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REVIEW ARTICLE

Methods of lithium recovery from geothermal water: Current status, problems, and development prospects

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ABSTRACT

With the rapid development of lithium-based new energy industries worldwide, traditional lithium extraction technologies face resource scarcity, environmental pollution, and high energy consumption, calling for the exploration of more sustainable alternatives. Based on this, geothermal brine resources have played an important role in lithium exploration due to the development of efficient recovery technologies. This paper establishes a general framework for evaluating lithium extraction technology from geothermal resources, including resource characteristics, development advantages, technology comparisons, and technology synergies. It discusses the global lithium resources, the advantages and key technologies of extracting lithium from geothermal resources, the key challenges in the technology, and the future. The key technologies include evaporation-crystallization, chemical precipitation, adsorption, solvent extraction, electrochemical, and membrane separation. Of these, membrane technology, especially forward osmosis, has become an important research hotspot. The development of geothermal lithium technology has become an important direction for the future, providing important guidance for the development of geothermal resources and the theory of the green transition in the global new energy industry.

Keywords: geothermal brine; lithium extraction; membrane separation; forward osmosis membrane technology

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1. Introduction

The current energy system is facing a serious crisis, which is caused by the accelerated depletion of fossil fuels, the continued degradation of the environment, and the increasing effects of climate change. The International Energy Agency (IEA) estimates that the energy demand is expected to increase by 25-30% by the year 2040, mainly due to the continued growth of industrial processes and urban growth in developing countries[1,2]. In the above context, lithium is identified as a strategically important element for the development of modern energy storage systems.

Lithium is recognized as a strategic material of central importance to modern energy storage and is widely applied in lithium-ion batteries, energy storage systems, and aerospace technologies. Among these fields, lithium-ion batteries occupy the leading position in the energy storage market because they combine high energy density with long service life and have benefited from continued technological progress. Driven by rising demand from electric vehicles and energy storage applications, the global LIB market is projected to expand at a compound annual growth rate (CAGR) of 18.3% through 2030, reaching USD 182.5 billion[3]. At present, worldwide lithium demand is increasing rapidly, as illustrated in **Figure 1**[4,5]. Moreover, global demand is expected to exceed 2 million metric tons of lithium carbonate equivalent (LCE) by 2030[6,7]. At the same time, the development of lithium resources, especially conventional sources such as spodumene ores and salt-lake brines, is constrained by several challenges. A primary limitation is resource availability: high-grade spodumene deposits are scarce on a global scale and concentrated in only a small number of countries, including Australia and Chile, thereby creating a fundamental supply constraint for lithium resource development[8-12].

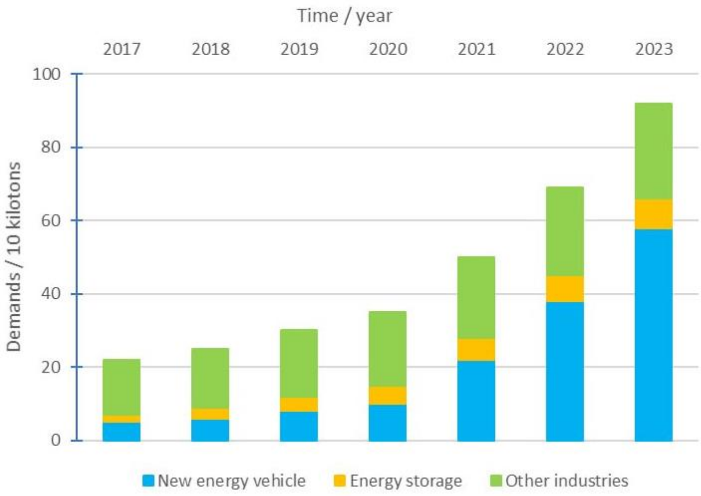

Figure 1. Global lithium demand by application[4,5].

Environmental constraints constitute the second major problem requiring attention in lithium resource development, especially in the extraction of lithium from salt lake brines. This method has several environmental issues that require attention. For instance, a water requirement of 2000 tons per ton of lithium extracted may cause ecological problems in plateau environments. This problem is particularly acute in arid zones like Qinghai and Tibet, which account for a significant part of China's lithium output from salt lakes. In these zones, lithium mining from salt lakes requires large amounts of water, thereby depleting already scarce water resources. Moreover, the water may end up polluting already scarce drinking water resources with ecotoxicants. On the other hand, lithium mining from spodumene requires a mining mode that involves many greenhouse gas emissions, thus leading to environmental pollution. In addition, several problems that include efficiency and cost issues characterize the lithium mining methods that are currently used. For instance, lithium separation from salt lake brines becomes less efficient if the ratio of Mg^{2+}/Li^{+} is above 8:1. Moreover, the methods require 15-20 tons of standard coal per ton of lithium extracted[13,14].

As the demand for lithium keeps increasing across the globe, the pressure on the lithium supply keeps growing, and the development of new lithium extraction technologies becomes increasingly important. In this context, geothermal brine has come to be regarded as an important lithium deposit[15]. The major advantages of geothermal brine lie in its large potential lithium resources, which total 20 million tons of lithium carbonate equivalent, or 20 to 30% of global lithium resources. Additionally, geothermal brine has the advantage of sustainability, including renewability, environmental friendliness, and long-term stability[16]. In comparison with fossil fuels, which are nonrenewable resources with finite lifetimes, geothermal brine resources are constantly renewed by the hydrological cycle driven by tectonic heat and magmatic activity. Moreover, lithium recovery from geothermal brine does not require the large-scale land disturbance and toxic waste disposal inherent in hard-rock mining[17]. The environmental impact can be further reduced by recycling spent brine back into the geothermal reservoirs to maintain aquifer health and prevent surface pollution. In addition, geothermal brine resources can be developed along with power generation, which means that this type of lithium can be utilized together with geothermal power. Another important benefit of geothermal brine is its global distribution: lithium-rich geothermal brines are found in major geothermal provinces worldwide, including the Circum-Pacific region and the East African Rift System, with notable deposits in the Salton Sea region of the United States and in Kenya[18-20].

As of now, most lithium extraction technologies have been designed to utilize salt lakes' brines. Based on the advancements in lithium extraction from salt lakes' brines, it appears that most of the research in this area is trying to improve the efficiency of lithium extraction from salt lakes' brines more sustainably[21]. For example, it has been observed that using titanium-based adsorbents can recover 90% of Li^+ from low-concentration Li^+ brines. However, this technology is not ready to be used on a larger scale. The main issues with this technology are its low selectivity, particularly in separating Mg^{2+} from Li^+, and its stability. On the other hand, there are also advancements in lithium extraction technology using electrochemical cells. For example, lithium-selective membrane technology using LISICON ($Li_{2+2x}Zn_{1-x}GeO_4$) can recover Li^+ with a purity level of more than 95%. However, this technology also has a drawback: it requires a fair amount of energy to operate, about 5 to 10 kWh per kilogram of lithium. Nevertheless, despite all these advancements in lithium extraction technology from salt lakes' brines, this technology has not shifted to other lithium-containing resources such as geothermal brines[22-26].

In contrast to the relatively advanced process for lithium recovery from salt lake brines, lithium recovery from geothermal brines remains an early-stage technology with limited commercialization. The progress of lithium recovery from geothermal brines is restricted by a number of technological limitations, such as high operating temperatures, high salinity, low lithium content, and the influence of a number of co-existing ions. However, lithium recovery from geothermal sources still represents a highly promising new route for lithium extraction. Therefore, its development possesses a high degree of importance for relieving lithium supply constraints and satisfying the material demands for the growing emerging energy sector[27,28].

The present review seeks to address the gaps identified by providing a multidimensional evaluation of the existing geothermal lithium extraction techniques. Unlike previous reviews, which focused on lithium extraction from salt lakes or lithium-containing ores, this review emphasizes the uniqueness of geothermal brines, such as their high temperature and complex ionic composition, and their influence on the choice of lithium extraction technology. While previous reviews focused on the technical viability of lithium extraction, this review considers not only the economic viability and sustainability of lithium extraction from geothermal sources, with particular emphasis on water recycling and integration with geothermal power production[29].

2. Distribution, general properties, and characteristics of world reserves of lithium and its compounds

2.1. Global distribution of lithium resources

Figure 2 shows that the distribution of lithium, as a strategic mineral, is quite uneven on the global scale[5,30]. It has been established that global lithium resources amount to over 98 million tons, with the highest concentrations of this mineral recorded in Oceania, South America, North America, Asia, and Africa (**Figure 3**)[16,31]. Among these regions, Australia ranks first, with the highest amount of lithium resources, specifically pegmatite-hosted lithium deposits. For instance, the Greenbushes pegmatite deposit has over 5 million tons of lithium ore with a Li_2O grade of 2.0%. In Asia, China ranks second, with highly developed lithium resources of various kinds, ranging from granitic pegmatite to salt lake deposits of lithium[32]. Specifically, the spodumene deposits of Sichuan Province are highly concentrated, with lithium levels averaging 1.30% to 1.42%. The lithium mine of Jiajika, Kangding, Sichuan, has 1.8 million tons of lithium reserves, rendering it the largest spodumene deposit in Asia[33]. Moreover, the salt lake deposits of lithium, specifically in the Qinghai and Tibet regions, account for 80% of China's lithium reserves. It should be noted that Zabuye Salt Lake, located in the Tibet Autonomous Region, ranks as one of the rare multi-component deposits of salt lake origin, containing boron, lithium, potassium, and cesium, with high levels of lithium and low levels of magnesium to lithium, rendering this deposit highly favorable for development[34].

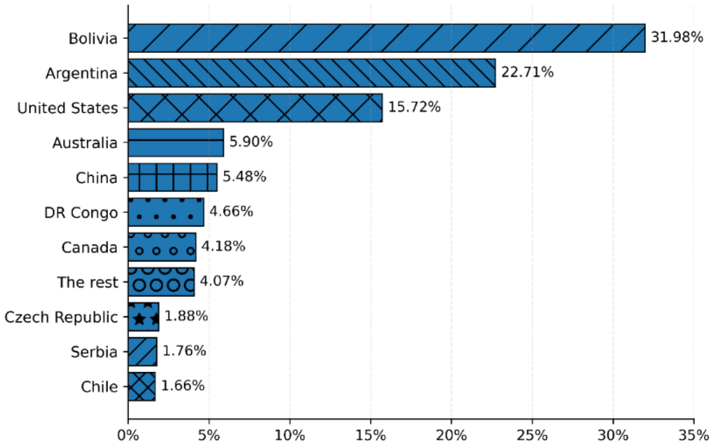

Figure 2. The global distribution of lithium ore (Li_2CO_3) resources.

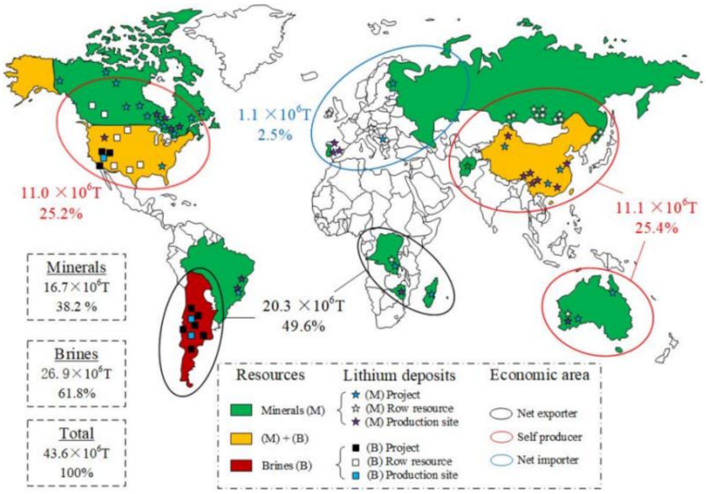

Figure 3. Distribution of world lithium reserves (modified from Stringfellow).

These lithium resource types can be broadly classified into two categories: one is the hard rock type, while the other is the brine type. There are over 150 different lithium-bearing minerals in the hard rock type. Some of the biggest lithium beds in the world can be found in countries like Zimbabwe, Brazil, and Australia. These lithium beds belong to the petalite type[35]. Countries like Bikita in Zimbabwe, Karibib in Namibia, and Bernic Lake in Canada have significant lepidolite-type lithium reserves. However, due to the mining activities that have been ongoing in these regions for a while, the lithium reserves in the hard rock type are depleting gradually. In China, lithium in hard-rock deposits is abundant. Some of the major lithium mining regions in China include Xinjiang, Jiangxi, Hubei, and the southwestern region[36]. On the other hand, lithium in the brine type also has higher lithium content in comparison to lithium in the hard rock type. In fact, over 60% of the lithium reserves in the world belong to the brine type. Among the lithium in the liquid type, the major type of lithium-bearing resource is the salt lake brine type. In fact, this type of lithium resource constitutes 59% of the lithium resource reserves in the world. Some of the major lithium-bearing salt lakes in the world can be found in countries like Bolivia, Chile, and Argentina. Some of the major lithium-bearing salt lakes in these countries include Uyuni, Atacama, and Hombre Muerto. In China, the lithium in the liquid type ranks second in terms of reserves. A major portion of the lithium in the liquid type can be found in the salt lakes like Qarhan, Yiliping in the Qinghai region, and Zabuye and Dangxiongcuo in Tibet[37-40].

Geothermal water is being recognized as another significant but relatively new liquid lithium source, owing to its significant lithium content and exceptionally low level of mineralization. Geothermal lithium deposits are unique in that they are mostly found as lithium contained within geothermal brine located within tectonically active regions, such as the Circum-Pacific Belt and the East African Rift. Geothermal brine consists of salty water with temperatures ranging from 150-350 ℃ and TDS levels over 100,000 ppm. Unlike other lithium sources such as hard rock minerals and salt lake brine, geothermal lithium deposits are considered to be renewable resources, as the brine within these deposits is replenished continuously. Geothermal brine contains 20-200 mg/L of lithium, which, although less than that found within salt lake brine (500-1500 mg/L) and more than that found within seawater (0.17 mg/L), makes up for it through the high fluid flow rates of 10-30 L/s per well[41-44].

Significant lithium reserves are found within geothermal water, particularly in Tibet, China. The geothermal resources within Tibet are extensive, with significant reserves of relatively high quality, as the lithium content of these resources exceeds 20 mg/L. This emphasizes the need to develop appropriate technology to exploit these geothermal water resources.

2.2. Formation Mechanisms of Geothermal Brine Lithium Resources

Geothermal brine lithium ore refers to lithium-rich warm brine fluids that contain lithium, boron, potassium, and other similar elements. Aside from their use in generating thermal power, geothermal brine and lithium ore can also be considered potential lithium resources (**Table 1**)[14,45,46]. The formation of geothermal lithium resources can be traced back to tectonic activities, where lithium gradually accumulates in hot water. In tectonically active settings like mid-ocean ridges and subduction zones, tectonic activity can result in vigorous magmatism. In such environments, hot magmas can undergo complex chemical interactions with their host rocks, during which lithium can be dissolved from the host rocks and transported to hot water via hydrothermal fluid migration. In some tectonically active settings, the interactions between hot water and lithium-rich host rocks can facilitate the leaching of lithium from the host rocks, where lithium can gradually accumulate in hot water[47-50].

The origin of geothermal lithium resources is closely related to the major geothermal belts of the Earth, most of which are located in the Circum-Pacific belt, the Mid-Atlantic Ridge belt, the Red Sea-Gulf of Aden-East African Rift belt, and the Mediterranean-Himalayan belt, etc. These belts are characterised by high geothermal activity and subsurface hot-water resources, which provide favourable conditions for lithium enrichment[51]. For example, the Salton Sea region in California, USA, located in the Circum-Pacific belt, is known worldwide as a global zone for geothermal lithium enrichment. The lithium content in the geothermal brines in this region ranges from 200 to 300 mg/L, and it is expected that this region will become a major domestic source of lithium for the United States in the near future. Another region, the Upper Rhine Valley in Europe, located in the Mediterranean-Himalayan belt, is known for its significant geothermal lithium resources. In China's Tibet region, known as one of the country's most geothermal resource-rich areas, significant geothermal lithium resources are distributed throughout the high-temperature geothermal fields in the Yarlung Zangbo River region[52]. The region contains 15 geothermal water resources, where the lithium content meets or exceeds the standard for industrial utilization, and the highest content reaches 200 mg/L. It is noteworthy that the geothermal resources, such as Moluojiang, Semi, Zhumosha River, and Riruo boiling springs, have lithium content levels higher than 35 mg/L[52].

Table 1. Representative unconventional lithium-bearing brines worldwide and their major chemical compositions, mg/L.

Type of brine	Country (region)	Region name	Li^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	B^{3+}	SiO_2	Cl^-	Br^-
Geothermal brine	United States (California)	Salton Sea	202	49.249	14.467	109	25.684	298	342	142.015	91
	France (Alsace)	Upper Rhine Graben	173	28.140	3195	131	7225	40.8	201	58.559	216
	China (Tibet Autonomous Region)	Lithium-rich hot springs	79.9	24.900	2160	850	2870	–	–	46.700	–

3. Advantages of lithium extraction from geothermal brines

Geothermal lithium resources are an important source of lithium. This source is advantageous in comparison to conventional lithium resources. Geothermal lithium resources are environmentally friendly compared to conventional lithium resources. The extraction of lithium using geothermal resources does not require large-scale mining in an open pit. This reduces the disturbance of the environment. **Table 2** presents a comparative analysis of lithium resources using conventional methods compared to geothermal lithium resources[12,14,34,53]. Moreover, the brine used in the extraction process is injected back into the ground. This enables water recycling and reduces water consumption. Additionally, the development of geothermal lithium resources can be combined with the utilization of geothermal energy. This leads to comprehensive utilization and maximizes the utilization efficiency of resources. Some geothermal lithium resources have additional benefits compared to conventional resources. This is due to the utilization of the heat energy contained in geothermal water for power generation. This heat energy is also used in lithium recovery. This maximizes the utilization efficiency of resources. This method is beneficial as it provides economic and environmental benefits[54].

For instance, the Salton Sea geothermal field in California, United States, is an example of the utilization of lithium resources in conjunction with geothermal power generation. This method achieves a lithium recovery rate of 98%. This is achieved using aluminate precipitation coupled with electrodialysis. This method is used in the recovery of lithium from brine containing 202 mg/L Li^+. The brine is injected back into the ground for geothermal power generation. This reduces water consumption by 90%. This method is also economical as the production cost is USD 4,200 per tonne of Li_2CO_3. This is 35% less compared to conventional lithium resources processed from spodumene. The global lithium market is increasing due to the increasing need for lithium in the new energy sector. Moreover, environmental protection is also an important aspect in the utilization of lithium resources. Geothermal lithium resources have broad prospects for utilization in the future. This is an important method for lithium recovery as it is environmentally friendly. This method is beneficial as it meets the lithium requirements for the new energy sector. This method is also important for green energy transition and sustainable development[54].

Table 2. Comparison of geothermal, salt-lake, and hard-rock lithium extraction.

Comparison Aspect	Geothermal Brine Extraction	Salt-Lake Brine Evaporation	Hard-Rock Ore Mining
Water consumption	85% lower (recycled via reinjection)	2000 m^3/t Li (open evaporation)	15-20 m 3/t Li (processing)

Energy intensity	0.8-1.2 kWh/kg Li (combined with geothermal power)	45-60 kWh/kg Li (solar evaporation)	250-300 kWh/kg Li (smelting)
CO_2 emissions	0.3-0.5 t/t Li (closed-loop system)	1.2-1.5 t/t Li (chemical processing)	3.5-4.2 t/t Li (mining + smelting)
Resource recovery	92% Li and coproduction of B, K, and Rb	75-80% Li (impurity losses)	60-65% Li (ore waste)
Byproduct recovery	Multi-element (B, K, and SiO_2)	Limited	Limited

Table 2. (*Continued*)

Even though there are various benefits in lithium extraction from geothermal sources, some challenges still need to be addressed. Firstly, the working conditions are extremely harsh due to high-temperature brine solutions at 150-300 ℃. This leads to equipment corrosion and necessitates the use of expensive corrosion-resistant materials, such as titanium alloys, in the process. Moreover, high salinity in brine solutions (TDS > 150 g/L) and the presence of scaling ions, such as Ca^{2+} and SiO_2, lead to membrane fouling and a decrease in adsorption capacity. Secondly, divalent metal ions, such as Mg^{2+} and Ca^{2+}, interfere with Li^+ adsorption sites and reduce lithium recovery efficiency from brine solutions. In the Olkaria lithium extraction project, Mg^{2+}/Li^+ ratios were as high as 20:1, requiring a pretreatment step by a nanofiltration process that increased energy consumption by 18%[55-58]. Thirdly, the long-term sustainability of geothermal resources remains uncertain due to the risk of overexploitation, which may reduce energy and lithium output.

4. Conventional and emerging methods of lithium resource extraction

Significantly, the pathways for the extraction of lithium differ considerably depending on the nature of the resource, the geological setting of the occurrences, and, most importantly, the adopted process for the recovery of the element. For example, traditionally, solid lithium ores, such as spodumene and lepidolite, have been the major conventional sources of lithium. These ores are often processed to obtain lithium via sulfuric acid digestion, limestone sintering, carbonate roasting, and halide roasting. Though the processes can achieve considerable enrichment of lithium, the application of the processes is often limited due to the recognized limitations of the processes. These limitations include the processes' high energy requirements, considerable corrosion of the plant equipment, and the relatively demanding process conditions. In recent years, the availability of high-grade solid lithium ores has been diminishing considerably[59-62]. Additionally, the processes for the recovery of lithium from solid ores have come to be limited due to the salience of the processes' energy requirements. Notably, the focus of the processes for the recovery of lithium has considerably shifted to liquid resources of lithium, especially salt lake brines[63-65]. **Figure 4** provides a general overview of the major pathways for the recovery of lithium. Additionally, the technical differences between geothermal and salt lake brine lithium recovery are provided in **Table 3**. Though the processes have been considerably applied for the recovery of lithium from salt lake brine, the application of the processes is often limited due to the recognized limitations and challenges of the processes. On the other hand, the recovery of lithium from geothermal resources is a relatively new area of application. Only a few processes have been applied for the recovery of lithium from geothermal resources. Notably, the processes applied for the recovery of lithium from geothermal resources are a subset of the conventional processes applied for the recovery of lithium from salt lake brine. However, the application of the processes for lithium recovery is often limited by geothermal constraints[66-70].

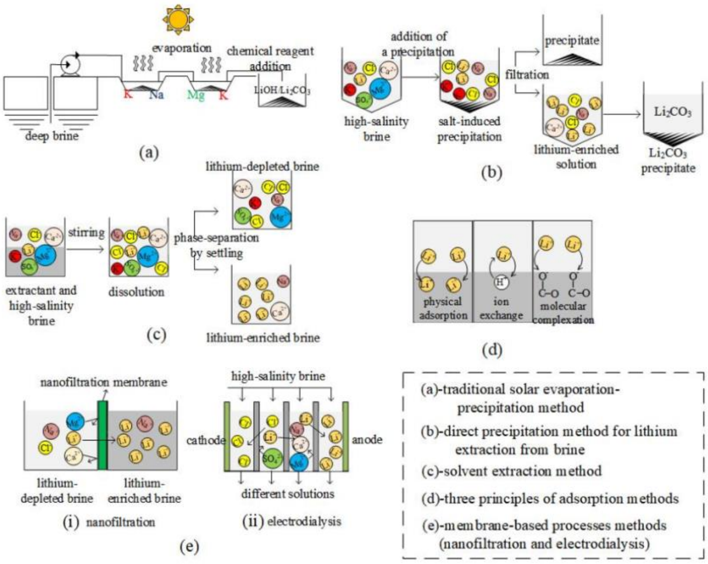

Figure 4. Schematic overview of major lithium extraction technologies.

Table 3. Technical differences between methods of extracting lithium from salt lakes and geothermal sources.

Method	Geothermal Brine Adaptation	Salt-Lake Brine Application	Unique Characteristics for Geothermal Brine
Evaporation-precipitation	Waste heat integration from geothermal power	Solar evaporation ponds	Reduced energy cost via waste-heat utilization
Chemical precipitation	Aluminates are preferred over carbonates due to high Mg/Li ratios	Carbonate precipitation at ambient temperature	Higher reaction rates at 80-120 °C
Adsorption	Thermally stable adsorbents (e.g., $LiMn_2O_4$)	Ambient-temperature adsorbents (e.g., zeolites)	Resistance to 150 °C brine conditions
Solvent extraction	High-temperature solvents like tri-isobutyl phosphate (TBP) maintain solubility at 100 °C	Organophosphates are commonly used for lithium extraction from salt-lake brines	Solvent degradation at 120 °C requires continuous regeneration, increasing operational complexity.
Electrochemical method	Electrodialysis with bipolar membranes operates mainly at 80 °C	Operating under low temperatures and low pressures, a concentration of 20 g per liter can be achieved at a pressure of only 0.1 megapascals	High-conductivity brines may cause ohmic losses
Membrane separation	Forward osmosis with thermal regeneration	Reverse osmosis at 25-40 °C	FO membrane tolerance to 90 °C operating temperature

4.1. Evaporation-Precipitation Method

The most popular technique for extracting lithium from salt-lake brines is still evaporation-crystallization, which works best for brines with extremely high lithium contents[71]. This approach can produce a significant amount of product and have definite financial advantages. However, there are a number of acknowledged drawbacks to the evaporation-precipitation pathway. Under natural evaporation conditions, the energy-intensive evaporation stage is severely limited by geographical and climatic factors. Because of this, the procedure usually has a lengthy lithium extraction cycle and low evaporation efficiency[72]. The entire treatment process may take months or even years because salt-lake brines are intricate multicomponent systems. Large amounts of carbonate raw materials and sodium hydroxide are needed to remove elements like Na, I, and K from the brine system[73]. Large amounts of carbonate raw materials and sodium hydroxide are needed to remove Ca^{2+} and Mg^{2+} from the brine system, while elements like Na, I, and K must be eliminated. This results in strict equipment requirements and higher production costs. Additionally, a significant amount of water is wasted due to evaporation, which is particularly problematic in areas with limited water supplies. By integrating with power plants and using residual heat (120-150 ℃) to speed up water evaporation, geothermal evaporation systems provide a similar but different configuration[74]. Compared to solar evaporation in salt lakes, this method uses 40% less energy[9]. For example, the Salton Sea project concentrates brine from 202 mg/L Li^+ to 5000 mg/L in 72 hours using geothermal steam[55]. However, high silica levels (300-500 mg/L) are frequently found in geothermal brines, which encourage scaling and call for pre-treatment like acidification or electrodialysis[75].

4.2. Chemical Precipitation Method

The use of suitable precipitating agents to trigger precipitation reactions that separate target lithium ions in the form of solid products is the fundamental basis of the chemical precipitation method[76]. In the primary procedure, impurities enriched in magnesium, potassium, and boron are eliminated by first concentrating salt-lake brine. Industrial-grade carbonates or aluminates are added once the concentration of the lithium-bearing solution is appropriate, and the resulting precipitate of lithium carbonate is separated from the mother liquor. This method can be used to extract lithium from salt lakes that have a low ratio of magnesium to lithium[76].

Aluminate, borate, and carbonate precipitation are examples of well-established variations of chemical precipitation, which is one of the oldest and most extensively used industrialised methods of extracting lithium[77,78]. For salt lakes with a high magnesium-to-lithium ratio, the first two approaches are appropriate.

In general, the chemical precipitation method of producing lithium carbonate is both technologically advanced and operationally simple, with lithium recovery and product qualification rates surpassing 80%. As shown in **Table 4**[5,79-82], this paper provides an overview of recent research on lithium extraction from geothermal and oilfield brines using precipitation-based techniques. Aluminates are the best precipitating agents for recovering lithium from geothermal brines, as shown in **Table 4**. For instance, $AlCl_3$ and limestone are frequently combined with aluminate-based precipitation in geothermal brine systems, and for Salton Sea geothermal brine in the US, lithium recovery rates of 89% to 98% have been attained[79].

However, the method is primarily limited to lithium-rich salt-lake brines with low magnesium-to-lithium ratios due to the high consumption of precipitating agents in industrial operation, which raises production costs and introduces certain environmental impacts. Its wider large-scale application in the salt-lake lithium extraction industry is hampered by this limitation.

Table 4. Technical differences between methods of extracting lithium from salt lakes and geothermal sources.

Raw Material Source	Year	Chemical Reagent	pH	Lithium Recovery Rate/%	Product and Purity
Salton geothermal brine	1976	$AlCl_3$, CaO	7.5	98	LiOH, –
Salton geothermal brine	1984	$AlCl_3$, CaO	7.5	89	LiCl, 99.9%
Hatchobaru geothermal brine	1986	$NaAlO_2$	11.5	98-99	–
Brine in the Nan Yishan Oilfield in Qinghai, China	2006	CaO, Na_2SO_4, Na_2CO_3	10	56.26	Li_2CO_3, 98.31%
Brine in a certain oilfield	2019	CCl_4, Na_2SO_4, Na_2CO_3	6.35-6.81	–	Li_2CO_3, 98.34%

4.3. Adsorption Method

The method of adsorbing relies upon using adsorbents which require only a small amount of energy, yet have a high ability to adsorb, an ability to selectively adsorb ions (high ion selectivity), and also an ability to have long-term stability. This makes adsorption commonly used for separating and concentrating lithium from liquid sources like the brines found in salt lakes[83,84].

Typical examples of adsorbent materials that are used to separate or concentrate lithium using this technique are organic, inorganic, and biological materials. In general, the adsorptive process for concentrating lithium through adsorption is accomplished using materials that contain a microscopic crystalline structure that has accessible sites to allow for the adsorption of lithium ions and to provide some separation or “screening” effect on the other ions present in the solution. In doing this, the non-targeted ions are removed from those sites where they can be adsorbed by the adsorbents. Once the lithium has been adsorbed on the adsorbent (separation), the lithium can then be eluted (enriched) using an acid solution[85-90].

There have been many successful experiments using this method of extraction on various types of salt lake brines (with both high Mg to Li ratios and low). Although the applicability of this method of lithium extraction using adsorption is broad, the ability of the method to produce good results depends significantly on the type of adsorbent material that is chosen[91].

Not only do salt lake brines contain a high concentration of lithium, but they also contain large amounts of other dissolved minerals, impurities (as well as competing ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}), which can interfere with the lithium extraction process[92]. Therefore, it is very important to choose an adsorbent that has structural stability against acid and base corrosion, and that will be able to withstand the disturbance caused by trace impurities in order to recover lithium from such an extremely complex medium[93]. Furthermore, an effective solution for recovering lithium from high-concentration, lithium-rich liquid will only be achieved with the use of an adsorbent that exhibits sufficient adsorption capacity/recyclability[94].

The study presented here will compile the different types of adsorbents used to recover lithium from brines and their lithium adsorption efficiencies with a particular focus on the performance of inorganic adsorbents. The results will be summarized in **Table 5**[95-97]. According to the studies in **Table 3**, the lithium adsorption by adsorbents for geothermal brines has a monolayer adsorption capacity (qmax) ranging from 6 to 69 mg/g and optimum pH between 9 and 12. Titanium oxides and manganese oxide are the most effective adsorbents studied. For example, the Lithium Manganese Oxide ($LiMn_2O_4$) adsorbent used to recover lithium from geothermal brine from Sidoarjo, Kuala Lumpur, exhibited an adsorption capacity greater than 68 mg/g for lithium[98,99].

In the meantime, one aspect of the ongoing research concerning lithium extraction from geothermal brines has been the development of granular, or particulate, inorganic adsorbents via organic polymer and biosorbents for this purpose[100,101]. Presently, only aluminum-based adsorbents have been used to obtain lithium from geothermal brine; however, the yield from such applications has been less than 60%[102].

The inability to achieve higher yield rates is primarily due to the complex chemical makeup of geothermal brines, wherein multiple competing cations have the potential of occupying active sites on the adsorbent and reducing lithium uptake. Therefore, when selecting an adsorbent, it is important to evaluate performance based on both adsorption capacity and specificity towards competing cations. Therefore, improving the recyclability of adsorbents and reducing material waste continues to be the key challenge for future development[103-108].

Table 5. Brief description of the main characteristics and adsorption capacity of lithium extraction technologies using the adsorption method.

Raw Material Source	Year	Adsorbent Name	Principle	pH	Adsorption Time/h	Maximum Adsorption Capacity
Kuala Lumpur Sidoarjo geothermal brine	2016	$LiMnO_2$	Ion exchange, physical adsorption	–	–	68.35 mg/g
Kuala Lumpur Sidoarjo geothermal brine	2019	$H_{1.6}Mn_{1.6}O_4$	Ion exchange, physical adsorption	12	19.0	43.80 mg/g
Sichuan Weiyuan gas-field water, China	2000	Li_2TiO_3	Ion exchange, physical adsorption	9	240	25.34 mg/g
Simulated lithium-containing water sample	2015	$Li_4Ti_5O_{12}$	Ion exchange, physical adsorption	9.17	120	39.43 mg/g
Geothermal brine	2021	Li_2TiO_3	Ion exchange, physical adsorption	12	6	12.29 mg/g

Raw Material Source	Year	Adsorbent Name	Principle	pH	Adsorption Time/h	Maximum Adsorption Capacity
Mixed lithium salt solution	2021	$LixAl_2$–LDH*SiO_2	Ion exchange, physical adsorption	–	–	18.00 mg/L
Chaerhan salt-lake brine	2018	Li/Al–LDH_5	Ion exchange, physical adsorption	–	2	7.27 mg/g
A certain geothermal brine in Tibet, China	2019	PVC–HTO	Ion exchange, physical adsorption	12	12	11.35 mg/g
Geothermal brine	2020	granular $H_4Mn_2O_{12}$/chitosan	Ion exchange, physical adsorption	12	24	8.98 mg/g
Rabka Zdroj geothermal brine in Poland	2018	Natural clinoptilolite	Complexation	5.5	3	5.00 mg/L

Table 5. (*Continued*)

4.4. Solvent Extraction Method

The approach referred to as solvent extraction uses an organic solvent that is suitable for selectively transferring lithium from a salt brine solution (salt brine) to recover and purify it[109]. The basis of this method is the difference in solubility of two different phases in the same solution (i.e., salt brine). The process begins when the extractant, which is completely immiscible in salt brine (salt lake brine), is added to the brine. After the addition of the extractant, lithium goes through a phase transition (i.e., moving from the salt brine to the extractant). If desired, lithium can then be further concentrated and separated from the extractant, where it can then be recovered from the salt brine. Extractants can be generally classified into three categories depending upon the manner in which they react with lithium: acidic, neutral, and alkaline[110].

The process of solvent extraction for lithium recovery from a complex chemical solution of a salt lake brine is primarily affected by the choice of an appropriate organic extractant, with tributyl phosphate (TBP) being an example of this type of neutral extractant [111]. TBP has been successfully used in the recovery of lithium from brines that contain less magnesium than lithium. Solvent extraction as a means of extracting lithium from liquid resources has the benefits of having high selectivity and being effective in a variety of environmental settings; however, the high amount of chemical reagents that are used in this process and the resulting pollution from these chemicals restrict the potential for this process to be implemented on a large scale[112-118].

4.5. Electrochemical Method

As a result of being a newer means of recovering lithium via electrochemistry, electrochemical lithium extraction offers a number of attributes compared to conventional lithium recovery strategies, including lower energy usage, high selectivity toward lithium ions, and minimum environmental impact[119]. The fundamental operation can be described as an electrochemical “ion pump,” with the applied electrical field acting as the energy source to facilitate both the selective intercalation into and extraction/deintercalation from an electrolyte of lithium ions[120,121]. As illustrated in **Figure 5**, during the process of lithium extraction, the geothermal solution underwent initial desilication through electrocoagulation with aluminum electrodes, followed by electrodialysis to remove dissolved lithium ions from the geothermal solution[14]. Despite the heightened interest shown in electrochemical lithium extraction, there remain many experimental limitations associated with developing a successful commercial operation. These limitations include stability of the system, lithium recovery efficiency, and low energy consumption. Nonetheless, electrochemical lithium extraction presents a viable opportunity for recovering lithium and is likely to have broader industrial implications moving forward[122].

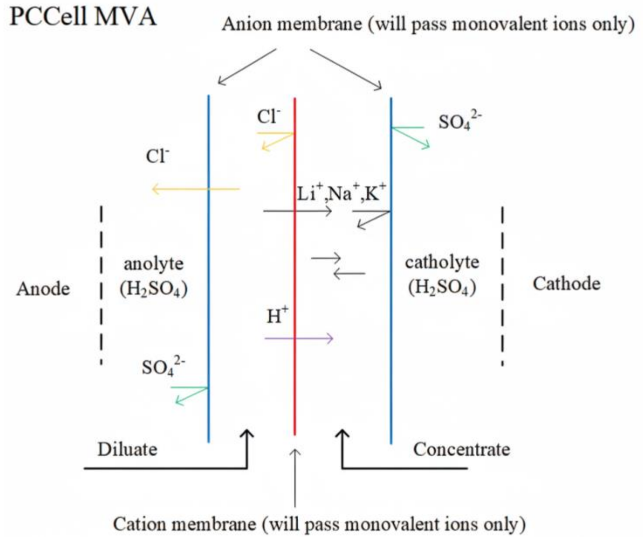

Figure 5. Schematic of the separation process using the idealized electrochemical method.

One possible route for recovering lithium is through electrochemical methods that are desirable because they provide faster extraction kinetics and much greater operational control over the extraction rate[123]. There are two main branches of research on lithium electrochemical extraction: systems using active electrodes for extraction and systems using solid electrolyte membranes[124-126]. The development of lithium electrochemical extraction methods using active electrodes dates back to Kanoh's initial work in 1993 on lithium extraction using λ-MnO_2 as an electrode material[127]. In this method, lithium ions are intercalated and deintercalated into the λ-MnO_2 electrode, allowing for the separation of lithium ions from lithium-rich liquids. During electrochemical processing, lithium is intercalated into λ-MnO_2 to produce $LiMn_2O_4$. Because λ-MnO_2 is strongly selective for lithium ions, large amounts of lithium ions are removed from solution, while other competing ions, such as sodium and magnesium, tend to remain in solution. After electrochemical processing, $LiMn_2O_4$ can be treated chemically with hydrochloric acid to yield lithium ions and produce a concentrated lithium solution[128-130].

In general terms, electrochemical lithium extraction is based on a two-electrode arrangement of two electrodes, one a working electrode (WE) and one a counter electrode (CE). The WE controls the selective intercalation/deintercalation of the Li+ ions, whereas the CE completes the electrical circuit and balances the charge from the WE. Therefore, materials that will be selected for use as the WE must be able to selectively discriminate between Li^+ and all other ions[131]. The $LiFePO_4$ and $LiMn_2O_4$ are among the most common types of Working Electrodes used today. Recently, engineers have begun focusing on combining solid electrolytes that have been used in commercial battery systems for their very high selectivity and efficiency of transporting lithium, with an externally applied electric field to develop new electrolytic membrane-based lithium extraction processes. These new systems can produce highly concentrated lithium-containing solutions or potentially lithium metal directly from a liquid source, including seawater[132,133].

The principal benefit of solid electrolyte membranes is their nearly exclusive separation of lithium: the lithium ion (Li^+) moves through the membrane while the other ions are excluded. When non-active electrodes are employed, lithium does not move to the surface of the electrode; it collects in the catholyte, allowing for concentrated lithium recovery. An illustration of this is the use of lithium-selective LISICON membranes as coupling devices with redox flow batteries to recover lithium from seawater simulation by Volker Presser's group at the Leibniz Institute for New Materials in Germany. Their system extracted 1 g of lithium (2.5 Wh) from a solution, giving a solution of 93.5% pure lithium[134].

4.6. Membrane Separation Method

Separation using membranes is gaining in popularity as a viable extraction technique that may be commercially lucrative. Membranes are particularly well-suited for lithium recovery from brines because they combine high selectivity with the ability to operate continuously. At the current time, reverse osmosis and nanofiltration are the predominant methods. Forward osmosis is still in development; it is becoming viewed by many researchers as a significant alternative for future geothermal lithium extraction[135-138].

4.6.1. Reverse Osmosis Technology

The application of reverse osmosis (RO) processes to separate lithium from lithium-rich geothermal brines typically occurs during pretreatment and/or concentration stages. While RO does not serve as a method of lithium isolation per se, the selective separation and consolidation that occur as a result of RO operation can significantly increase the efficacy of subsequent lithium extraction processes[139]. The principle of operation for the RO process is related to the separation of the solvent from the solutes based upon a pressure gradient; hence, as the applied pressure differentials force the solvent through the RO membrane, it will also assist in limiting the passage of dissolved materials through the membrane[140].

The successful operation of reverse osmosis treatment of geothermal brine depends on adequate pretreatment of the feed prior to entering the RO membranes. First, the geothermal brine is typically passed through different stages. The feed stream is usually filtered to remove large solids by passing it through a multimedia filter, then subjected to ultrafiltration to remove colloidal materials and high molecular weight organic substances. This pretreatment is very important because it serves two purposes: it stabilises the quality of the brine before entering the membranes, and it helps minimise fouling of the RO membranes during operation. As soon as the lithium-containing geothermal brine is introduced into the RO membranes, the brine consists not only of lithium ions but also numerous other ions that exist in combination with the lithium ions. The lithium brine is then pressured on one side of the RO membrane; the water passes through the RO membrane, but the lithium ions and other dissolved ions remain mostly on the same side of the RO membrane as they were prior to being pressurised. Therefore, the RO process provides an initial concentration of lithium and also partially separates impurities from the lithium[141-145].

The practical benefits of reverse osmosis (RO) for lithium extraction from brine include both the raising of lithium concentration in the brine to a level more ideal for subsequent extraction and purification, and the removal of a significant portion of salts, organic matter, and other contaminants, thereby facilitating subsequent processing and increasing the purity of the final lithium products. RO systems are also relatively simple to operate and have relatively low environmental impacts. However, these advantages do not alter the primary technical limitations associated with reverse osmosis[146]. Increasing concentrations during RO lead to the precipitation of ions such as calcium, magnesium, and sulfate, resulting in membrane scaling and reduced performance of the process. This technology is also energy-intensive since effective separation requires relatively high operating pressures. In addition, the fact that RO membranes are not selectively retentive of lithium, rather they non-selectively reject all ions, means that lithium purity will be negatively impacted, and the efficiency of subsequent separation steps will also be negatively impacted[147-150].

4.6.2. Nanofiltration Technology

Nanofiltration (NF) is a class of membrane processes characterized by high rejection of divalent and multivalent ionic species; yet, at the same time, some monovalent ionic species, such as lithium can also be permitted across the membrane at the same time. Because of this unique method of separation, NF can be used to separate lithium from other divalent cations such as magnesium, calcium, and many others found in brine conditions, due to a wide variety of factors[151,152]. Under appropriate operating conditions (i.e., pressure; 0.5-2 MPa), NF membranes are capable of selectively holding back some of the impurities, while at the same time allowing lithium ions to flow through the membrane; thus providing a preliminary separation of lithium ions from other contaminants, from which secondary separation processes can be developed[146].

One of the primary benefits of using a nanofiltering system is that they require comparatively little energy. In addition, they can also help to minimize the amount of lithium that will be lost during brine concentration by allowing the lithium to remain in the brine. However, they do have some limitations. All membrane systems will eventually accumulate materials on the membrane surfaces, causing a reduction in performance or a reduction in the length of time the membrane can be used or the efficiency of extracting lithium; this could potentially affect lithium separation or purification downstream. There is also the fact that nanofiltration membranes do not provide complete lithium selectivity. Therefore, the separation obtained through the nanofiltration process may not be high enough to produce highly purifiable sources for subsequent purification[152].

NF systems can perform well when used in conjunction with various separation techniques. An example of using nanofiltration for lithium/magnesium separation was presented by Kang et al.[153]. This study examined the use of commercially available DK nanofiltration membranes to treat diluted salt-lake brines, resulting in the feasibility of nanofiltration to allow for lithium extraction from brine. Although the authors operated using a single-stage separation process and found that the magnesium to lithium mass ratios (Mg/Li) were below 0.1 for each of three different brine compositions (Mg/Li mass ratios were 48.50, 42.31, and 28.30), they were able to recover lithium from brine while retaining a significant fraction of calcium and sulfate ions as well as at least 73.81% of boron in the concentrate. The resulting Mg/Li mass ratios for the permeate were 4.04, 3.21, and 1.86, respectively. Overall, these experimental results support the conclusion that nanofiltration can be an effective means of separating and recovering lithium from brine[153].

4.6.3. Forward osmosis membrane technology

Forward osmosis (FO) works with two distinct liquid streams that move through a semi-permeable membrane due to osmotic pressure; lithium-thickened saline water is the feed stream, while a higher osmotic pressure stream provides the “driving force” of water movement through the membrane. Based on the water and draw solution osmotic pressures, water will move from the brine side of the membrane to the draw solution side as long as sufficient energy is created by the difference between the two osmotic pressures. This results in lithium chloride and other dissolved solids being concentrated on the brine side and partially separated from their original aqueous solution[154].

FO differs from pressure-driven membrane technologies such as reverse osmosis and nanofiltration in how water is transported. The practical advantage of FO is that, due to this method of water transport, less energy is required to move water through the membrane because the osmotic pressure is driving the transport, rather than applying a large external pressure to push water through the membrane[155]. It has been demonstrated that FO separates lithium from other ions present in solution (i.e., lithium separation from impurity ions), resulting in a lithium concentrate with good purity. This increases the likelihood of receiving a suitable feed for subsequent lithium extraction and purification processes. In addition, low-pressure operation results in other advantages: the lower demand for equipment to be able to withstand high internal pressures decreases both capital costs and operational risk, and low-pressure operations avoid using large quantities of chemicals; create small quantities of waste; and place a minimal environmental burden on the environment, which aligns with green extraction practices[156].

Despite the many advantages that FO has over other membrane separation technologies, it does face unique challenges. Membrane Fouling occurs with FO (like all membrane separation technologies), and so do the challenges raised by draw solution selection and recovery. To this end, we must select an effective draw solution that meets three criteria: it must possess a high osmotic pressure, be soluble as well as stable, and lastly, have a low affinity for lithium ions. Cost and environmental compliance factors will affect the total feasibility of FO, both of which directly impact the cost to operate. Finally, recovery and replenishment (regeneration) of the draw solutions will pose significant challenges to FO's ongoing economic viability without the implementation of efficient and cost-effective processes for their recovery and replenishment (regeneration) after being utilized by FO operations[156].

Currently, there has been no exploration or use of forward osmosis membrane technology for geothermal lithium extraction. The major limitation is that there are currently no FO membrane materials and devices capable of providing both high flux and high rejection, which are critical for concentrating geothermal lithium. The use of high-selectivity nanofiltration membranes and FO membrane materials has already been investigated and used for the extraction of lithium from salt-lake brines[157]. Therefore, once the key limitations of the materials and devices are resolved, FO will play an important role in the extraction of lithium from geothermal resources.

5. Development trends in geothermal lithium extraction

5.1. Membrane technology as a key development direction

There is an increasingly growing trend in the extraction of membrane-based technologies for the extraction of lithium from geothermal brine, as these are viewed as being the most promising combination of process efficiency and environmentally favourable characteristics. Several membranes, including reverse osmosis, are at the point of commercialization, although widespread adoption of these technologies has been limited due to challenges associated with high energy requirements. Future developments of membrane materials will focus on three sub-targets: improvement of selectivity, improvement of flux, and increased resistance to fouling[158].

Forward osmosis provides a new innovative approach towards the recovery of lithium from geothermal brines due to its low energy consumption, good resistance to fouling, and ability to adjust selectivity. The FO Membrane Technology is presently under development along two lines. The first line will focus on optimizing process conditions (such as temperature, flow rates, and pressure) to enhance operational stability and efficiency. For example, a moderate increase in temperature will enhance molecular thermal motions, resulting in more rapid diffusion of water molecules; thus increasing membrane water flux. The second area is Flow Rate Optimization; optimising flow rate is also important in terms of reducing concentration polarisation, which will help to improve separation efficiency[159].

The effort to reconsider FO Separation Technology from a purely FO perspective to an Engineering-Technology perspective opens numerous possibilities to advance the technology of the forward osmosis process. The initial goal will be to create better-performing and more compact forward osmosis membranes and modules; however, the real benefits to forward osmosis may come from collaboration with other separation technologies. One example would be to couple forward osmosis with Ion Exchange. For illustration, if geothermal brine is first preconcentrated and separated by forward osmosis and the lithium component of the brine is ultimately purified by ion exchange, both the lithium extraction efficiency and product lithium purity will be improved through the implementation of such a hybrid system. Another example would be to couple forward osmosis with Adsorption processes - e.g., if forward osmosis is first used to remove a majority of the impurities from the brine and then the selective lithium is extracted from the brine with an adsorbent, both the quantity of adsorbent used and the required frequency of adsorbent regeneration would be reduced, thus reducing the overall cost of lithium recovery[160].

The combination of FO with other membrane technologies, such as electrodialysis and membrane distillation, provides significant integrative potential, allowing the opportunity to optimize the benefits of using different separation methods together rather than relying on one method to meet all separation needs. If successful, the hybrid systems created through this type of technological synergy have the potential to develop improvements in the extraction of lithium from geothermal brines through increased efficiency, reduced energy costs, and increased sustainability. The application of FO membrane technology to the extraction of geothermal lithium represents a promising opportunity. The continued advancement of membranes, optimization of processes, and particularly the integration of the various technologies will likely influence the future of geothermal lithium electricity supply[160].

5.2. Trends in geothermal lithium extraction industrialization

The fast-growing business of electric vehicles and battery energy storage will drive continued demand, which will create the potential for large-scale industrialization of geothermal lithium mining technologies. The demand from the market is only part of the equation, as the ability to create an industrialized system at scale will also depend on the extent to which the enabling conditions are established in time and in sufficient quantity to reduce investment uncertainty and support the maturation of all technologies used in geothermal lithium extraction[161].

Government backing will play a decisive role in geothermal lithium extraction. Governments must strengthen their role by supporting geothermal lithium projects with targeted measures such as granting subsidies, providing tax incentives (and other support measures) to allow enterprises to invest in geothermal lithium projects with confidence. Additionally, industrial infrastructure development is equally significant. In certain nations, there are currently efforts underway to expedite the establishment of an integrated industrial chain linking geothermal resource exploration to technology development for lithium extraction, as well as the manufacturing of equipment and the downstream processing of lithium products. In fact, this is becoming an integrated industrial ecosystem rather than just a single technology pathway[162].

The establishment of deeper levels of collaboration between industry, academia, and research organizations is also critical. To support industrial growth, these three parties will need to work together closely not only to advance technology but also to train a workforce capable of meeting the needs of the industry. Working together will enable a more rapid transition from laboratory research to engineering applications, thus increasing the chances that technology advances will be applied through commercial processes. Demonstration projects provide the means to create operational experience and reduce the perceived technical risk of utilizing geothermal lithium extraction; therefore, they will be important for creating the confidence required to attract additional companies into the geothermal lithium extraction field.

5.3. Geothermal lithium extraction as a catalyst for the full utilisation of geothermal resources

An impetus driving the progression of geothermal lithium extraction is the continued improvement of geothermal resource-use efficiency; the current goal is to extract as much lithium as possible from the source. Additionally, the focus of recovery efforts has expanded from lithium alone to include boron, potassium, and rubidium as constituent parts of geothermal brine, thereby maximising the investment from the geothermal resources[162]. As such, the future of geothermal lithium extraction is reliant on efficient extraction processes and how they will integrate into wider resource recovery strategies.

Developing geothermal lithium extraction in a synergistic way with other industries is also important. An example of this would involve the use of geothermal power for lithium extraction. In this case, waste heat produced during electricity generation could provide useful thermal energy for lithium extraction, reducing the total energy needed to extract lithium. Coupling the extraction process with renewable energy sources (such as wind or solar) would also provide the electricity required to operate the extraction process. There are also opportunities to partner with agriculture/aquaculture; utilized appropriately, brine streams could be reused for irrigation/aquaculture after treatment, increasing resource utilization beyond just the lithium extraction stage[163].

The combination of these methodologies illustrates an expanded industrial framework focused on lithium extraction from geothermal energy but reaching further than simply extracting lithium from geothermal sources. Coordinating the development of geothermal energy with lithium extraction, geothermal energy generation, hot springs and tourism, agriculture, and aquaculture can create a system of integrated use of geothermal resources; therefore, it will increase the overall value derived from geothermal energy. This integrated system will have the option to create many different types of economic development opportunities for local communities.

5.4. Geothermal lithium mining, opportunities and challenges

Geothermal lithium extraction offers significant potential to transform the supply chain for lithium; however, several interrelated technical, economic, and environmental issues will limit its industrial-scale development in geothermal operations. Technical issues are likely to create barriers to successful lithium recovery due to factors such as the low concentrations of lithium found in geothermal fluids (20-200 mg/l) and the complexity of the chemistry of produced fluids. Lithium recovery will be limited due to high levels of ionic interference (such as Mg^{2+}:Li^{+} ratios over 10:1 in Tibetan brines) and the use of high-temperature (150-350 ℃) and high total dissolved solids (>100,000 ppm) geothermal fluids. Consequently, lithium recovery efficiencies of less than 60% can be expected, and materials used in the lithium recovery process will experience accelerated degradation. However, the recent progress made in developing alternative recovery technologies suggests that technical limitations can be overcome. Hybrid process configurations (including adsorption/electrochemical processes) and novel materials (including forward osmosis membranes made from graphene oxide) have shown very good performance, with lithium recoveries of 85% reported from high-salinity brines produced at the Salton Sea[164-166].

Economic impediments continue to be substantial, with capital expense constraints from $200-500 million, as well as operational penalties due to membrane fouling referenced earlier (15-20% increase in OPEX), keeping larger-scale deployment from happening. However, if lithium extraction were to be included in geothermal power, then the economics become more favorable due to shared infrastructure expense reductions of 30-40%, as shown with the Hell’s Kitchen project, where $200-500 million in capital expenditures and $15-203,500/ton break-even point operations create a basis for this. In addition, preliminary results from Germany suggest that artificial intelligence-based process optimization will reduce OPEX (by 25%), indicating that digital control methodologies could become more than just complementary, but rather could become economically critical[167].

From an environmental perspective, injecting recycled brine with a brine content greater than 90% is an effective way to reduce water resource depletion; however, injection still poses risks underground. For example, ground subsidence rates in California, estimated at 2-5 cm per year, also pose a risk due to seismic activity, as demonstrated by the magnitude 3.4 Basel earthquake in 2006. However, these hazards can be managed; closed-loop monitoring systems in Iceland, along with biosorbents to reduce the amount of solids/waste generated, serve as models for more responsible operation. Unfortunately, the regulatory framework for injection is less developed. Fragmented regulation (the EU still has vague brine guidelines, and the US has a lengthy permitting process) leads to implementation delays; therefore, a more standardised policy framework is needed to build on Chile’s example of a balanced national lithium strategy[168].

Looking ahead, we see the industry benefiting from a phased approach to technology development. Regarding hybrid plants, we believe such systems will be the best choice for low-concentration brines in the first phase (2025-2030), while modular plants with AI capabilities will be suitable for low-concentration brines in the second phase (2030-2040), and carbon-negative geothermal lithium mining methods will likely emerge after 2040. Market reform also plays a significant role: tax incentives for electric vehicles linked to sustainable sourcing and partnerships between automakers (such as Tesla) will have a significant impact on commercialization. Furthermore, the rapid adoption of geothermal lithium mining technologies must consider social responsibility issues related to “green colonialism” that could arise from mining processes used in developing countries (e.g., Kenya, Indonesia). All three elements, quantitative risk-benefit analysis, a combination of policy and technology, and equitable governance that takes into account the needs of local environments and communities, form a broader and more realistic basis for incorporating geothermal lithium into the overall picture of achieving a sustainable energy transition[169,170].

6. Conclusion

The extraction of lithium from geothermal energy is considered to be a new, innovative, and sustainable method of extracting lithium compared to conventional methods. The importance of geothermal lithium extraction is not only to provide an alternative source of lithium and reduce risk for lithium producers globally, but also to provide additional alignment with climate and equity-related goals. This review discusses the potential impact of geothermal lithium extraction through the following perspectives: technical, economic, environmental, and policy. The potential impact of geothermal lithium extraction should result in the geothermal lithium resource becoming a strategic direction for new energy innovation opportunities. There are several ways currently to extract lithium from geothermal energy: evaporation/precipitation, precipitation, adsorption, solvent extraction, electrochemical process, and membranes. Among these methods, it would appear that membrane processes, particularly forward osmosis, will be of significant research interest as geothermal lithium extraction advances.

Forward osmosis (FO) technology plays a significant role as an efficient process for extracting lithium compounds from water sources. The key advantages of this method include low energy consumption, the absence of contamination by various reagents, and reduced requirements for complex pretreatment. Selective water separation during FO increases the solution concentration, significantly enhancing the efficiency of subsequent separation methods. Furthermore, flexible integration into hybrid systems makes FO an essential component of the lithium separation process chain. Therefore, it is appropriate to evaluate this method as a direct separation technology, which offers the potential to improve the efficiency of the entire process by reducing reagent use and further improving the purification of lithium-containing water. It is anticipated that the use of FO for lithium extraction from water sources may become a promising alternative in the future.

Conflict of interest

The authors declare no conflict of interest.

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