia	Pegmatite	4000
USA	Western Lithium	Kings Valley	Hectorite clay	26 000
Mexico	Bacanora Minerals Ltd.	Sonora	Hectorite clay	35 000
USA	Simbol	Salton Sea	Geothermal brines	16 000
USA	Standard Lithium	Arkansas	Adjacent waters of the oil field	20 000
Total: 319 500				

In order to produce large automotive batteries and overcome the difficulties and barriers in recycling lithium batteries, it is necessary to create a standard method for using lithium in batteries. Battery recycling programs for large vehicles are developed using the current lead-acid battery recycling system as a guide. Unlike traditional lead-acid batteries used in vehicles, large automotive batteries are expected to have a service life of up to 20 years from the date of purchase.(54,55,56,57) Despite advances in the production of lithium and its compounds, new sources will need to be discovered to meet the growing demand. A set of 15 new projects for the extraction of lithium from solid and liquid sources is presented in table 2. These projects started in 2020, and their total production capacity could reach approximately 320 000 tonnes per year in terms of lithium carbonate equivalent (LCE).(58,59,60,61)

The global lithium market in 2021 was valued at $6,83 billion and is expected to grow at a compound annual growth rate of 12,0 % from 2022 to 2030.(62,63,64) The United States is the world's second-largest consumer of lithium, after China, in battery production.(65,66,67,68) The United States has vast reserves of this important metal, and according to the U.S. Geological Survey, in 2020, the United States had 7,9 million tons of lithium-containing liquid and solid resources.(69) However, the country only processes 1 % of the world's total demand. In 2020, production in the United States was carried out only in Nevada. However, the country is expected to expand its production in this area in the coming years.(70,71) Due to mass production, unit costs will decrease, which will reduce the price of lithium-based products (such as lithium-ion batteries). As production capacity increases, the market supply of lithium increases, which helps to stabilise prices and create competitive market conditions.(72) New mineral processing methods and highly efficient extraction technologies increase the efficiency of lithium resource use. The geopolitical distribution of lithium (mainly concentrated in Australia, Chile, and China) and environmental problems (depletion of water resources) affect the stability of the market. The lithium market remains volatile due to supply-demand imbalances and geopolitical risks (e.g., geographical concentration of resources).(73) The transition to "green energy" and the development of artificial intelligence will steadily increase the demand for lithium, which may cause prices to remain high in the long term.(73)

Maintaining lithium prices at this level is important for accelerating the global transition to green energy and artificial intelligence.

Sources of lithium-containing liquid raw materials and their properties

Lithium sources are mainly found in pegmatites, oceanic, marine, and subsurface brines. Pegmatites are solid mineral deposits that contain crystallised lithium, usually in the form of spodumene. Brine is a mineral-rich saline solution that can occur both on the surface of the Earth and in groundwater (geothermal). Lithium can be concentrated in brines by various processes, such as mobilisation from its primary source and accumulation in closed vessels. Additional sources of lithium are also found in clays. Lithium-rich clays are formed by leaching and alteration, for example, by interaction with hectorite or hydrothermal fluids (figure 3).(74,75)

Lithium-rich saline groundwater deposits are collections of highly concentrated saline groundwater. Lithium is known to be isolated from brines, geothermal waters, clays, volcanic deposits, or other potential rock sources. Lithium is also present in ocean waters, but cannot be economically concentrated without enrichment from the above sources. Figure 3 shows the identified sources of brines on a global scale.(76,77,78,79) Some brine sources contain lithium, and their chemical properties are important in preserving and increasing lithium concentrations. These sources allow for long-term storage of lithium and help maintain its naturally high levels.(79)

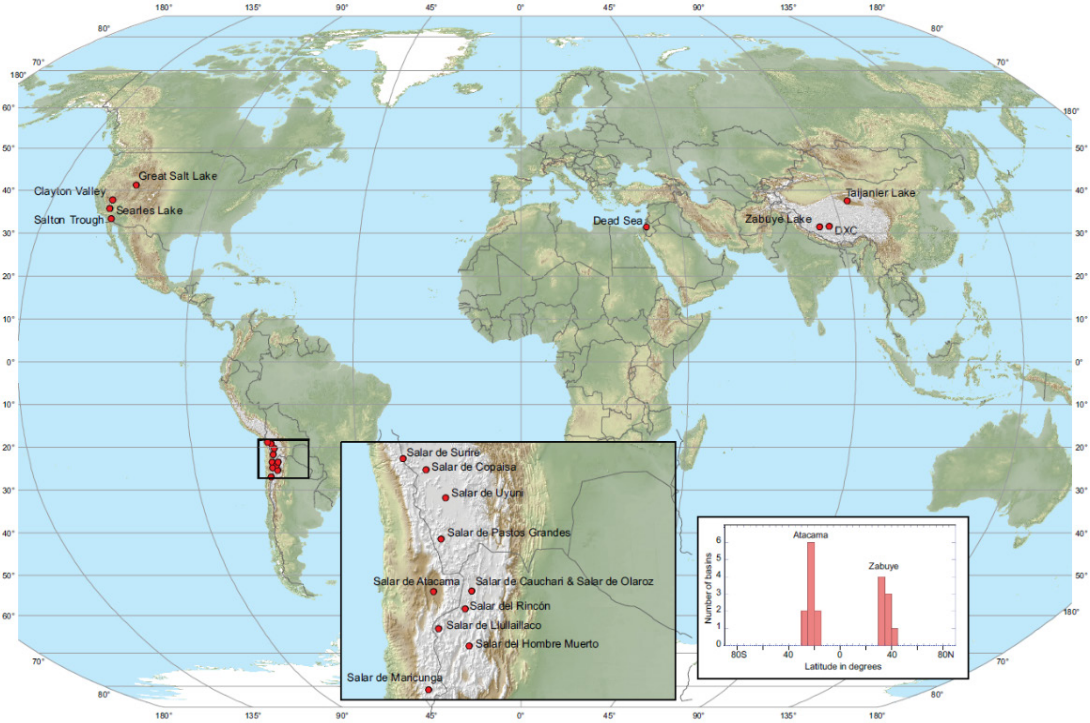

Figure 3. World map of lithium-rich brines, clays, and zeolites

All lithium-bearing fluid sources share a number of common characteristics that are important for lithium storage and concentration. Lithium is usually mobilised during the extraction process from rocks or formed by the interaction of hydrothermal fluids with continental rocks. Closed basins are where water or continental currents collect, and these basins are important for lithium storage because they prevent water from draining away, which increases the concentration of minerals.[80] Over time, a closed basin can only be preserved if the water level does not exceed the capacity of the basin. Otherwise, fluid and mineral loss from the basin will occur. Dry climates lead to faster evaporation, which allows lithium to be concentrated. Lithium tends to remain suspended in saline solutions and does not precipitate. If there is enough time for the brine to concentrate, the closed basin can become a lithium-rich aquifer or a dry lake.[80,81]

The process of producing lithium from liquid sources is often much cheaper and more energy efficient than extracting it from solid rock. 70 % of the world's industrial reserves are located in South America, a region known as the "lithium triangle".[82] The lithium triangle includes Chile, Bolivia, and Argentina. The Salar de Atacama region of Chile contains an estimated 1400 million cubic meters of high-quality lithium salt. It is estimated that the region contains 450 000 tons of lithium before the lithium extraction process began. Lithium is extracted from salt pans in Chile, which are then collected in a closed basin.[83] In the Salar de Atacama, special attention is paid to concentrating lithium salt using solar energy. This concentration method has a 50 % recovery rate and is based on the arid climate and altitude of the Atacama Desert. This process takes an average of eight to twelve months, but the method is highly efficient due to the significant increase in lithium concentration.[84]

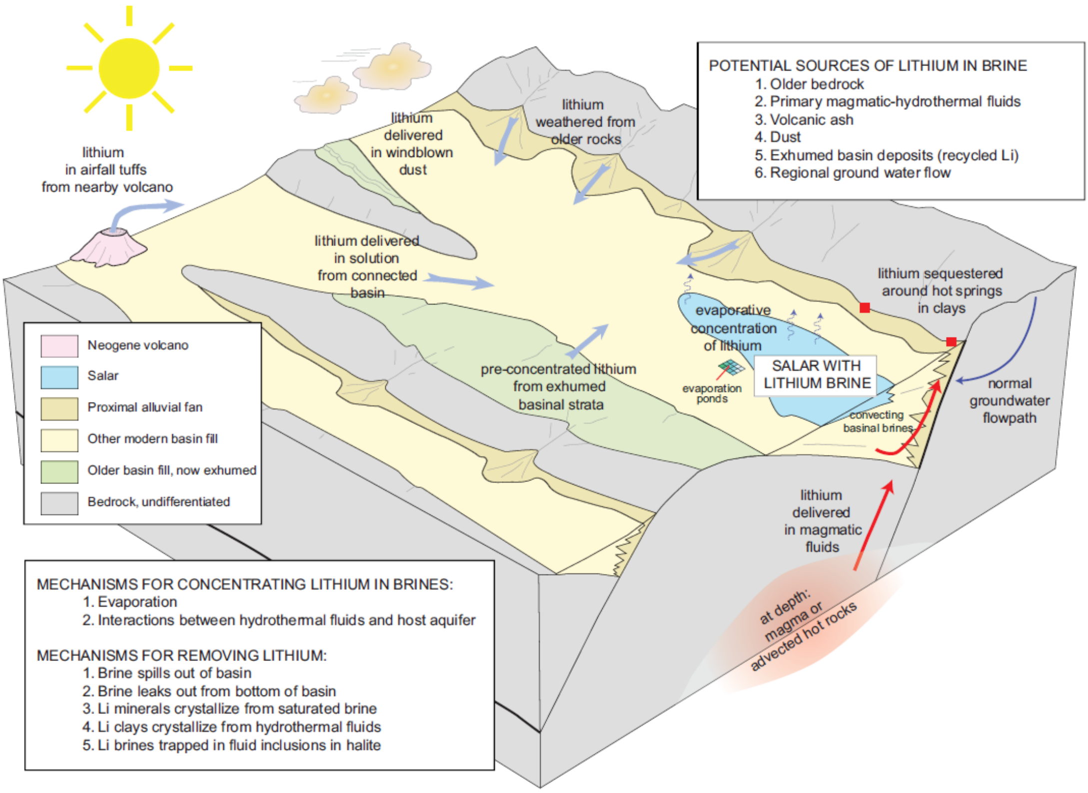

Figure 4. Geological-geochemical and hydrogeological model of the origin and migration of lithium in saline waters

The Salar de Uyuni is located in Bolivia and contains an estimated 9 million tons of lithium, which is 15 % of the world's lithium reserves.(85) The Salar de Uyuni is a 10 000 km2 salt flat with lithium concentrations ranging from 500 to 4,700 ppm. The area also has a magnesium concentration that is three times higher than that of the Atacama Salt Flats.(86) Magnesium salts are recycled during the lithium extraction process. Due to the large area, variable concentrations, high magnesium content, and less arid climate than the Atacama, producers are trying to establish industrial-scale production in the Salar de Uyuni area. Lithium production is currently estimated at 120 metric tons per year.(87)

Salar de Hombre Muerto is located in Argentina. Although the Hombre Muerto deposit is smaller in area than the Salar de Atacama, it is deeper for lithium extraction. Its average concentration is 650 ppm, and it is estimated to contain approximately 375 000 metric tons of lithium. Lithium is extracted in this area mainly by the alumina adsorption process, which provides a recovery rate of 47 %. Hombre Muerto has an annual production of approximately 12 000 tons of lithium carbonate (Li2CO3). Lithium is also extracted in Argentina from other salt pans, such as the Salar del Rincon and the Salar del Olaros. Lithium reserves in these areas are estimated at 250 000 and 325 000 tons, respectively.(87)

Outside the Lithium Triangle, China and the United States have additional lithium reserves. China has three major sources of lithium reserves: the Zhabuye and Kaidan salt lakes. The Zhabuye salt lake is the only recorded case of natural precipitation and crystallization of lithium carbonate. The salt lake is a small source with an average concentration of 400 ppm and contains 160 000 tons of lithium reserves. The Kaidan basin is also home to the world's largest lithium carbonate production plant. In the United States, lithium salt production began in 1966 at Clayton Valley, Nevada, using solar energy to increase the concentration of the salt. Before production began, lithium reserves were estimated at 118 000 tons. Lithium concentrations have declined from an initial 360 ppm in 1966 to 230 ppm in 2008.[87,88]

Another potential source of lithium is geothermal waters. The main value of geothermal waters lies in the heat they contain, which is of particular importance in that it can be converted into mechanical energy.[89]

In addition, lithium-rich oil reserves have been discovered. In the United States, lithium-containing reserves have been found in Texas, Arkansas, North Dakota, Wyoming, and Oklahoma. The highest concentrations have been found in the Smaskover Formation, but exact figures are not given due to certain limitations in estimating lithium reserves.[90]

In recent years, methods for extracting lithium salts from unconventional sources have been actively developed. Lithium is extracted from natural brines in the United States and Chile. In Chile, a lithium extraction plant has been built based on underground brine reserves in the Atacama Desert. The composition of various lithium-rich brines is presented in table 3.[91,92]

Table 3. Chemical composition of the world's most famous lithium hydromineral raw materials

Location	Composition (wt.%)							
	Na	K	Li	B	Cl	Mg	Ca	SO_4
Zabuye, China	7,29	1,66	0,05	-	9,53	0,003	0,01	-
Salar de Uyuni, Bolivia	7,06	1,17	0,03	0,07	5,0	0,65	0,03	-
Clayton Valley, USA	4,69	0,40	0,02	0,05	7,26	0,02	0,05	0,34
Great Salt Lake, USA	7,00	0,40	0,01	0,01	14,0	0,80	1,50	-
Hombre Muerto, Argentina	10,0	0,70	0,10	-	16,0	0,09	0,08	1,00
Salar de Atacama, Chile	9,10	2,36	0,16	0,04	18,9	0,97	0,05	1,59
Bonneville, USA	8,30	0,50	0,01	0,01	14,0	0,40	0,01	-
Dead Sea, Israel	3,01	0,56	0,001	0,003	16,1	3,09	1,29	0,06
Taijinaier, China	5,63	0,44	0,31	-	13,4	2,02	0,02	3,41
Sua Pan, India	6,00	0,20	0,002	-	7,09	-	-	0,83
Aral Sea, Uzbekistan	5,49	0,36	0,011	0,003	7,09	1,025	0,08	2,21

Brine waters with a natural lithium content of 0,32 to 1 g/l are usually concentrated by solar evaporation and then processed. Among the mineral raw materials containing lithium, deposits in South America, especially the Salar (salt basins), occupy an important place. Here, the lithium concentration in the brines reaches 1,0 to 2,5 g/l. By using the galurgic evaporation scheme, it is possible to obtain concentrates with a lithium content of more than 40 g/l. The main hydromineral reserves of lithium are concentrated in Chile, in the famous Atacama Salar, which occupies an area of about 3000 km2. It is located in the north of Chile, at an altitude of 2300 meters above sea level, and is bordered to the east by the eastern branch of the Cordillera, and to the west by the Domeyco Cordillera and the Atacama Desert. In this region, water evaporation is 3200 mm per year, while the amount of atmospheric precipitation is only

15 mm. Typically, the concentration of lithium in saline waters is highest at a depth of 30 to 40 meters.[93,94,95]

Modern methods of lithium extraction from water resources

Various modern techniques and technologies are used to separate lithium from water sources. These methods are selected mainly depending on the concentration of lithium in the water, its physicochemical properties, and economic aspects. Lithium is mainly separated from water sources using solar evaporation, chemical precipitation, ion exchange, adsorption, membrane technology, and electrochemical methods.[96,97] The widely used solar evaporation technology includes several stages of precipitation and crystallisation of Li2CO3.[98] Unfortunately, this process is one of the most time-consuming processes. In addition, the precipitation of Li2CO3 occurs together with other salts, such as NaCl, Mg(OH)2, and MgCO3. As a result, it is necessary to clean it of the salts. Chemical precipitation involves the precipitation of lithium in the form of aluminate or lithium carbonate, which is achieved by adding aluminium chloride or soda ash.[98] However, this method is ineffective in cases where the ratio of magnesium to lithium is high and there are a large number of mixed salts. This method uses a large amount of chemical reagents and leads to the formation of a large amount of sludge. Solvent extraction allows the selective separation of lithium in the presence of other metal ions using special chelating agents, such as trioctylphosphine oxide and tributylphosphate.[99,100,101] However, this method is only applicable to saline waters with a low ratio of magnesium to lithium. More seriously, the use of large volumes of organic solvents as extractants not only corrodes technological equipment but also pollutes the environment. Therefore, it is urgent to develop sustainable technologies for extracting lithium from aqueous sources.[102]

Extracting lithium from seawater using electrochemical methods is one of the most widespread methods that could potentially address the lithium shortage in the future. However, electrochemical extraction is only effective in solutions with high lithium concentrations. Many scientists have shown in their research that temperature and concentration have a significant effect on the electrochemical extraction of lithium.[102,103,104,105,106]

Membrane technology is a promising and environmentally friendly method for lithium separation, as it is characterised by high energy efficiency and the possibility of using it in continuous processes.[107,108,109] The use of membranes for lithium separation is still at the stage of laboratory research. Lithium separation processes under pressure, in particular, research on the nanofiltration method, are widespread.[110] Nanofiltration allows the separation of monovalent lithium cations from divalent calcium and magnesium cations.[111,112] Nanofiltration separates more than 26 % of lithium and 85 % of magnesium from seawater.[113] Studies on the effect of monovalent potassium and sodium cations on the nanofiltration process are still ongoing.[114] The solutions obtained by this method are very low in concentration, requiring an additional concentration process before further processing. Membrane distillation is also used to concentrate lithium from salt solutions. This method is used to separate salts from solutions, but is not practically used in the enrichment process.[115,116,117,118] Currently, research on the simultaneous extraction of lithium and obtaining clean water is limited. Research is being conducted on combining nanofiltration and membrane distillation processes, which will allow the separation of not only lithium but also multivalent cations.[119] Research on the extraction of lithium from saline lake solutions, using preliminary nanofiltration and membrane distillation to reduce the magnesium content, allows for the extraction of lithium in sufficient concentrations.[120] Membrane filtration retains more than 90 % of calcium and magnesium cations, and from 42 to 60 % of potassium, sodium, and lithium cations. The nanodistillation method allows for a significant reduction in the ratio of magnesium to lithium.[121]

In the early 1990s, the first successful experiments were carried out on the electrochemical transfer of lithium cations from the initial solution to the material of lithium-ion batteries.[122] During these studies, spinel λ-MnO2 was used as the working electrode, and a platinum (Pt) wire, which produces oxygen or hydrogen, was used as the counter electrode. However, the disadvantage of this method is that the water splitting process occurs simultaneously with lithium separation, and this process is expensive.[123,124,125] The electrode materials used for lithium separation are similar to the cathode electrodes of lithium-ion batteries, which can separate and incorporate lithium. They have been studied in detail in terms of lithium-ion mechanisms, theoretical and practical possibilities, oxidation, reduction potentials, and various methods needed to improve their electrochemical properties.[126,127]

The main advantage of these methods is that they use current as the driving force for lithium separation, i.e., no additional chemical reagents are required to regenerate the active material. Although the capacity of the battery materials (approximately 30-35 mg/g) is close to that of previous adsorption materials, the rate of lithium separation increases dramatically under the influence of current, allowing the same amount of Li to be separated in a shorter time.[128] At the same time, the hygroscopicity of the materials limits the final lithium concentration, since the solution adsorbed on the electrodes mixes with the lithium-rich solution during each cycle. However, this problem can be solved by washing the solutions and using a small, compact electrode block cell design.[129]

Lithium extraction from salt lake brine by the sedimentation method

The sedimentation method has the advantages of simplicity of the process, low cost, and industrial applicability. In recent decades, these methods have been actively studied from an economic and scientific point of view for the separation of lithium from solutions. Such methods include precipitation by carbonation, co-precipitation of borates and lithium, and precipitation with phosphates and aluminates. As a result of research by many scientists, new methods for the precipitation of magnesium salts have been developed to separate lithium from magnesium. These methods will allow for the integrated use of lithium and magnesium sources.[130,131,132,133]

Among hydrometallurgical processes, the most widely used method for separating Li from solution is the sedimentation method. This method is based on the difference in solubility of metal compounds in aqueous solution, and the solubility is controlled by the temperature and pH of the medium.[134,135,136] Typically, reagents such as Na2CO3, Na3PO4, and NaOH are used as precipitants, which are used to precipitate metal ions from the solution. In this process, lithium is separated in the form of Li3PO4 or Li2CO3, which occurs as a result of the reaction between Li+ ions and the precipitating reagents.[137] By adding NH4OH and NaOH, the pH of the solution is increased, and precipitation of Ni, Mn, and Co in the form of hydroxides is achieved. After the separation of other metals, Na2CO3 is introduced into the reaction zone and precipitated in the form of lithium carbonate (Li2CO3).[138,139]

The results of the study show that LiFePO4 can also be isolated from cathode materials from used lithium-ion batteries (LIB) waste using the lithium precipitation method. Before the cathode material was extracted, its crystal structure was disrupted by chemical treatment. FePO4 was isolated from the cathode material using 0,6 M H3PO4, and then lithium was precipitated as Li3PO4 by adding NaOH to the remaining solution.[140,141]

The solubility of lithium carbonate decreases with increasing temperature. Therefore, the carbonation step is usually carried out at elevated temperatures in the range of 80-90°C (where the maximum solubility of lithium carbonate is 1,5-1,8 g/L Li (corresponding to 7,8-8,2 g/L lithium carbonate). Under these conditions, when working with an initial solution with a concentration of 20 g/L Li, it is possible to achieve a lithium recovery of more than 90 % in the final step.[141]

When using room temperature oxalic acid (H2C2O4), the precipitation results in the removal of 22,43 % and 11,51 % of calcium and magnesium, respectively. In addition, carbonates can remove up to 73,82 % and 98,86 % of calcium and magnesium. Both precipitation processes also remove aluminum and boron, with the removals being 32,24 and 23,42 % for oxalic acid (H2C2O4) and about 80 and 23 % for carbonates. Therefore, the use of carbonates is more efficient than that of oxalic acid (H2C2O4).[142,143]

However, in both methods, 14-23 % of lithium is lost along with the precipitates, so it is necessary to improve the process to eliminate high lithium losses.[143] The product obtained as a result of this sedimentation method has a good crystalline structure, and, by washing it in hot water, it is possible to obtain lithium carbonate of high purity (99,55 %).[144] Figure 5 shows a technological scheme for obtaining lithium carbonate from a liquid raw material source. According to scientists from developed scientific centres of the world, in the future, it will be possible to further increase efficiency in such technologies as a result of the use of artificial intelligence.

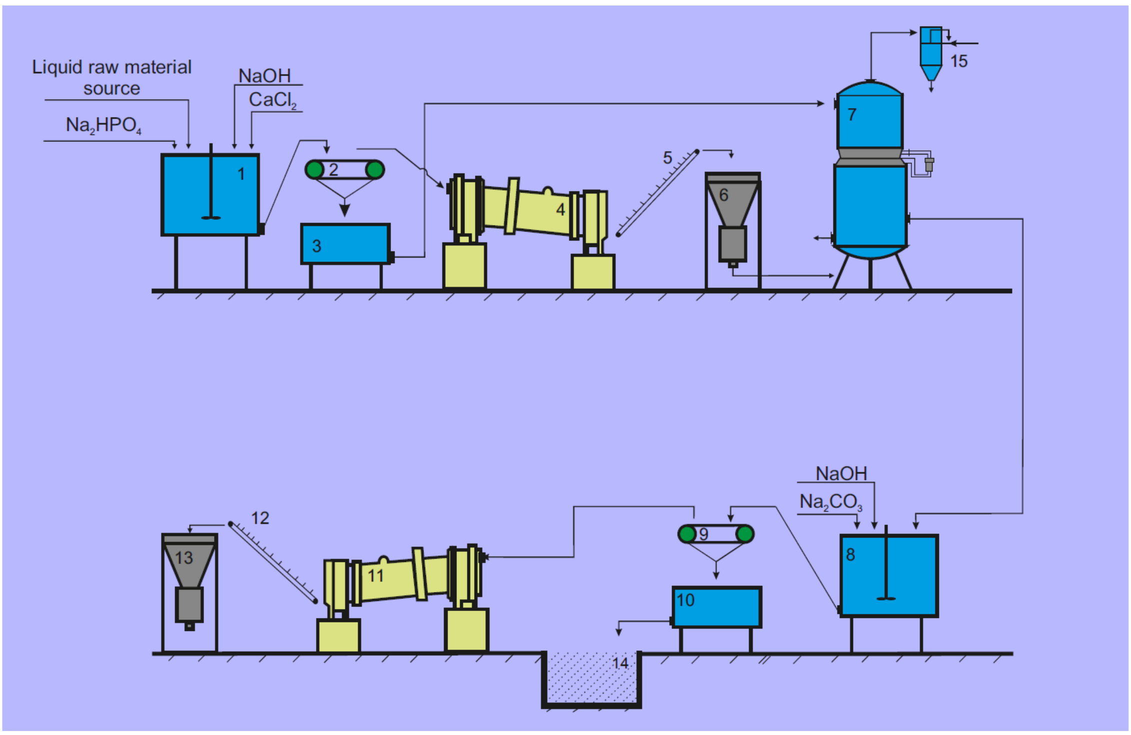

Figure 5. Principal technological scheme of obtaining lithium carbonate from aqueous raw materials by the sedimentation method

After mechanical and other impurities have been filtered, the water is transferred to a reactor (1) supplied with sodium hydrogen phosphate, calcium chloride, and sodium hydroxide. The suspension formed as a result of the reaction is transferred to a vacuum filter (2) for filtration. The separated solid phase is dehumidified in a drum dryer (4) and packaged and sent to a warehouse as a complex fertiliser. The liquid phase is transferred to an evaporator (7) for concentration and is transferred to a reactor (8) supplied with sodium carbonate and sodium hydroxide. The suspension formed as a result of the reaction is pumped to a vacuum filter device (9) for filtration. The filtered lithium carbonate is dried in a drum device (11) and then transferred to a packaging device (13).

Lithium extraction from aqueous raw materials by the adsorption method

Improving the technologies for the effective separation and processing of lithium remains one of the most important areas of scientific research worldwide. In this process, various methods for the separation of lithium from natural and artificial sources are being developed, among which the adsorption method is recognised as one of the promising directions.[145,146]

Separation of lithium by the adsorption method is the most convenient method due to the possibility of integrating it into general lithium production processes (for example, recovery and collection). The adsorption method is environmentally friendly and has a promising perspective in terms of selectivity and simplicity of the operating process. The adsorption method is an environmentally friendly, selective, and simple-to-operate method. In this method, lithium ions are easily and selectively separated from aqueous solutions by a physical or chemical adsorption process.[147]

Scientific studies have shown that various inorganic crystalline solids, such as aluminium hydroxides (AlOH), aluminium oxides (AlOx), manganese oxides (MnOx), and titanium oxides (TiOx), are used as selective adsorbents for lithium.[148] Many of the adsorbents used for direct lithium separation from brines are also used as cathode materials for lithium-ion batteries.[149] The Dow Chemical Company first proposed the use of microcrystalline AlOH incorporated into anion exchange resins for the selective separation of lithium from brines.[150] Manganese oxides (MnOx) have been proposed as sorbents for the separation of lithium from seawater.[151,152] TiOx materials are used in lithium-ion batteries and are proposed for the separation of lithium from saline solutions.[153,154,155,156]

The properties of inorganic crystalline sorbents have been scientifically studied, and work is currently underway to use these solid sorbents in production systems for the selective separation of lithium from natural and industrial liquids.[157] Crystalline metal structures provide selectivity in lithium adsorption, since they have a large number of cation exchange centres protected within the crystalline matrix. This matrix acts as a molecular sieve, allowing small lithium ions to enter the internal ion exchange centres, while larger cations are prevented from entering. Researchers have shown that the main reaction in the adsorption of lithium by MnOx is not oxidation-reduction, but ion exchange.[158,159] The adsorption capacity of MnOx is related to its crystalline structure, which acts as a molecular sieve to allow lithium ions to enter the crystal lattice. However, it restricts the entry of other ions through steric hindrance.[160,161,162] Steric hindrance mechanisms have also been proposed for the intercalation of lithium ions in TiOx and AlOH crystals.[163]

Major studies on adsorbents based on titanium and manganese oxides have been mainly aimed at studying their effectiveness in lithium separation processes.[164] It has been found that metal oxides containing manganese have a higher separation coefficient than other adsorbents.[165,166] As a result of studying the mechanism of adsorption and desorption of lithium on manganese oxide, it was found that this process occurs in a tapotactic manner, as well as desorption, without destroying the crystal structure.[167]

Lithium-ion sieves are selective adsorbents with high functionality for the separation of lithium from complex aqueous systems and the separation of ions. Lithium-ion sieves are divided into two types: sieves based on manganese oxide (LMO) and titanium oxide (LTO).[168] Among the technologies for the separation of lithium from solutions, the adsorption method on ion sieves is considered one of the most promising methods due to its low energy consumption and environmental safety.[169]

Manganese-based oxides (LMO) are the most studied and selective adsorbents for lithium, due to their high adsorption capacity. To date, several types of LMO have been synthesised, which have high adsorption capacities and are based on MnO2, MnO2·0,3H2O, and MnO2·0,5H2O.[170] The adsorption capacity of the adsorbents depends on the molar ratio of Li and Mn. The adsorption capacity improves with increasing Li/Mn molar ratio. It has been proven that MnO2·0,5H2O has the highest adsorption capacity at a molar ratio of Li/Mn.[171] LMO-type lithium-ion adsorbents have a spinel structure. The ratio of Li and Mn cations in the spinel LiMn2O4 is 1:2, but this ratio can be disturbed under certain conditions.[171] The stability of the spinel structure is affected by the solubility of manganese in the processing, which reduces the adsorption capacity of lithium during the processing.[171]

Since the adsorption capacity is strongly dependent on the morphology, porosity, and crystal structure of the material, research is focused on increasing the efficiency through nanomaterials with an increased surface area and adsorption-desorption centres.[172] It has been found that the degradation of lithium single crystal nanotubes (LMO) can be eliminated by using (NH4)2S2O8 as an eluent, reducing the solubility of manganese, and maintaining the capacity during the adsorption-desorption processes.[173] In experiments conducted on pure lithium chloride solutions, the lithium absorption rate was 89,7 % of the theoretical capacity of the adsorbent. It is proposed to use environmentally friendly chitosan for the adsorption of lithium from aqueous solutions.[174] The hydroxyl and amino groups in chitosan react with the enoxy group and alkyl chloride in epionchlorohydrin under acidic and alkaline conditions, and the addition of a chitosan coating (1:1 mass ratio) to a transient ionic sieve (H4Mn5O12) results in a material with high thermal and chemical stability. The solubility of manganese does not exceed 1,15 %. The adsorption capacity for the separation of lithium from geothermal water at a temperature of 433 K (≈160°C) and a concentration of 25,8 mg/l reaches 88,4 %.[174]

Despite the high efficiency of lithium-ion LMO adsorbents in aqueous solutions compared to lithium, their industrial application is limited due to the decrease in adsorption capacity caused by manganese dissolution.[173] To solve this problem, iron-doped spinel-composed LiMn2-xFexO4 magnetic recyclable adsorbents were synthesised by the solid-phase reaction method, and the adsorption capacity was found to reach 34,8 mg.[175,176]

Manganese dissolution was 2,5 % in undoped adsorbents, and decreased to 0,5 % in doped ones. This is explained by the inhibition of the disproportionation reaction as a result of the increase in the total manganese content. The adsorption capacity of undoped adsorbents decreased by ~50 % after the 4th cycle, and in doped ones it was ~32 %. As a result, iron-doped lithium-ion adsorbents showed long-term stability.[177] The simplicity of the process and high selectivity of adsorption allow the separation of lithium from low-concentration solutions. Lithium-titanium-based lithium-ion adsorbents are more chemically stable than manganese-based adsorbentsv.[178] Although adsorption is one of the most promising methods for the separation of lithium from geothermal waters, the difficulty of synthesising adsorbents with high adsorption properties and stability limits their practical application.(178) In order to overcome these problems, the mobilisation of Ti-LiS powders with various composite materials is effective in increasing the efficiency of chitosan-based adsorbents. However, these adsorption properties are not sufficient to increase stability. Polymeric binders such as polystyrene, polyacrylonitrile, polyvinyl chloride, and polysulfone have high chemical stability and mechanical strength and are good materials for coatings.(179)

However, the adsorption rate and capacity of such composite materials are much lower than those of powder adsorbents.(180) In this regard, polymer fibre-based epoxidised materials with high specific surface area and improved adsorption capacity are more promising.(181) However, without coating with binding polymer materials, their stability, despite their high adsorption capacity, remains unsatisfactory.(182,183)

Scientists from the People's Republic of China(180) have succeeded in synthesising a fibre-based epoxidised composite adsorbent for large-scale synthesis of Li2TiO3. Four polymer binders were used to improve the adsorption properties and stability: polystyrene, polyacrylonitrile, polyvinyl chloride, and polysulfone. In order to maintain the structural stability of small particles of Li2TiO3, they are synthesised using a modified solid-phase method before the preparation of composite fibres and have been used in the extraction of lithium from geothermal water.(180)

The use of ultrafine H2TiO3 synthesised by the modified solid phase method with moderate adsorption capacity gave high efficiency. The maximum equilibrium adsorption capacity for lithium reached 30,5 mg/g. Cyclic tests showed an average solubility loss of Ti of less than 0,6 %.(184)

Based on the results obtained, a principal technological scheme for the separation of lithium from aqueous raw materials by the adsorption method was developed (figure 6).

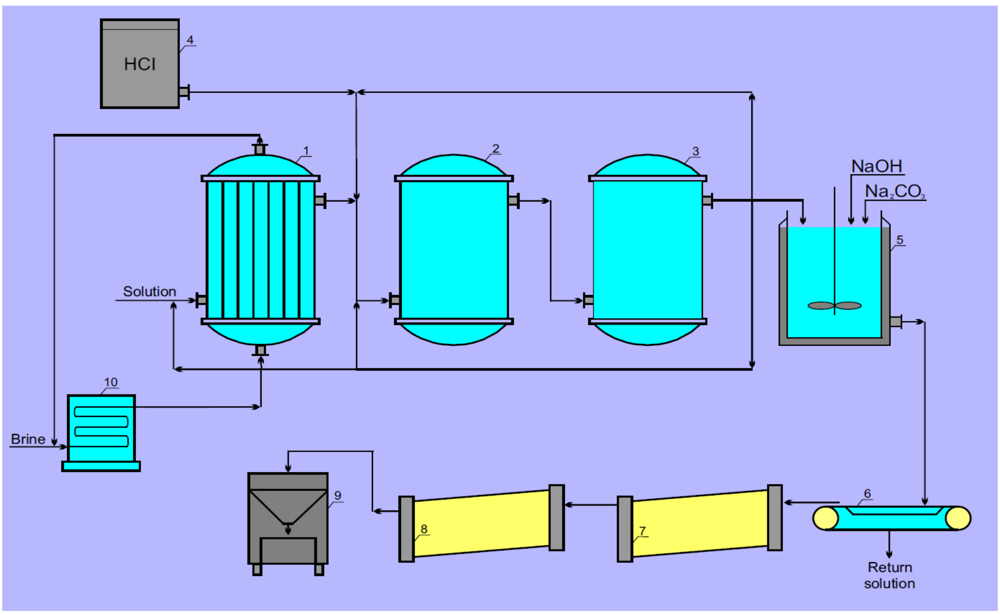

Figure 6. Principal technological scheme of obtaining lithium carbonate from aqueous raw materials by the adsorption method

The technological process of separating Li2CO3 from liquid raw materials containing lithium by adsorption consists of the following main stages: Collection of lithium-containing waters; selective adsorption of lithium; desorption of lithium into a hydrochloric acid solution; precipitation of lithium carbonate; separation of precipitated lithium carbonate salts; drying of wet lithium carbonate crystals; packaging and storage of the obtained product.

The lithium-containing brine is transferred to a heat exchanger to heat the water (step 1) and then to the adsorption units (step 2). After the adsorbent is saturated with lithium, the lithium is desorbed into a chloride acid solution in a desorption unit (step 3). The desorbed lithium solution is sent to a reactor to precipitate lithium carbonate using soda ash (step 5). The lithium carbonate slurry is sent to a belt vacuum filter to separate the lithium carbonate from the liquid phase (step 6). Then, the separated wet lithium carbonate is transferred to a drum dryer for drying (step 7). The dried lithium carbonate is cooled to room temperature in a cooling drum (step 8). The dried and cooled lithium carbonate is sent to the packaging unit.

As a result of the scientific improvement of adsorbents used for lithium separation, it has been proposed to use activated aluminium oxide (AlOx) as an adsorbent for lithium separation from salt lake water.(185,186,187) A group of scientists(188) synthesised aluminium-lithium composite adsorbents by reacting activated aluminium oxide with lithium salts, which have a high degree of porosity.(189) Such materials allow for effective sorption of lithium and its re-separation. The use of volatile powder industrial waste and its processing not only reduces the cost of the lithium separation process, but also has significant environmental significance.(190)

The adsorption method produces less waste than traditional methods of lithium separation, including evaporation and chemical precipitation.(190)

Further improving the composition and structure of adsorbent materials increases their sorption capacity and optimises processing processes. The development of new types of nanomaterials and hybrid adsorbents, and their industrial application, will allow the creation of new technologies in the field of lithium separation. It is assumed that the use of artificial intelligence can contribute to making the technology more attractive.

The adsorption method is one of the most promising technologies in terms of energy and material saving, environmental and economic efficiency in the separation of lithium from aqueous sources.

CONCLUSIONS

Lithium is among the most demanded elements; there are ample supplies of this element in the form of raw materials. Lithium occurs in more than 150 minerals; it does not occur in its free form in nature. The demand for Lithium has been steadily increasing due to the significant demand for electric cars.

Currently, more than 60 % of the world's lithium supply comes from water resources such as lithium-rich brines, seawater, and geothermal water that contain 70-80 % of the world's deposits.

Therefore, there is a need to look for means to extract the lithium from water resources that are suitable for processing compounds of lithium. Various process technologies have been developed to extract compounds of lithium from aqueous resources, such as the use of precipitation, solvent extraction, membrane separation, liquid-liquid extraction, ion exchange adsorption, and electro dialysis, among others.

From this brief analysis of research about lithium extraction with variable concentration, it is obvious that the most promising methods to be applied to this extraction are those such as purification by impurity precipitation from saturated solutions and adsorption. These are low-cost methods with no negative impact on the environment. They can be applied to saturated solutions with various components as well as to solutions with low lithium concentration. It would be perfect to implement all these processes. They include purification of aqueous solutions with impurities' precipitation, preparation of lithium-containing solutions, and then extraction of lithium with these purified solutions.

Based on the above analysis, it has been concluded that the processes of impurity precipitation and adsorption are most appropriate for the objective of recovering lithium. The combination of these processes ensures that the purity levels are absolutely perfect within the brines and that lithium can be successfully isolated from saturated solutions. The process of impurity precipitation also allows targeting the unwanted components in the saturated brines. Lithium can be isolated from the targeted solutions with the aid of another process called adsorption.

The coupling process of adsorption-precipitation methods may be seen as an attractive option to meet the anticipated requirements in terms of the supply of lithium compounds in the forthcoming periods. The process ensures energy sustainability and has environmental and "circular economy" benefits.

BIBLIOGRAPHIC REFERENCES

1. Reddy M.V, Mauger A, Julien C.M, Paolella A, Zaghib K. Brief history of early lithium-battery development. Material. 2020;13(8);1884. https://doi.org/10.3390/ma13081884

2. Wen H, Liu Z, Xu J, Chen JP. Nanofiltration membrane for enhancement in lithium recovery from salt-lake brine: A review. Desalination. 2024;591:117967. https://doi.org/10.1016/j.desal.2024.117967

3. Tadesse B, Makuei F, Albijanic B, Dyer L. The beneficiation of lithium minerals from hard rock ores: A review. Minerals Engineering. 2019;131:170–184. https://doi.org/10.1016/j.mineng.2018.11.023

4. Abdullayev B, Rifky M, Makhmayorov J, Usmanov I, Deng T, Samadiy M. Adsorption method and adsorbents for the recovery of lithium compounds from water sources. International Journal of Engineering Trends and Technology. 2023;71(9):212–226. https://doi.org/10.14445/22315381/IJETT-V71I9P219

5. Choubey PK, Kim M, Srivastava RR, Lee J, Lee JY. Advance review on the exploitation of the prominent energy-storage element: Lithium. Part I: From mineral and brine resources. Minerals Engineering. 2016;89:119–137. https://doi.org/10.1016/j.mineng.2016.01.010

6. Li X, Mo Y, Qing W, Shao S, Tang CY, Li J. Membrane-based technologies for lithium recovery from water lithium resources: A review. Journal of Membrane Science. 2019;591:117317. https://doi.org/10.1016/j.memsci.2019.117317

7. Hasan MA, Hossain R, Sahajwalla V. Critical metals (Lithium and Zinc) recovery from

battery waste, ores, brine, and steel dust: A review. Process Safety and Environmental Protection. 2023;178:976–994. https://doi.org/10.1016/j.psep.2023.08.069

8. Parvizi P, Jalilian M, Amidi A. M, Zangeneh M.R, Riba J.R. From present innovations to future potential: the promising journey of lithium-ion batteries. Micromachines. 2025;16(2); 194. https://doi.org/10.3390/mi16020194

9. Sun X, Hao H, Zhao F, Liu Z. Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation and Recycling. 2017;124:50–61. https://doi.org/10.1016/j.resconrec.2017.04.012

10. Loganathan P, Naidu G, Vigneswaran S. Mining valuable minerals from seawater: A critical review. Environmental Science: Water Research and Technology. 2017;3(1):37–53. https://doi.org/10.1039/C6EW00268D

11. Kesler SE, Gruber PW, Medina PA, Keoleian GA, Everson MP, Wallington TJ. Global lithium resources: Relative importance of pegmatite, brine and other deposits. Ore Geology Reviews. 2012;48:55–69. https://doi.org/10.1016/j.oregeorev.2012.05.006

12. Kavanagh L, Keohane J, Garcia Cabellos G, Lloyd A, Cleary J. Global lithium sources, industrial use and future in the electric vehicle industry: A review. Resources. 2018;7(3):57. https://doi.org/10.3390/resources7030057

13. Gu J, Liang B, Luo X, Zhang X, Yuan W, Xiao B, Tang X. Recent Advances and Future Prospects of Lithium Recovery from Low-Grade Lithium Resources: A Review. Inorganics. 2025; 13(1):4. https://doi.org/10.3390/inorganics13010004

14. Dursun T, Soutis C. Recent developments in advanced aircraft aluminium alloys. Materials and Design. 2014;56:862–871. https://doi.org/10.1016/j.matdes.2013.12.002

15. Cao Y, Zhou C, Gao F, Huang Y, Zhu W, Liu G, Wang J. Lithium recovery from typical coal-based solid wastes: Critical technologies, challenges, and prospects. Chemical Engineering Journal. 2024;498:155121. https://doi.org/10.1016/j.cej.2024.155121

16. Ji ZY, Yang FJ, Zhao YY, Liu J, Wang N, Yuan JS. Preparation of titanium-base lithium ionic sieve with sodium persulfate as eluent and its performance. Chemical Engineering Journal. 2017;328:768–775. https://doi.org/10.1016/j.cej.2017.07.047

17. Yu H, Naidu G, Zhang C, Wang C, Razmjou A, Han DS, He T, Shon H. Metal-based adsorbents for lithium recovery from aqueous resources. Desalination. 2022;539:115951. https://doi.org/10.1016/j.desal.2022.115951

18. Szlugaj J, Radwanek-Bąk B. Lithium sources and their current use. Gospodarka Surowcami Mineralnymi. 2022;38(1):61–68. http://dx.doi.org/10.24425/gsm.2022.140613

19. Song JF, Nghiem LD, Lia XM, He T. Lithium extraction from Chinese salt-lake brines: Opportunities, challenges, and future outlook. Environmental Science: Water Research and Technology. 2017;3(4):593–597. https://doi.org/10.1039/C7EW00020K

20. Li Z, Mercken J, Li X, Riaño S, Binnemans K. Efficient and sustainable removal

of magnesium from brines for lithium/magnesium separation using binary extractants. ACS Sustainable Chemistry & Engineering. 2019;7:19225–19234. https://doi.org/10.1021/acssuschemeng.9b05436

21. Krishnan R, Gopan G. A comprehensive review of lithium extraction: From historical perspectives to emerging technologies, storage, and environmental considerations. Cleaner Engineering and Technology. 2024;20:100749. https://doi.org/10.1016/j.clet.2024.100749

22. Vega-Muratalla VO, Ramírez-Márquez C, Lira-Barragán LF, Ponce-Ortega JM. Review of lithium as a strategic resource for electric vehicle battery production: availability, extraction, and future prospects. Resources. 2024;13(11):148. https://doi.org/10.3390/resources13110148

23. Grosjean C, Miranda PH, Perrin M, Poggi P. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew Sust Energ Rev. 2012;16(3):1735–1744. https://doi.org/10.1016/j.rser.2011.11.023

24. U.S. Geological Survey. Mineral Commodity Summaries. Washington, DC, USA; 2024.

25. Jaskula BW. Lithium. In: Metals and Minerals: U.S. Geological Survey Minerals Yearbook 2020. Vol. 1. Washington, DC: USGS; 2024:44.1–44.11. https://pubs.usgs.gov/myb/vol1/2020/myb1-2020-lithium.pdf

26. Toba AL, Nguyen RT, Cole C, Neupane G, Paranthaman MP. US lithium resources from geothermal and extraction feasibility. Resour Conserv Recycl. 2021;169:105514. https://doi.org/10.1016/j.resconrec.2021.105514

27. Carles L. Modeling Long-Term Global Lithium Stocks and Flows. Master Thesis. Federal Institute of Technology in Lausanne, Switzerland; 2019. https://about.bnef.com/electric-vehicle-outlook/#toc-viewreport

28. Roskill. Lithium Outlook to 2028 – Tables. 2019. https://roskill.com/market-reports/

29. Wang J, Hu H, Wu K. Extraction of lithium, rubidium and cesium from lithium porcelain stone. Hydrometallurgy. 2020;191:105233. https://doi.org/10.1016/j.hydromet.2019.105233

30. Barrera P. Lithium market update: Q1 2020 in review. 2020. https://investingnews.com/daily/resource-investing/battery-metals-investing/lithium-investing/lithium-market-update/

31. Bell T. An overview of commercial lithium production. 2020. https://www.thoughtco.com/lithium-production-2340123

32. Balaram V, Santosh M, Satyanarayanan M, Srinivas N, Gupta H. Lithium: A review of applications, occurrence, exploration, extraction, recycling, analysis, and environmental impact. Geosci Front. 2024;15(5):101868. https://doi.org/10.1016/j.gsf.2024.101868

33. Meng F, McNeice J, Zadeh SS, Ghahreman A. Review of lithium production and recovery from minerals, brines, and lithium-ion batteries. Miner Process Extr Metall Rev. 2021;42(2):123-141. https://doi.org/10.1080/08827508.2019.1668387

34. Swain B. Recovery and recycling of lithium: A review. Sep Purif Technol. 2017;172:388–403. https://doi.org/10.1016/j.seppur.2016.08.031

35. Michelini E, Höschele P, Ratz F, et al. Potential and most promising second-life applications for automotive lithium-ion batteries considering technical, economic and legal aspects. Energies. 2023;16(6):2830. https://doi.org/10.3390/en16062830

36. Ralls AM, Leong K, Clayton J, et al. The role of lithium-ion batteries in the growing trend of electric vehicles. Materials. 2023;16(17):6063. https://doi.org/10.3390/ma16176063

37. Benson TR, Coble MA, Rytuba JJ, Mahood GA. Lithium enrichment in intracontinental rhyolite magmas leads to Li deposits in caldera basins. Nat Commun. 2017;8(1):270. https://doi.org/10.1038/s41467-017-00234-y

38. Halkes RT, Hughes A, Wall F, Petavratzi E, Pell R, Lindsay JJ. Life cycle assessment and water use impacts of lithium production from salar deposits: challenges and opportunities. Resour Conserv Recycl. 2024;207:107554. https://doi.org/10.1016/j.resconrec.2024.107554

39. da Silva Lima L, Cocquyt L, Mancini L, Cadena E, Dewulf J. The role of raw materials to achieve the Sustainable Development Goals: tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain. J Ind Ecol. 2023;27(3):777–794. https://doi.org/10.1111/jiec.13336

40. European Commission. Critical Raw Materials Resilience: Charting a Path Towards Greater Security and Sustainability. Brussels, Belgium; 2020. https://doi.org/10.1007/978-3-030-40268-6_9

41. Martin G, Rentsch L, Höck M, Bertau M. Lithium market research–global supply, future demand and price development. Energy Storage Mater. 2017;6:171–179. https://doi.org/10.1016/j.ensm.2016.11.004

42. Sathyamoorthi S, Tejangkura W, Sawangphruk M. Turning carbon-ZnMn2O4 powder in primary battery waste to be an effective active material for long cycling life supercapacitors: in situ gas analysis. Waste Manag. 2020;109:202–211. https://doi.org/10.1016/j.wasman.2020.05.007

43. Lithium-Ion Battery Inventor Introduces New Technology for Fast-Charging, Noncombustible Batteries. UT News. 2017 Feb 28. Available from: https://news.utexas.edu/2017/02/28/goodenough-introduces-new-battery-technology

44. Bradley D, McCauley A. A preliminary deposit model for lithium-cesium-tantalum (LCT) pegmatites (ver. 1.1, December 2016): U.S. Geological Survey Open-File Report 2013-1008. 2013;7. https://doi.org/10.3133/ofr20131008

45. Dall-Orsoletta A, Ferreira P, Dranka GG. Low-carbon technologies and just energy transition: prospects for electric vehicles. Energy Convers Manag X. 2022;16:100271. https://doi.org/10.1016/j.ecmx.2022.100271

46. Hearn AX, Sohre A, Burger P. Innovative but unjust? Analysing the opportunities and justice issues within positive energy districts in Europe. Energy Res Soc Sci. 2021;78:102127. https://doi.org/10.1016/j.erss.2021.102127

47. U.S. Geological Survey. Mineral Commodity Summaries 2023. Washington (DC): U.S. Geological Survey; 2023. Available from: https://www.usgs.gov/centers/nmic/mineral-commodity-summaries

48. Roskill. The Lithium Market: Outlook to 2030. 2023. Available from: https://roskill.com/

49. Dorn FM, Peyré FR. Lithium as a strategic resource. J Lat Am Geogr. 2020;19(4):68–90. https://doi.org/10.1111/jiec.12949

50. Alessia A, Alessandro B, Maria VG, Carlos VA, Francesca B. Challenges for sustainable lithium supply: a critical review. J Clean Prod. 2021;300:126954. https://doi.org/10.1016/j.jclepro.2021.126954

51. Srivastava V, Rantala V, Mehdipour P, Kauppinen T, Tuomikoski S, Heponiemi A, et al. A comprehensive review of the reclamation of resources from spent lithium-ion batteries. Chem Eng J. 2023;474:145822. https://doi.org/10.1016/j.cej.2023.145822

52. Wood Mackenzie. Lithium Supply and Demand Outlook. 2023. Available from: https://www.woodmac.com/

53. Vikström H, Davidsson S, Höök M. Lithium availability and future production outlooks. Appl Energy. 2013;110:252–266. https://doi.org/10.1016/j.apenergy.2013.04.005

54. Zhao S, You F. Comparative life-cycle assessment of Li-ion batteries through process-based and integrated hybrid approaches. ACS Sustain Chem Eng. 2019;7(5):5082–5094. https://doi.org/10.1021/acssuschemeng.8b05902

55. Dong W, Wang W, Shen D, Sun W, Zhao M, Meng L, et al. Structure and low-temperature performance of waste graphite used in lithium-ion battery anode. ChemistrySelect. 2022;7(8):e202104547. https://doi.org/10.1002/slct.202104547

56. Hu X, Yan W, Zhang X, Feng Z, Wang Y, Ying B, et al. LRP-based design of sustainable recycling network for electric vehicle batteries. Processes. 2022;10(2):273. https://doi.org/10.3390/pr10020273

57. Shangguan E, Wang Q, Wu C, Wu S, Ji M, Li J, et al. Novel application of repaired $LiFePO_4$ as a candidate anode material for advanced alkaline rechargeable batteries. ACS Sustain Chem Eng. 2018;6(10):13312–13323. https://doi.org/10.1021/acssuschemeng.8b02885

58. Jang M, Yi G, Jeon H, Yoon C. Current status of processes and hazardous chemicals of lithium-ion battery industries in the Republic of Korea. Saf Health Work. 2025;16(1):1–12. https://doi.org/10.1016/j.shaw.2024.10.005

59. Dugamin EJ, Richard A, Cathelineau M, Boiron MC, Despinois F, Brisset A. Groundwater in sedimentary basins as potential lithium resource: a global prospective study. Sci Rep. 2021;11(1):21091. https://doi.org/10.1038/s41598-021-99912-7

60. Carrasco S. The role of business in Chile's lithium policy. In: From (De)regulation to

Industrialization? Chilean Lithium Policy in Comparative Perspective. Cham: Springer Nature Switzerland; 2025. p. 123–151. https://doi.org/10.1007/978-3-031-77130-9_6

61. Gu J, Liang B, Luo X, Zhang X, Yuan W, Xiao B, et al. Recent advances and future prospects of lithium recovery from low-grade lithium resources: a review. Inorganics. 2024;13(1):4. https://doi.org/10.3390/inorganics13010004

62. Oxford Analytica. Electric cars and smartphones to drive lithium demand. Expert Briefings. 2016. https://doi.org/10.1108/OXAN-DB214868

63. Knapik E, Rotko G, Marszałek M. Recovery of lithium from oilfield brines – current achievements and future perspectives: a mini review. Energies. 2023;16(18):6628. https://doi.org/10.3390/en16186628

64. Ettehadi A, Chuprin M, Mokhtari M, Gang D, Wortman P, Heydari E. Geological insights into exploration and extraction of lithium from oilfield produced water in the USA: a review. Energy Fuels. 2024;38(12):10517–10541. https://doi.org/10.1021/acs.energyfuels.4c00732

65. Mishrif A, Khan A. Clean energy transition through the sustainable exploration and use of lithium in Oman: potential and challenges. Sustainability. 2023;15(20):15173. https://doi.org/10.3390/su152015173

66. Berezkin M, Degtyarev K, Sinyugin O. Market dynamics of lithium as a key element for modern energy. E3S Web Conf. 2023;407:03002. https://doi.org/10.1051/e3sconf/202340703002

67. Sun X, Liu Z, Zhao F, Hao H. Global competition in the lithium-ion battery supply chain: a novel perspective for criticality analysis. Environ Sci Technol. 2021;55(18):12180–12190. https://doi.org/10.1021/acs.est.1c03376

68. Zhang C, Zhao X, Sacchi R, You F. Trade-off between critical metal requirement and transportation decarbonization in automotive electrification. Nat Commun. 2023;14(1):1616. https://doi.org/10.1038/s41467-023-37373-4

69. Sun Y, Guo X, Hu S, Xiang X. Highly efficient extraction of lithium from salt lake brine by LiAl-layered double hydroxides as lithium-ion-selective capturing material. J Energy Chem. 2019;34:80–87. https://doi.org/10.1016/j.jechem.2018.09.022

70. Miao Y, Hynan P, Von Jouanne A, Yokochi A. Current Li-ion battery technologies in electric vehicles and opportunities for advancements. Energies. 2019;12(6):1074. https://doi.org/10.3390/en12061074

71. Roy H, Roy BN, Hasanuzzaman M, Islam MS, Abdel-Khalik AS, Hamad MS, et al. Global advancements and current challenges of electric vehicle batteries and their prospects: a comprehensive review. Sustainability. 2022;14(24):16684. https://doi.org/10.3390/su142416684

72. Rangarajan S, Sunddararaj SP, Sudhakar AVV, Shiva CK, Subramaniam U, Collins ER, et al. Lithium-ion batteries – the crux of electric vehicles with opportunities and challenges. Clean Technol. 2022;4(4):908–930. https://doi.org/10.3390/cleantechnol4040056

73. Boroumand Y, Razmjou A. Adsorption-type aluminium-based direct lithium extraction:

the effect of heat, salinity and lithium content. Desalination. 2024;577:117406. https://doi.org/10.1016/j.desal.2024.117406

74. Gil-Alana LA, Monge M. Lithium: production and estimated consumption – evidence of persistence. Resour Policy. 2019;60:198–202. https://doi.org/10.1016/j.resourpol.2019.01.006

75. Aylmore MG, Merigot K, Quadir Z, Rickard WD, Evans NJ, McDonald BJ, et al. Applications of advanced analytical and mass spectrometry techniques to the characterisation of micaceous lithium-bearing ores. Miner Eng. 2018;116:182–195. https://doi.org/10.1016/j.mineng.2017.08.004

76. Pálsdóttir A, Alabi CA, Tester JW. Characterization of 14-crown-4 ethers for the extraction of lithium from natural brines: synthesis, solubility measurements in supercritical carbon dioxide, and thermodynamic modeling. Ind Eng Chem Res. 2021;60(21):7926–7934. https://doi.org/10.1021/acs.iecr.1c00346

77. Stringfellow WT, Dobson PF. Technology for the recovery of lithium from geothermal brines. Energies. 2021;14(20):6805. https://doi.org/10.3390/en14206805

78. Zeng Y, Li W, Wan Z, Qin S, Huang Q, Cai W, et al. Electrochemically mediated lithium extraction for energy and environmental sustainability. Adv Funct Mater. 2024;34(33):2400416. https://doi.org/10.1002/adfm.202400416

79. Steiner Z, Landing WM, Bohlin MS, Greaves M, Prakash S, Vinayachandran PN, et al. Variability in the concentration of lithium in the Indo-Pacific Ocean. Glob Biogeochem Cycles. 2022;36(6):e2021GB007184. https://doi.org/10.1029/2021GB007184

80. Zhang B, Qi FY, Gao XZ, Li XL, Shang YT, Kong ZY, et al. Geological characteristics, metallogenic regularity, and research progress of lithium deposits in China. China Geol. 2022;5(4):734–767. https://doi.org/10.31035/cg2022054

81. Munk LA, Hynek SA, Bradley DC, Boutt D, Labay K, Jochens H. Lithium brines: a global perspective. Rev Econ Geol. 2016;18:339–365. https://doi.org/10.5382/Rev.18.14

82. Zeng X, Li J. Implications for the carrying capacity of lithium reserve in China. Resour Conserv Recycl. 2013;80:58–63. https://doi.org/10.1016/j.resconrec.2013.08.003

83. Álvarez-Amado F, Tardani D, Poblete-González C, Godfrey L, Matte-Estrada D. Hydrogeochemical processes controlling the water composition in a hyperarid environment: new insights from Li, B, and Sr isotopes in the Salar de Atacama. Sci Total Environ. 2022;835:155470. https://doi.org/10.1016/j.scitotenv.2022.155470

84. Jerez B, Garcés I, Torres R. Lithium extractivism and water injustices in the Salar de Atacama, Chile: the colonial shadow of green electromobility. Polit Geogr. 2021;87:102382. https://doi.org/10.1016/j.polgeo.2021.102382

85. Haferburg G, Gröning JA, Schmidt N, Kummer NA, Erquicia JC, Schlömann M. Microbial diversity of the hypersaline and lithium-rich Salar de Uyuni, Bolivia. Microbiol Res. 2017;199:19–28. https://doi.org/10.1016/j.micres.2017.02.007

86. Sanchez-Lopez MD. Territory and lithium extraction: the Great Land of Lipez and the Uyuni Salt Flat in Bolivia. Polit Geogr. 2021;90:102456. https://doi.org/10.1016/j.polgeo.2021.102456

87. Zhang Y, Hu Y, Sun N, Khoso SA, Wang L, Sun W. A novel precipitant for separating lithium from magnesium in high Mg/Li ratio brine. Hydrometallurgy. 2019;187:125–133. https://doi.org/10.1016/j.hydromet.2019.05.019

88. Ma Y, Qin X, Pan T, Chen J, Jiang Z, Ding C, et al. Sedimentary environment and source analysis of sedimentary lithium deposits in Dezong Mahai Salt Lake, Qaidam Basin. Sustainability. 2024;16(23):10561. https://doi.org/10.3390/su162310561

89. Sun S, Yu X, Li M, Duo J, Guo Y, Deng T. Green recovery of lithium from geothermal water based on a novel lithium iron phosphate electrochemical technique. J Clean Prod. 2020;247:119178. https://doi.org/10.1016/j.jclepro.2019.119178

90. Balaram V, Armstrong-Altrin JS, Khan RM, Rao BS. Land and marine sedimentary deposits as potential sources of lithium. Int Geol Rev. 2025;67(9):1217–1250. https://doi.org/10.1080/00206814.2024.2431815

91. Torres D, Pérez K, Galleguillos Madrid FM, Leiva WH, Gálvez E, Salinas-Rodríguez E, et al. Salar de Atacama lithium and potassium productive process. Metals. 2024;14(10):1095. https://doi.org/10.3390/met14101095

92. Flexer V, Baspineiro CF, Galli CI. Lithium recovery from brines: a vital raw material for green energies with a potential environmental impact in its mining and processing. Sci Total Environ. 2018;639:1188–1204. https://doi.org/10.1016/j.scitotenv.2018.05.223

93. Gruber PW, Medina PA, Keoleian GA, Kesler SE, Everson MP, Wallington TJ. Global lithium availability: a constraint for electric vehicles? J Ind Ecol. 2011;15(5):760–775. https://doi.org/10.1111/j.1530-9290.2011.00359.x

94. Khalil A, Mohammed S, Hashaikeh R, Hilal N. Lithium recovery from brine: recent developments and challenges. Desalination. 2022;528:115611. https://doi.org/10.1016/j.desal.2022.115611

95. Butylskii DY, Troitskiy VA, Smirnova NV, Pismenskaya ND, Wang Y, Jiang C, et al. Review of recent progress on lithium recovery and recycling from primary and secondary sources with membrane-based technologies. Desalination. 2024;117826. https://doi.org/10.1016/j.desal.2024.117826

96. An JW, Kang DJ, Tran KT, Kim MJ, Lim T, Tran T. Recovery of lithium from Uyuni salar brine. Hydrometallurgy. 2012;117:64–70. https://doi.org/10.1016/j.hydromet.2012.02.008

97. Onishi K, Nakamura T, Nishihama S, Yoshizuka K. Synergistic solvent impregnated resin for adsorptive separation of lithium ion. Ind Eng Chem Res. 2010;49(14):6554–6558. https://doi.org/10.1021/ie100145d

98. Battaglia G, Berkemeyer L, Cipollina A, Cortina JL, Fernandez de Labastida M, Lopez Rodriguez J, et al. Recovery of lithium carbonate from dilute Li-rich brine via homogenous

and heterogeneous precipitation. Ind Eng Chem Res. 2022;61(36):13589–13602. https://doi.org/10.1021/acs.iecr.2c01397

99. Coterillo R, Gallart LE, Fernández-Escalante E, Junquera J, García-Fernández P, Ortiz I, et al. Selective extraction of lithium from seawater desalination concentrates: study of thermodynamic and equilibrium properties using density functional theory (DFT). Desalination. 2022;532:115704. https://doi.org/10.1016/j.desal.2022.115704

100. Ni C, Liu C, Wang J, Khan A, Zhong H, He Z. Selective separation of lithium from the hydrochloric acid leachate of lithium ores via the extraction system containing TBP-$FeCl_3$. Desalination. 2024;583:117677. https://doi.org/10.1016/j.desal.2024.117677

101. Ahmed S, Madikere Raghunatha Reddy AK, Zaghib K. Transformations of critical lithium ores to battery-grade materials: from mine to precursors. Batteries. 2024;10(11):379. https://doi.org/10.3390/batteries10110379

102. Alera AC, Benitez JP, Fernandez RJ, Pascual CK, Policarpio F, Lopez ECR. Recent advances in lithium extraction. Eng Proc. 2024;67(1):52. https://doi.org/10.3390/engproc2024067052

103. Liu Q, Yang P, Tu W, Sun H, Li S, Zhang Y. Lithium recovery from oil and gas produced water: opportunities, challenges, and future outlook. J Water Process Eng. 2023;55:104148. https://doi.org/10.1016/j.jwpe.2023.104148

104. Marcinov V, Klimko J, Takáčová Z, Pirošková J, Miškufová A, Sommerfeld M, et al. Lithium production and recovery methods: overview of lithium losses. Metals. 2023;13(7):1213. https://doi.org/10.3390/met13071213

105. Danso DK, Alhajeri MM, Bicerano J, Heller DP, Longe PO, Ghahfarokhi RB. A review of polyelectrolytes and their complexes for lithium recovery from oilfield and geothermal brines. Appl Energy. 2025;392:125966. https://doi.org/10.1016/j.apenergy.2025.125966

106. Yin X, Xu P, Wang H. Applications of crown ether-based materials for enhancing lithium recovery from brines. Sep Purif Technol. 2025;371:133093. https://doi.org/10.1016/j.seppur.2025.133093

107. Zhu Y, Gao F, Jia H, Chen Z, Ni BJ, Wang J. Applications of membrane technology in the resource recovery of power lithium-ion battery precursor wastewater: a review. Environ Res. 2025;275:121372. https://doi.org/10.1016/j.envres.2025.121372

108. Cerda A, Quilaqueo M, Barros L, Seriche G, Gim-Krumm M, Santoro S, et al. Recovering water from lithium-rich brines by a fractionation process based on membrane distillation-crystallization. J Water Process Eng. 2021;41:102063. https://doi.org/10.1016/j.jwpe.2021.102063

109. Nadzri N, Lim YJ, Liao X, Liang Y, Goh K, Liao Y, et al. Lithium recovery from seawater desalination brines using ion-sieve electrospun nanofibrous membranes: the role of nanofiber design. Chem Eng J. 2025;162886. https://doi.org/10.1016/j.cej.2025.162886

110. Yang S, Zhang F, Ding H, He P, Zhou H. Lithium metal extraction from seawater. Joule.

2018;2(9):1648–1651. https://doi.org/10.1016/j.joule.2018.07.006

111. Sun SY, Cai LJ, Nie XY, Song X, Yu JG. Separation of magnesium and lithium from brine using a Desal nanofiltration membrane. J Water Process Eng. 2015;7:210–217. https://doi.org/10.1016/j.jwpe.2015.06.012

112. Bi Q, Zhang Z, Zhao C, Tao Z. Study on the recovery of lithium from high Mg^{2+}/Li^{+} ratio brine by nanofiltration. Water Sci Technol. 2014;70(10):1690–1694. https://doi.org/10.2166/wst.2014.426

113. Pramanik BK, Asif MB, Kentish S, Nghiem LD, Hai FI. Lithium enrichment from a simulated salt lake brine using an integrated nanofiltration–membrane distillation process. J Environ Chem Eng. 2019;7(5):103395. https://doi.org/10.1016/j.jece.2019.103395

114. Pramanik BK, Asif MB, Roychand R, Shu L, Jegatheesan V, Bhuiyan M, et al. Lithium recovery from salt-lake brine: impact of competing cations, pretreatment and preconcentration. Chemosphere. 2020;260:127623. https://doi.org/10.1016/j.chemosphere.2020.127623

115. Rivero-Falcón A, López-López Y, Suárez BP, Melián-Martel N. Performance evaluation of nanofiltration membranes for SWRO brine valorisation: insights from a pilot plant under real conditions. Sep Purif Technol. 2025;359:130774. https://doi.org/10.1016/j.seppur.2024.130774

116. Salsabila N, Biçer Y. Application of monovalent selective membranes and bipolar membranes in electrodialysis: a review. J Environ Chem Eng. 2025;117504. https://doi.org/10.1016/j.jece.2025.117504

117. Hubach T, Pillath M, Knaup C, Schlüter S, Held C. Li^{+} separation from multi-ionic mixtures by nanofiltration membranes: experiments and modeling. Modelling. 2023;4(3):408-425. https://doi.org/10.3390/modelling4030024

118. Brião VB, Mossmann J, Seguenka B, Graciola S, Piccin JS. Integrating whey processing: ultrafiltration, nanofiltration, and water reuse from diafiltration. Membranes. 2024;14(9):191. https://doi.org/10.3390/membranes14090191

119. Thakur AK, Malmali M. Advances in polymeric cation exchange membranes for electrodialysis: an overview. J Environ Chem Eng. 2022;10(5):108295. https://doi.org/10.1016/j.jece.2022.108295

120. Fan H, Huang Y, Yip NY. Advancing ion-exchange membranes to ion-selective membranes: principles, status, and opportunities. Front Environ Sci Eng. 2023;17(2):25. https://doi.org/10.1007/s11783-023-1625-0

121. Alghamdi M, Altmann T, Das R. Direct lithium extraction from seawater brine: an assessment of technology and existing commercial systems. Minerals. 2025;15(5):512. https://doi.org/10.3390/min15050512

122. Kanoh H, Feng Q, Hirotsu T, Ooi K. AC impedance analysis for Li^{+} insertion of a Pt/**λ**-MnO2 electrode in an aqueous phase. J Electrochem Soc. 1996;143(8):2610. https://doi.org/10.1149/1.1837056

123. Khalid R, Shah A, Javed M, Hussain H. Progress and obstacles in electrode materials for lithium-ion batteries: a journey towards enhanced energy storage efficiency. RSC Adv. 2025;15(20):15951–15998. https://doi.org/10.1039/d5ra02042e

124. Zavahir S, Elmakki T, Gulied M, Ahmad Z, Al-Sulaiti L, Shon HK, et al. A review on lithium recovery using electrochemical capturing systems. Desalination. 2021;500:114883. https://doi.org/10.1016/j.desal.2020.114883

125. Sun J, Liang D, Meng X, Li Z. Recent advances in lithium extraction using electrode materials of Li-ion battery from brine/seawater. Processes. 2022;10(12):2654. https://doi.org/10.3390/pr10122654

126. Joshi A, Mishra DK, Singh R, Zhang J, Ding Y. A comprehensive review of solid-state batteries. Appl Energy. 2025;386:125546. https://doi.org/10.1016/j.apenergy.2025.125546

127. Jose SA, Stoll JL, Smith T, Jackson C, Dieleman T, Leath E, et al. Critical review of lithium recovery methods: advancements, challenges, and future directions. Processes. 2024;12(10):2203. https://doi.org/10.3390/pr12102203

128. Lee J, Yu SH, Kim C, Sung YE, Yoon J. Highly selective lithium recovery from brine using a λ-MnO2–Ag battery. Phys Chem Chem Phys. 2013;15(20):7690–7695. https://doi.org/10.1039/C3CP50919B

129. Liu D, Xu W, Xiong J, He L, Zhao Z. Electrochemical system with $LiMn_2O_4$ porous electrode for lithium recovery and its kinetics. Sep Purif Technol. 2021;270:118809. https://doi.org/10.1016/j.seppur.2021.118809

130. Lai X, Xiong P, Zhong H. Extraction of lithium from brines with high Mg/Li ratio by the crystallization–precipitation method. Hydrometallurgy. 2020;192:105252. https://doi.org/10.1016/j.hydromet.2020.105252

131. Zhang Y, Xu R, Wang L, Sun W. Separation of magnesium from lithium in salt-lake brine through struvite precipitation. Miner Eng. 2022;180:107468. https://doi.org/10.1016/j.mineng.2022.107468

132. Ma C, Zhang J, Liu Y, Sun L, Liu Q. Integrated separation of precipitation and three-liquid-phase extraction for boron, lithium and magnesium from salt lake brine with high magnesium–lithium ratio. Sep Purif Technol. 2024;347:127541. https://doi.org/10.1016/j.seppur.2024.127541

133. Song Y, Zhao Z. Recovery of lithium from spent lithium-ion batteries using precipitation and electrodialysis techniques. Sep Purif Technol. 2018;206:335–342. https://doi.org/10.1016/j.seppur.2018.06.022

134. Ilyas S, Srivastava RR, Kim H, Ilyas N, Sattar R. Extraction of nickel and cobalt from a laterite ore using the carbothermic reduction roasting–ammoniacal leaching process. Sep Purif Technol. 2020;232:115971. https://doi.org/10.1016/j.seppur.2019.115971

135. Zhang C, Mu Y, Zhao S, Zhang W, Wang Y. Lithium extraction from synthetic brine with

high Mg2+/Li+ ratio using the polymer inclusion membrane. Desalination. 2020;496:114710. https://doi.org/10.1016/j.desal.2020.114710

136. Zhang J, Hu J, Liu Y, Jing Q, Yang C, Chen Y, et al. Sustainable and facile method for the selective recovery of lithium from cathode scrap of spent $LiFePO_4$ batteries. ACS Sustain Chem Eng. 2019;7(6):5626–5631. https://doi.org/10.1021/acssuschemeng.9b00404

137. Bae H, Kim Y. Technologies of lithium recycling from waste lithium-ion batteries: a review. Mater Adv. 2021;2(10):3234–3250. https://doi.org/10.1039/D1MA00216C

138. Wang J, Zhang Y, Cui K, Fu T, Gao J, Hussain S, et al. Pyrometallurgical recovery of zinc and valuable metals from electric arc furnace dust–a review. J Clean Prod. 2021;298:126788. https://doi.org/10.1016/j.jclepro.2021.126788

139. Wang M, Tan Q, Liu L, Li J. Selective regeneration of lithium from spent lithium-ion batteries using ionic substitution stimulated by mechanochemistry. J Clean Prod. 2021;279:123612. https://doi.org/10.1016/j.jclepro.2020.123612

140. Li J, He Y, Fu Y, Xie W, Feng Y, Alejandro K. Hydrometallurgical enhanced liberation and recovery of anode material from spent lithium-ion batteries. Waste Manag. 2021;126:517–526. https://doi.org/10.1016/j.wasman.2021.03.052

141. Van der Ent A, Parbhakar-Fox A, Erskine PD. Treasure from trash: mining critical metals from waste and unconventional sources. Sci Total Environ. 2021;758:143673. https://doi.org/10.1016/j.scitotenv.2020.143673

142. Zhang Y, Hu Y, Wang L, Sun W. Systematic review of lithium extraction from salt-lake brines via precipitation approaches. Miner Eng. 2019;139:105868. https://doi.org/10.1016/j.mineng.2019.105868

143. Raiguel S, Nguyen VT, Reis Rodrigues I, Deferm C, Riaño S, Binnemans K. Recovery of lithium from simulated nanofiltration-treated seawater desalination brine using solvent extraction and selective precipitation. Solvent Extr Ion Exch. 2023;41(4):425–448. https://doi.org/10.1080/07366299.2023.2206440

144. Xiao C, Zeng L. Thermodynamic study on recovery of lithium using phosphate precipitation method. Hydrometallurgy. 2018;178:283–286. https://doi.org/10.1016/j.hydromet.2018.05.001

145. Zhang L, Zhang T, Lv S, Song S, Galván HJO, Quintana M, et al. Adsorbents for lithium extraction from salt lake brine with high magnesium/lithium ratio: from structure-performance relationship to industrial applications. Desalination. 2024;117480. https://doi.org/10.1016/j.desal.2024.117480

146. Yu Z, Hai C, Li Y, Li X, Sun H, Zhou Y, et al. Unblocking the Li^+ transporting ways of granulated LiAl·LDHs with polyvinyl chloride by sodium alginate. Sep Purif Technol. 2025;134084. https://doi.org/10.1016/j.seppur.2025.134084

147. Xu Z, Ding Y, Han SC, Zhang C. Predicting the performance of lithium adsorption and recovery from unconventional water sources with machine learning. Water Res. 2024;266:122374. https://doi.org/10.1016/j.watres.2024.122374

148. Li L, Deshmane VG, Paranthaman MP, Bhave R, Moyer BA, Harrison S. Lithium recovery from aqueous resources and batteries: a brief review. Johnson Matthey Technol Rev. 2018;62(2):161–176. https://doi.org/10.1595/205651317X696676

149. Meshram P, Pandey BD, Mankhand TR. Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: a comprehensive review. Hydrometallurgy. 2014;150:192–208. https://doi.org/10.1016/j.hydromet.2014.10.012

150. Lee JM, Bauman WC. Recovery of lithium from brines. U.S. Patent 4,159,311. 1979 Jun 26. p. 5–7.

151. Ooi K, Miyai Y, Katoh S. Recovery of lithium from seawater by manganese oxide adsorbent. Sep Sci Technol. 1986;21(8):755–766. https://doi.org/10.1080/01496398608056148

152. Miyai Y, Ooi K, Katoh S. Recovery of lithium from seawater using a new type of ion-sieve adsorbent based on $MgMn_2O_4$. Sep Sci Technol. 1988;23(1–3):179–191. https://doi.org/10.1080/01496398808057641

153. Zhu GN, Wang YG, Xia YY. Ti-based compounds as anode materials for Li-ion batteries. Energy Environ Sci. 2012;5(5):6652–6667. https://doi.org/10.1039/C2EE03410G

154. Chaban MA, Rozhdestvenskaya LM, Palchik AV, Belyakov VN. Selectivity of new inorganic ion-exchangers based on oxides of titanium and manganese at sorption of lithium from aqueous media. J Water Chem Technol. 2016;38:8–13. https://doi.org/10.3103/S1063455X16010021

155. Wang S, Li P, Zhang X, Zheng S, Zhang Y. Selective adsorption of lithium from high Mg-containing brines using HxTiO3 ion sieve. Hydrometallurgy. 2017;174:21–28. https://doi.org/10.1016/j.hydromet.2017.09.009

156. Chaban MO, Rozhdestvenska LM, Palchyk OV, Dzyazko YS, Dzyazko OG. Structural characteristics and sorption properties of lithium-selective composite materials based on TiO2 and MnO2. Appl Nanosci. 2019;9:1037–1045. https://doi.org/10.1007/s13204-018-0749-1

157. Han Y, Yang Y, Ma Y, Liang D, Wen L, Ma J, et al. Selective ion channel adsorbents facilitate efficient and low environmental impact extraction of liquid lithium resources. J Hazard Mater. 2024;480:136335. https://doi.org/10.1016/j.jhazmat.2024.136335

158. Feng Q, Miyai Y, Kanoh H, Ooi K. Lithium (1+) extraction/insertion with spinel-type lithium manganese oxides: characterization of redox-type and ion-exchange-type sites. Langmuir. 1992;8(7):1861–1867. https://doi.org/10.1021/la00043a029

159. Feng Q, Miyai Y, Kanoh H, Ooi K. Li+ and Mg2+ extraction and Li+ insertion reactions with LiMg0.5Mn1.5O4 spinel in the aqueous phase. Chem Mater. 1993;5(3):311–316. http://dx.doi.org/10.1002/chin.199324019

160. Chitrakar R, Kanoh H, Miyai Y, Ooi K. Recovery of lithium from seawater using manganese oxide adsorbent (H1.5Mn1.6O4) derived from Li1.6Mn1.6O4. Ind Eng Chem Res. 2001;40(9):2054–2058. https://doi.org/10.1021/ie000911h

161. Zhang QH, Sun S, Li S, Jiang H, Yu JG. Adsorption of lithium ions on novel nanocrystal MnO_2. Chem Eng Sci. 2007;62(18–20):4869–4874. https://doi.org/10.1016/j.ces.2007.01.016

162. Liu L, Zhang H, Zhang Y, Cao D, Zhao X. Lithium extraction from seawater by manganese oxide ion sieve MnO2·0.5H2O. Colloids Surf A Physicochem Eng Asp. 2015;468:280–284. https://doi.org/10.1016/j.ces.2007.01.016

163. Besserguenev AV, Fogg AM, Francis RJ, Price SJ, O'Hare D, Isupov VP, et al. Synthesis and structure of the gibbsite intercalation compounds (LiAl2(OH)6)X(X=Cl, Br, NO3) and (LiAl2(OH)6) Cl·H2O using synchrotron X-ray and neutron powder diffraction. Chem Mater. 1997;9(1):241-247. https://doi.org/10.1021/cm960316z

164. Ighalo JO, Amaku JF, Olisah C, Adeola AO, Iwuozor KO, Akpomie KG, et al. Utilisation of adsorption as a resource recovery technique for lithium in geothermal water. J Mol Liq. 2022;365:120107. https://doi.org/10.1016/j.molliq.2022.120107

165. Ryu T, Shin J, Ghoreishian SM, Chung KS, Huh YS. Recovery of lithium in seawater using a titanium intercalated lithium manganese oxide composite. Hydrometallurgy. 2019;184:22–28. https://doi.org/10.1016/j.hydromet.2018.12.012

166. Noerochim L, Satriawangsa GA, Susanti D, Widodo A. Synthesis and characterization of lithium manganese oxide with different ratio of mole on lithium recovery process from geothermal fluid of Lumpur Sidoarjo. J Mater Sci Chem Eng. 2015;3(11):56–62. http://dx.doi.org/10.4236/msce.2015.311007

167. Shen XM, Clearfield A. Phase transitions and ion exchange behavior of electrolytically prepared manganese dioxide. J Solid State Chem. 1986;64(3):270–282. https://doi.org/10.1016/0022-4596(86)90071-X

168. Bajestani MB, Moheb A, Masigol M. Simultaneous optimization of adsorption capacity and stability of hydrothermally synthesized spinel ion sieve composite adsorbents for selective removal of lithium from aqueous solutions. Ind Eng Chem Res. 2019;58(27):12207–12215. https://doi.org/10.1021/acs.iecr.9b00804

169. Weng D, Duan H, Hou Y, Huo J, Chen L, Zhang F, et al. Introduction of manganese-based lithium-ion sieve – a review. Prog Nat Sci Mater Int. 2020;30(2):139–152. https://doi.org/10.1016/j.pnsc.2020.01.017

170. Ooi K, Miyai Y, Katoh S. Lithium-ion sieve property of λ-type manganese oxide. Solvent Extr Ion Exch. 1987;5(3):561–572. https://doi.org/10.1080/07366298708918581

171. Darul J, Nowicki W, Piszora P. Unusual compressional behavior of lithium-manganese oxides: a case study of Li4Mn5O12. J Phys Chem C. 2012;116(33):17872–17879. https://doi.org/10.1021/jp302227p

172. Moazeni M, Hajipour H, Askari M, Nusheh M. Hydrothermal synthesis and characterization of titanium dioxide nanotubes as novel lithium adsorbents. Mater Res Bull. 2015;61:70–75. https://doi.org/10.1016/j.materresbull.2014.09.069

173. Shi K, Luo M, Ying J, Zhen S, Xing Z, Chen R. Extraction of lithium from single-

crystalline lithium manganese oxide nanotubes using ammonium peroxodisulfate. iScience. 2020;23(11):101768. https://doi.org/10.1016/j.isci.2020.101768

174. Ding W, Zhang J, Liu Y, Guo Y, Deng T, Yu X. Synthesis of granulated H4Mn5O12/chitosan with improved stability by a novel cross-linking strategy for lithium adsorption from aqueous solutions. Chem Eng J. 2021;426:131689. https://doi.org/10.1016/j.cej.2021.131689

175. Gao JM, Du Z, Zhao Q, Guo Y, Cheng F. Enhanced Li+ adsorption by magnetically recyclable iron-doped lithium manganese oxide ion-sieve: synthesis, characterization, adsorption kinetics and isotherm. J Mater Res Technol. 2021;13:228–240. https://doi.org/10.1016/j.jmrt.2021.04.073

176. Zhang G, Zhang J, Zhou Y, Qi G, Wu Y, Hai C, et al. Synthesis of aluminum-doped ion-sieve manganese oxides powders with enhanced adsorption performance. Colloids Surf A Physicochem Eng Asp. 2019;583:123950. https://doi.org/10.1016/j.colsurfa.2019.123950

177. Sun J, Li X, Huang Y, Luo G, Tao D, Yu J, et al. Preparation of high hydrophilic H2TiO3 ion sieve for lithium recovery from liquid lithium resources. Chem Eng J. 2023;453:139485. https://doi.org/10.1016/j.cej.2022.139485

178. Chen S, Chen Z, Wei Z, Hu J, Guo Y, Deng T. Titanium-based ion sieve with enhanced post-separation ability for high-performance lithium recovery from geothermal water. Chem Eng J. 2021;410:128320. https://doi.org/10.1016/j.cej.2020.128320

179. Zhu G, Wang P, Qi P, Gao C. Adsorption and desorption properties of Li+ on PVC-H1.6Mn1.6O4 lithium ion-sieve membrane. Chem Eng J. 2014;235:340–348. https://doi.org/10.1016/j.cej.2013.09.068

180. Zhao K, Tong B, Yu X, Guo Y, Xie Y, Deng T. Synthesis of porous fiber-supported lithium ion-sieve adsorbent for lithium recovery from geothermal water. Chem Eng J. 2022;430:131423. https://doi.org/10.1016/j.cej.2021.131423

181. Qiu Z, Wang M, Chen Y, Zhang T, Yang D, Qiu F. Li4Mn5O12-doped cellulose acetate membrane with low Mn loss and high stability for enhancing lithium extraction from seawater. Desalination. 2021;506:115003. https://doi.org/10.1016/j.desal.2021.115003

182. Arslan M, Acik G, Tasdelen MA. The emerging applications of click chemistry reactions in the modification of industrial polymers. Polym Chem. 2019;10(28):3806–3821. https://doi.org/10.1039/C9PY00510B

183. Han Y, Kim S, Yu S, Myung NV, Kim H. Electrospun hydrogen manganese oxide nanofibers as effective adsorbents for Li+ recovery from seawater. J Ind Eng Chem. 2020;81:115–123. https://doi.org/10.1016/j.jiec.2019.08.061

184. Gu D, Sun W, Han G, Cui Q, Wang H. Lithium ion sieve synthesized via an improved solid-state method and adsorption performance for West Taijinar Salt Lake brine. Chem Eng J. 2018;350:474–483. https://doi.org/10.1016/j.cej.2018.05.191

185. Fujii K. Dependence of adsorptive capability for lithium ions in molten salt on surface

properties of activated alumina. J Ceram Soc Jpn. 1994;102(1192):1097–1101. https://doi.org/10.2109/jcersj.102.1097

186. Fujii K. Selective adsorption of lithium ions from molten salt by activated alumina. J Ceram Soc Jpn. 1994;102(1190):902–907. https://doi.org/10.2109/jcersj.102.902

187. Luo MB, Li BP, Yang Z, Liu W, Sun YZ. Determination of trace lithium in uranium compounds by adsorption on activated alumina using a micro-column method. Anal Sci. 2008;24(8):1013–1017. https://doi.org/10.2116/analsci.24.1013

188. Harrison S, Sharma CVK, Conley MS. Porous activated alumina-based sorbent for lithium extraction. U.S. Patent 9,764,318 B2. 2017 Sep 19.

189. Ma Z, Zhang S, Zhang H, Cheng F. Novel extraction of valuable metals from circulating fluidized bed-derived high-alumina fly ash by acid–alkali–based alternate method. J Clean Prod. 2019;230:302–313. https://doi.org/10.1016/j.jclepro.2019.05.113

190. Snydacker DH, Hegde VI, Aykol M, Wolverton C. Computational discovery of Li–M–O ion exchange materials for lithium extraction from brines. Chem Mater. 2018;30(20):6961–6968. https://doi.org/10.1021/acs.chemmater.7b03509