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Lithium extraction assessment from brines in Kerman province: challenges and opportunities for clean energy transition and climate change mitigation

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ABSTRACT

The global transition toward clean and sustainable energy systems has elevated lithium to a position of critical importance due to its exceptional electrochemical properties, low density, and lightweight characteristics. Lithium's role in enabling the widespread adoption of electric vehicles (EVs) and portable electronics, coupled with the urgency of addressing climate change, underscores the need for efficient and sustainable resource exploration. This study focuses on assessing the potential for lithium extraction from brine sources in Kerman Province, Iran, with particular emphasis on the Shahrebabak region. Unlike previous studies that primarily focused on well-established lithium resources globally, this research explored an under-investigated region in Iran, providing a new understanding of its lithium-bearing potential and associated challenges. By integrating advanced remote sensing techniques with field-based geochemical analyses, this study pioneers a comprehensive methodology that has not been applied to Iran's brine sources before. To identify lithium-rich zones, advanced remote sensing methods, including Landsat 8 and Sentinel-2 imagery, were employed alongside geochemical analysis conducted via Inductively Coupled Plasma Mass Spectrometry (ICP-MS). 15 brine samples were collected at depths ranging from 0.5 to 2 meters, with lithium concentrations measured between 94 and 105 ppm. The Mg/Li ratios in these samples varied between 1.2 and 3.8, indicating potential challenges in achieving cost-effective extraction. Spectral Angle Mapper (SAM) analysis highlighted promising lithium-bearing zones, which were further validated through field sampling. The geochemical analysis of brine revealed that magnesium, potassium, sodium, and calcium were the dominant elements in the region, with lithium and boron present in trace amounts. Despite the presence of lithium, its relatively low concentration and high Mg/Li ratios suggest that the economic feasibility of large-scale lithium extraction in Shahrebabak remains limited. However, the study confirms the potential for lithium occurrence in Iran's brine resources and highlights the need for further research into alternative extraction methods and the evaluation of other regions with more favorable geochemical conditions .This study contributes to the global discourse on clean energy and climate change mitigation by providing a foundational framework for lithium resource exploration in Iran. It aligns with the sustainable development goals by promoting environmentally compatible resource utilization, reducing greenhouse gas emissions, and fostering economic growth through the development of strategic clean energy resources. Further multidisciplinary research efforts are essential to fully realize Iran's lithium potential and support the global transition to a greener energy future.

Keywords: *Lithium, Critical elements, Clean energy, Climate change, Lithium extraction.*

1. Introduction

Within the context of the growing concern due to the unsustainable exploitation of fossil resources, contributing to climate change, clean and alternative sources of energy have gained more importance than ever. The growing greenhouse gas emissions, for instance, carbon dioxide, rising sea levels, and the resultant environmental catastrophes, such as droughts and water shortages, have presented the world with compelling issues that require nations to revise their energy policies with a shift toward renewable resources (Sims, 2004; Panwar, Kaushik & Kothari, 2011). Because of its high electrochemical potential, coupled with its low weight and recyclability, lithium has become very important in the battery manufacturing industry for electric vehicles and portable electronic gadgets. The demand for lithium has more than doubled within the last decade and is expected to continue well into the future (Scrosati & Garche, 2010; Gaines & Nelson, 2009; Wanger, 2011).

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As a result, the consumption of non-renewable resources has produced toxic pollutants and widespread crises that have caused significant economic losses. Research evidence shows that due to climate change, carbon dioxide levels have increased by about 31% over the last two hundred years, while global warming has been causing sea-level rise at the rate of 1–2 millimeters annually (Sims, 2004; Panwar, Kaushik & Kothari, 2011). According to the records of altimeter sensors, the average sea-level rise is about 3.3 ± 0.4 millimeters per year. Therefore, globally, the shift from fossil fuel industries toward clean and carbon-free energy industries is progressing. This shift promises a sustainable future, as it opens avenues for the reduction of greenhouse gas emissions and global warming. Additionally, this crucial and efficient measure promotes employment opportunities, ensures sustainable development, and preserves the environment and natural resources.

Brines and silicate minerals are the main sources of lithium. However, brines have been considered superior in terms of lithium extraction, because operational costs are lower and their environmental impact is lesser (Scrosati & Garche, 2010). About 80% of lithium is extracted from brines whose magnesium-to-lithium molar ratio is below 3, as a lower ratio increases economic efficiency (Vikström, Davidsson & Höök, 2013). In brines with a higher magnesium-to-lithium ratio, advanced technologies of solvent extraction, adsorption, and ion exchange are used. Due to their respective technical complexity, these processes require further research and development (Nygren, Aleklett & Höök, 2009).

Iran's geographical position presents unique potential, providing opportunities for clean energy resources such as solar, wind, and lithium reserves. The exploitation of these resources would further open avenues for reducing dependence on fossil fuels and attracting investment in the renewable energy sector. According to the IEA (2008), with the increased demand for lithium, particularly in the electric vehicle sector, extensive research on resource discovery and enhancing extraction methods is essential. This approach will simultaneously reduce greenhouse gas emissions and hence aid in sustainable development, improving economic and environmental conditions. According to Hoegh-Guldberg & Bruno (2010) and Walther et al. (2002), lithium, being one of the important elements for clean energy and high-technology advancement, has become essential in recent decades. Lithium resources are divided into brine environments, hard rock deposits, and industrial clays. Brine environments, such as the Salar de Atacama in Chile, can be economically feasible because of their high concentration of lithium at 0.14% with low extraction costs (Munk et al., 2016; Schulz et al., 2018). On the other hand, hard rock deposits such as those in Greenbushes, Australia, have a lithium concentration of 1.59% and exhibit high economic potential despite their higher processing costs (Garrett, 2004; Gruber et al., 2011).

Thus, remote sensing has emerged as an effective means of spotting lithium resources, while the observation of these deposits has been conducted with greater precision. From these studies, sensors, such as ASTER, Landsat 8, and Sentinel 2 have been able to distinguish the spectral behaviors of minerals bearing lithium with high clarity, especially in their SWIR bands (Abrams, 2000; Jensen, 2015). These technologies provide powerful, cost-effective alternatives to traditional ground-based exploration methods for mapping and modelling mineral resources (Rajesh, 2004).

Lithium finds broad applications in lithium-ion batteries, electric vehicles, electronic devices, and energy storage systems (Speirs et al., 2014; Blomgren, 2017). The forecast for lithium demand, especially for battery production, indicates an extremely significant increase by 2030. Hence, it is considered a strategic mineral in the development of sustainable industries globally (Curry, 2017). Statistical studies conducted by the United States Geological Survey (USGS) and the British Geological Survey (BGS) identify countries, such as Chile, Argentina, and Australia as having the largest reserves and producers of lithium globally (USGS, 2019; Brown et al., 2018).

The demand for lithium has grown exponentially in recent years due to its role in lithium-ion batteries, essential for electric vehicles and renewable energy storage systems. Lithium, the lightest of all metals, is used in air treatment, batteries, ceramics, glass, metallurgy, pharmaceuticals, and polymers. Rechargeable lithium-ion batteries are particularly important in efforts to reduce global warming because they make it possible to power cars and trucks from renewable sources of energy (for example, hydroelectric, solar, or wind) instead of by burning fossil fuels. Today, lithium is extracted from brines that are pumped from beneath arid sedimentary basins and extracted from granitic pegmatite ores. The leading producer of lithium from brine is Chile, and the leading producer of lithium from pegmatites is Australia. Other potential sources of lithium include clays, geothermal brines, oilfield brines, and zeolites. Worldwide resources of lithium are estimated to be more than 39 million metric tons, which is enough to meet projected demand to the year 2100. The United States is not a major producer at present but has significant lithium resources. (Bradley et al., 2017). The global push for clean energy and climate change mitigation, supported by international agreements, such as the Paris Agreement, has intensified this demand (Tabelin et al., 2021). Lithium's unique properties make it vital in the transition to low-carbon energy systems. Various methods for sustainable lithium extraction have been explored. Technological advancements in extracting lithium from salt lake brine reveal challenges with conventional evaporation methods, emphasizing the potential of direct lithium extraction (DLE) for higher efficiency and reduced water usage (Fuentealba et al., 2023). Similarly, the environmental impacts of conventional and emerging technologies, including the superior recovery rates of DLE, highlight its role in minimizing degradation (Vera et al., 2023). Unconventional sources, such as geothermal brines and oilfield-produced water, are gaining attention. Life cycle assessments emphasize site-specific environmental impacts and the need for early evaluations to optimize methods (Schenker et al., 2024). Reviews of lithium recovery from oilfield brines underscore the potential to address global supply gaps (Ettehadi et al., 2024). Environmental assessments of DLE demonstrate reduced greenhouse gas emissions and water consumption, particularly when renewable energy sources, such as solar power are integrated (Mousavinezhad et al., 2024). Challenges associated with evaporative and alternative methods emphasize the importance of assessing water usage, energy consumption, and waste generation holistically (Vera et al., 2023). The socio-economic impacts of lithium extraction, particularly in regions, such as the Andean Altiplano, highlight the trade-offs between mining and sustainable development goals. Sustainable management practices are essential to mitigate ecosystem disruption and social inequalities (Rentier et al., 2024). Emerging technologies and historical insights into lithium extraction reveal gaps in sustainable practices, particularly for unconventional sources, such as geothermal and desalination brines. Promising methods, such as DLE and membrane processes, show potential for enhancing yields while reducing environmental impacts (Krishnan & Gopan, 2024; Nikkhah et al., 2024).

This study evaluates the lithium extraction potential from brine sources in Kerman Province, Iran. Using advanced remote sensing technologies and geochemical analyses, it aims to contribute to the global transition to clean energy while addressing the environmental and economic challenges of lithium production. With its high specific heat capacity and outstanding electrochemical potential, lithium has secured a crucial position in modern industries. Further research into extraction methods, particularly those leveraging advanced remote sensing, open new perspectives for sustainable resource management and development.

2. Material and methods

2.1. Lithium resources

As shown in Figure 1, lithium resources are diverse and include the following. Brine environments are among the most significant and cost-effective sources of lithium. Closed basin brines, typically found in arid regions, are formed in endorheic basins where evaporation concentrates dissolved salts, including lithium. These brines often have high lithium concentrations and are considered economically viable for extraction.

Geothermal brines, which are produced during geothermal energy generation, represent another important source. They contain lithium along with other valuable elements, although their extraction can be technically challenging due to high temperatures and complex chemical compositions. Oilfield brines, a byproduct of oil and gas extraction, also hold considerable potential for lithium production, though they remain underexplored compared to other brine types. Lithium-rich rocks and soils provide another critical source of this element. Pegmatites, such as spodumene and lepidolite, are the most well-known rock-hosted lithium deposits and serve as a major source for commercial lithium extraction. Hectorite, a clay mineral, contains lithium in significant quantities and has been increasingly studied for extraction feasibility. Jadarite, a rare mineral found primarily in Serbia, is another promising source, containing both lithium and boron. Granites, particularly those enriched with lithium-bearing minerals, also hold potential as a source of lithium, although their economic feasibility depends on the concentration and accessibility of lithium within the rock matrix. Seawater and salt lakes contain vast amounts of dissolved lithium, making them an almost unlimited potential resource. However, the concentration of lithium in seawater is relatively low, approximately 0.17 ppm, making its extraction energy-intensive and currently uneconomical. Salt lakes, on the other hand, are a more feasible source, especially in regions, such as the Lithium Triangle of South America, where high lithium concentrations and favorable climatic conditions facilitate evaporation-based extraction methods. These resources are particularly important for long-term sustainability as demand for lithium continues to rise. Emerging lithium sources, such as lithium-rich clay deposits and sedimentary rocks, are gaining attention. These unconventional deposits are abundant and geographically widespread, offering significant potential for diversifying lithium supply. Although extraction technologies for these sources are still in the development phase, they could play a vital role in meeting the growing demand for lithium in the future.

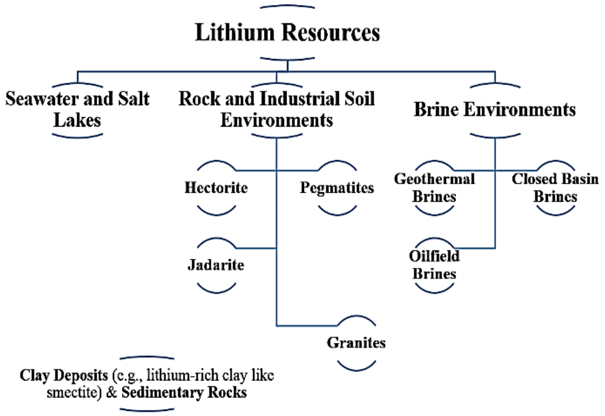

Figure 1: Lithium resources.

The research methodology needed to conduct this research included experimental design on lithium resource studies by collecting data that included finding and researching potential areas on small-scale geological and tectonic maps ranging from 1:100,000 to 1:50,000 of the study area. It also included sampling procedures to suit the type of samples, weight required, appropriate depth, and methods for sample collection. It also developed the geochemical lithium sampling protocols for both rocky outcrop and brine environments. Information relevant to the study was compiled in a database from books and articles. Following this, the study embarked on field operations, sample collection from target environments, laboratory investigations, and data analysis.

2.2. The types of extraction methods for lithium-bearing resources and potentials

The extraction methods for lithium-bearing resources and potentials can be categorized into two main types: brine environments and hard rock and industrial soil environments.

2.2.1. Lithium extraction methods from brine environments

Brine environments, responsible for approximately three-quarters of global lithium production, are the most cost-effective source for lithium extraction (Munk et al., 2016; Yaksic & Tilton, 2009). Their low cost, abundant supply, reduced energy requirements, and environmental compatibility make them the primary choice for lithium extraction (Warren, 2006). To achieve high-purity lithium, impurities such as magnesium, calcium, iron, and aluminum must be removed (Chagnes & Swiatowska, 2015). Various techniques for the extraction of lithium from brine have been reviewed: precipitation, solvent extraction, ion exchange, adsorption, and electrolysis. Currently, about 80% of lithium extraction from brines with a magnesium-to-lithium molar ratio of less than 3 is done by precipitation process (Mozdini Afarani, 2013). A lower magnesium-to-lithium ratio makes the process more economical (Vikstrom, Davidsson, & Hook, 2013). For brines with higher magnesium-to-lithium ratios, methods, such as solvent extraction, adsorption, or ion exchange processes are preferable because precipitation results in the co-deposition of lithium and magnesium, making the latter method inefficient (Mozdini Afarani, 2013).

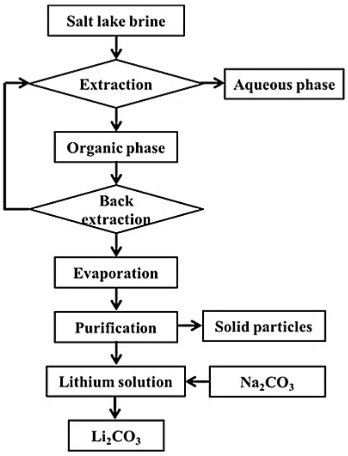

Figure 2: The extraction process of Lithium.

2.2.1.1. Precipitation process

Brine environments typically contain lithium concentrations ranging from 200 to 1400 mg/L, which are pumped to the surface and then concentrated through evaporation in artificial ponds (Bradley et al., 2013). The lithium concentration in economically viable brines ranges from 200 to 4000 mg/L (Bradley et al., 2013; Kesler et al., 2012). After sampling and natural evaporation for several months, depending on the climatic conditions, a lithium concentrate of 1–2% is processed to final products, such as lithium carbonate, in a factory (Bradley et al., 2013). In a study conducted by Davari et al., (2017) about the changing composition of elements in the brine of Lake Urmia, natural evaporation ponds were used for the precipitation of the elements. Table 3-1 provides the chemical analysis of these elements. The current volume of surface brine of Lake Urmia is estimated to contain up to 84,000,000 tons of unrefined magnesium, 15,000,000 tons of unrefined potassium, and more than 28,000 tons of unrefined lithium (Davari et al., 2017).

Conventional methods of flame spectroscopy or atomic absorption are appropriate for measuring lithium in environments with salinity below 7 g/L. However, in natural brines with dissolved salt concentrations exceeding 300 g/L, detecting trace amounts of lithium using these methods is challenging due to interference from other salts (Davari et al., 2017). To address this, a process is required to separate lithium salts from other salts or remove interfering salts while retaining lithium in the solution (Davari et al., 2017).

In the precipitation process, the precipitated element is separated from the solution through filtration or thickening, followed by washing with water or other diluted electrolytes to purify it (Soleimani Khalaji, 2016). Precipitated elements with higher density and crystalline properties are generally less prone to contamination and can be better separated and washed (Soleimani Khalaji, 2016). In research on lithium extraction from the brine of Khur and Biabanak deserts, the precipitation method used five reagents, including sodium hydroxide, ammonia, calcium carbonate, lithium hydroxide, and dolomite for the removal of magnesium and boron from brine, whereas sulfuric acid was used for the removal of calcium. Lithium phosphate and lithium carbonate were extracted using sodium dihydrogen phosphate and sodium carbonate as reagents, respectively.

Table 1. The results of the elemental analysis of Lake Urmia (Davari et al., 2017).

The results of element analysis after 3 months and 3 days				
Time Frame	Mg(gr/L)	K(gr/L)	Li(ppm)	Na(gr/L)
Initial	56	10	21	37
Final	104	23	34	4

2.2.1.2. Adsorption process

Chemical analysis results from three sources, including petrochemical bittern, Lake Qom's saline water, and Khur and Biabanak brine were compared. It was concluded that lithium extraction from petrochemical bittern and Lake Qom's saline water, which had high magnesium-to-lithium ratios and lithium concentrations below 10 ppm, was costly and difficult. In contrast, Khur and Biabanak brine, with a lithium concentration of 80 ppm, was identified as the most suitable source for lithium extraction.

Selective lithium adsorption using synthetic adsorbents based on MnO_2, TiO_2, aluminum hydroxide, and others has been extensively studied using synthetic seawater, brine from Salars, and geothermal resources (Chagnes & Swiatowska, 2015). Figure 3 highlights research on lithium recovery through adsorption with synthetic adsorbents. This method involves the reversible exchange of ions in the solution with ions associated with an insoluble ion-exchange material, which can absorb ionic components and simultaneously release an equivalent number of ions back into the solution. Key practical techniques for ion-exchange applications include batch, columnar, continuous, and fluidized-bed processes.

Selecting a suitable adsorbent is critical for both efficiency and economic feasibility. Among the adsorbents used as ion sieves for lithium extraction from brines, titanium dioxide exhibits high efficiency (Moazeni, 2013). Nanostructured materials, particularly titanium dioxide nanotubes with their high specific surface area, are preferred for enhancing adsorption rates (Soleimani Khalaji, 2016). Moazeni and colleagues suggest that adsorption is more suitable than other methods for low-lithium concentrations typically found in seawater and local brines (Moazeni et al., 2015). Additionally, as noted in the second chapter of this study, adsorption outperforms solvent extraction, coprecipitation, and other methods for lithium recovery from seawater (Chitrakar et al., 2001; Nishihama et al., 2011; Umeno et al., 2002).

Japanese researchers have demonstrated the recovery of 750 grams of lithium carbonate from 4200 cubic meters of water using the ion-sieve $MgMn_2O_4$ adsorbent (Fasel & Tran, 2005). The lithium loading capacity of various synthetic adsorbents ranges from 5 to 35 mg/L per gram, depending on factors such as solution type, lithium concentration, and adsorbent composition (Chagnes & Swiatowska, 2015). High loading capacities (greater than 20 mg/g) are generally achieved only in lithium-enriched solutions with concentrations exceeding 5 mg/L (Chagnes & Swiatowska, 2015).

The following section addresses the important parameters in the processes of adsorption and desorption (Xiao et al., 2012):

$$R_i = \frac{\left(\frac{Ci \times V}{ms}\right)}{mi} \quad (1)$$

In this equation, Ri represents the lithium-ion extraction ratio, Ci stands for the concentration of the target metal in solution (mg/L), V is the volume of the solution in liters, ms is the mass of raw material in grams, and mi gives the mass of lithium in the raw material exchanged with hydrogen cations (HCl) in grams (Xiao et al., 2012).

$$Q = \frac{(C0-Ce)\times V}{W} \quad (2)$$

In Equation 2, Q is the adsorption capacity of the adsorbent (mg/g), C0 is the initial lithium concentration in solution (mg/L), Ce is the equilibrium lithium concentration (mg/L), V is the solution volume (L), and W is the mass of the ion sieve in grams (Xiao et al., 2012).

$$\text{Ads }\% = \frac{(C0-Ce)}{C0} \times 100 \quad (3)$$

Equation 3 describes the percentage of lithium adsorption by the adsorbent, where C0 is the lithium concentration before the adsorption process, and Ce is the lithium concentration after adsorption.

Lithium recovery in the adsorption mechanism occurs through several steps. First, lithium ions diffuse from the bulk solution to the surface of the adsorbent. Subsequently, the lithium ions penetrate from the surface into the ion exchange sites, followed by the ion exchange step, which determines the reaction rate. Finally, the desorption step occurs.

Titanium dioxide exhibits three primary crystalline phases: anatase, rutile, and brookite. Among these, rutile is stable at room temperature, while anatase and brookite are metastable in their non-nano forms but can convert to rutile under appropriate conditions. It is worth noting that in the nanoscale structure, all three primary phases can remain stable at room temperature.

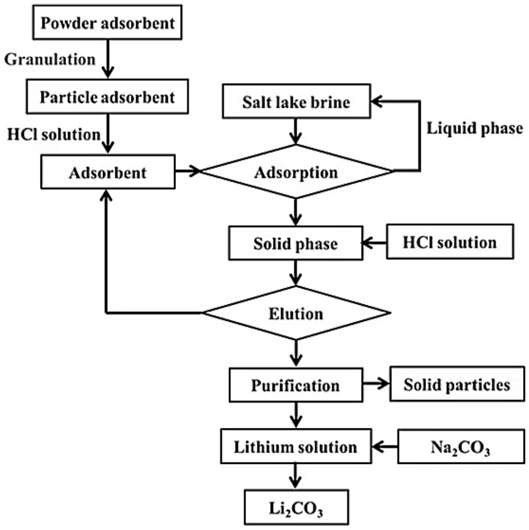

Figure 3. The adsorption process of lithium recovery.

Initially, titanium oxide nanostructures are amorphous. Upon thermal treatment at 280°C, they transform into a mixture of anatase and rutile. Titanium oxide can be used as an ion adsorbent due to its capability for lithium adsorption and desorption through ion exchange reactions. It can be utilized in forms such as nanotubes, nanorods, nanosheets, and nanofibers, which feature high specific surface areas. Over recent decades, titanium dioxide nanostructures, especially titanium nanotubes, have garnered significant attention due to their unique properties, such as high specific surface area, ion exchange capability, photocatalytic potential, and other distinctive characteristics.

Common methods for producing titanium dioxide nanotubes include the sol-gel method, anodic oxidation, and hydrothermal synthesis.

2.2.1.3. Solvent extraction process

Solvent extraction, or in other words liquid-liquid extraction, is a unit operation embraced in dilute solutions separation of carboxylic acids, amino acids, amines, phenols, metal ions, and more. It has recently received considerable interest in lithium extraction. Similar to adsorption, solvent extraction is also applicable in extracting lithium from brines when the magnesium-to-lithium molar ratio is more than 3. Since the Salt Lake brine contains 0.006% Li with 0.8% Mg, in the Salt Lake region solvent extraction is one of the proposed methods for recovery. Other methods for brines with high magnesium-to-lithium ratio include the use of tributyl phosphate diluted with kerosene, methyl isobutyl ketone, or 2-octanol, in the presence of $FeCl_3$, $CrCl_3$, or $ZnCl_3$ as co-agents in the extraction process. However, solvent extraction faces limitations due to the high cost of organic reagents and associated environmental hazards.

2.2.2. Lithium extraction from hard rock and industrial soil deposits

This part of the study focuses on the methods used for lithium extraction from hard rock and industrial soil deposits. The starting point in the processing of minerals, such as spodumene, petalite, lepidolite, amblygonite, and others consists of their crushing, followed by a process of flotation, magnetic separation, optical sorting, or heavy media separation in order to obtain a concentrate with 4–6% lithium oxide (Chagnes & Swiatowska, 2015).

2.2.2.1. Spodumene processing

Spodumene is the richest lithium-bearing mineral in economic deposits. Presently, the Greenbushes mine in Australia, with an average lithium concentration of 1.59%, is the largest lithium producer from minerals, operated by Talison Lithium Pty Ltd. Lithium extraction in this region involves processes, such as gravity separation, flotation, and magnetic separation. Recently, Nemaska Lithium Inc. proposed a new roasting-acid approach that can simultaneously produce Li_2CO_3 and $LiOH{\cdot}H_2O$; the approach uses an electrodialysis module to generate LiOH solution after the removal of impurities by precipitation and ion exchange. By this process, a purity of over 99.9% in final products can be obtained.

2.2.2.2. Lepidolite processing

Lepidolite $K\ (Li,\ Al)_3(Al,\ Si,\ Rb)_4O_{10}(F,\ OH)_2$ containing 3.8% lithium, has been extensively studied because of its importance in lithium extraction. Its efficiency is poor due to the high fluorine concentration, despite its high lithium content. Lepidolite has a hardness of 2.5–3 and a density of 2.8–3 g/cm³. In 2012, Yan et al. proposed a process for producing high-purity lithium carbonate from Chinese lepidolite deposits containing 1.4% lithium. Roasting at 860°C in the presence of steam, followed by washing of the roasted product with lime milk at 150°C, was involved in this process. The method achieved a lithium extraction efficiency of 98.9%, and after calcium removal, solution purification, and crystallization, the final product of lithium carbonate had a purity of 99.9%.

2.2.2.3. Zinnwaldite, Amblygonite, and Petalite processing

Very few studies have been conducted on lithium extraction from zinnwaldite, amblygonite, and petalite. Zinnwaldite is usually recovered as a by-product during the processing of China clay and tin-tungsten deposits. In 2009, Zheng et al. sintered zinnwaldite containing 1.4% lithium with $CaSO_4$ and $Ca(OH)_2$ at 950°C for 2 hours. Washing the product at 90°C with a liquid-to-solid ratio of 10:1 resulted in 96% lithium recovery. The final product was 99% pure lithium carbonate.

Amblygonite $(Li,Na)AlPO_4(F,OH)$ while widely available, amblygonite is less economically viable. Having a hardness of 5.5-6 and a density of 3kg/m³, the processes for amblygonite extraction were first presented by Ziegens and Roeder in 1936 through the use of sulfuric acid. Later, the calcination of amblygonite with gypsum and lime at 950°C yielded a 97.3% recovery of lithium for Kalinowski and Ranke.

Petalite $LiAlSi_4O_{10}$ has 4.2% lithium oxide and is one of the essential mineral resources for the ceramics and glass industries. Sitando and Kuroz studied in Zimbabwe and presented a process that included decrepitation at 1100°c and product washing resulted in 97.3% lithium recovery, and 99.21% lithium carbonate.

2.2.2.4. Clays and other sources processing

The concentration of lithium in different clay minerals including montmorillonite, kaolinite, hectorite, and many more varies within a large range from 7 to 6000 ppm (Chagnes and Swiatowska, 2015). The lithium-bearing clays predominantly comprise hectorite. Hectorite $(Mg,\ Li)_3\ Si_4\ O_{10}(OH)_2$ is a smectite mineral with a high content of magnesium and lithium. The mineral exhibits a hardness of 1-2 with a density of 2-3 kg/m³ (BGS, 2016). The most significant deposits of hectorite, with about 0.7% lithium, occur in Hector, California (Garrett, 2004; Gruber et al., 2011; Meshram, Pandey, and Mankhand, 2014).

The extraction of lithium from montmorillonite and hectorite clays is a two-step process: pre-treatment by aqueous slurries containing sodium or potassium carbonates or hydroxides is followed by leaching with sulfuric acid (Chagnes & Swiatowska, 2015). First, clays are slurried with caustic soda at 85°C for 3 hours. The residue, after filtration, undergoes leaching with 95% H_2SO_4 at 85°C for 3 hours under pH 1 conditions. Then, the slurry is heated to 100°C for 5 hours and cooled to ambient temperature. Purification involves lime treatment to adjust the pH to 7, followed by soda ash addition to achieve pH 12, precipitating impurities. The best result obtained by this method was 66% maximum lithium recovery (Chagnes & Swiatowska, 2015).

Leaching granite samples with 0.5% and 0.07% lithium with 120 g/L H_2SO_4 at 260°C for 3.5 hours achieved recoveries of 68.2% and 55.6%, respectively. Pressure-leaching pegmatite samples with 0.65% lithium resulted in 71.3% lithium recovery (Chagnes & Swiatowska, 2015). In addition, treatments using 300 g/L HCl at 90°C for 3.5 hours on granite samples yielded 76.2% and 64.7% lithium recoveries, which were higher than sulfuric acid. However, this process had to undergo further purification since impurities, such as aluminum, magnesium, and calcium were also leached (Chagnes & Swiatowska, 2015).

To understand the lithium in drainage systems, sampling should be done upstream. Stream sediment sampling has, therefore, been carried out through a sequence of planning, sampling, preparation, and dispatch of samples to the laboratory. In an optimized sampling design, tributaries in a catchment area are numbered, as indicated by Hasani Pak (2012). The number of each tributary is assigned to the sum of upstream branches. The spacing between samples is dependent on the stream order; the first-order tributaries, or headwaters, are the most critical (Guidelines for Geochemical Exploration of Large-Scale Stream Sediments 2011).

2.3. Setting guidelines for lithium geochemical sampling in rock and brine environments

The methods of sampling for lithium depend on the deposit type. Rock outcrop deposits are usually sampled by methods similar to those used for many other metals, using either surface (open-pit) or subsurface (underground) extraction methods. In brine environments, sampling is different because of the liquid nature of the material, where brine is pumped from wells to the surface for collection and analysis.

In this stage, for designing the worksheets of each of the techniques, a final summary regarding the form and content of the worksheets will be reached through interviews with experts in the studied industry and the formation of expert meetings.

2.3.1. Rocky environments

Open-pit mining applies to shallow deposits (<100 meters) and involves the removal of overburden, drilling, and transportation of ore for processing. The various sampling methods include channel sampling, where trenches are cut along mineralized zones, chip sampling involving broken rock pieces, especially in hard rocks, and combined methods, conventionally called channel-chip sampling. Sample design is done as random or systematic grids, depending on uniformity. Samples for lithium exploration target the minerals spodumene, petalite, lepidolite, and amblygonite in pegmatites, with sample size determined by crystal size and mineral type. Larger samples are required from pegmatites because of coarse grain size.

Both surface and underground mining are applied, as these are usually required to access materials at different depths. An example is the Greenbushes Mine in Australia, where spodumene in dry pegmatites is extracted by blasting and hydraulic excavation to produce low-iron concentrates for ceramics and chemical-grade products. Waste is recycled for site rehabilitation. In a similar way, the Bikita Mine of Zimbabwe also follows open-pit and underground methods for lithium extraction from petalite, lepidolite, and amblygonite. For deeper deposits, underground mining is preferred because of cost efficiency, with access in horizontal, vertical, or inclined directions, as early operations at Bikita revealed a 610-meter tunnel system.

2.3.2. Brine environments

These worksheets will then be distributed among the team formed to complete them. This group's work in the occupational health risks section includes five specialists with expertise in civil engineering, structures, road and construction, occupational health, industrial safety, and concrete quality control engineering. In the environmental risks section, two environmental specialists replace the occupational health and industrial safety specialists. All occupational health and environmental risks.

Lithium-rich brines occur in aquifers in porous rocks generally at depths of hundreds but up to several thousands of meters, with lithium concentrations usually in a range of 200–1400 mg/L, although economic resources usually require 200–4000 mg/L Li. Brines are pumped to the surface and concentrated by evaporation in artificial ponds. The number, location, and spacing of wells are dependent on aquifer geometry, size, porosity, depth, and brine flow rates. For instance, the number of wells in Clayton Valley, Nevada, USA was 30 operating at 500 L/s in 1969, whereas Salar de Atacama operated 40 wells each well over 1400 L/s in the late 1980s. Light brine sampling, such as <2 m, can be performed manually using small pits. Random or systematic sampling grids are selected based on the project objectives; GPS tracks the location, path, and depth of samples. Physical and chemical parameters such as pH, salinity, EC, and TDS are measured by multiparameter devices. Samples are stored in 1-liter polyethylene containers for lab analysis.

Materials and Equipment for Lithium Extraction and Synthesis of Nano-Titania Sieves proposed materials for lithium extraction include ethanol, distilled water, titanium dioxide-nano, and micro, HCl 37%, NaOH, LiOH, and various chlorides-lithium, magnesium, sodium, potassium. Equipment to synthesize nano-titania sieves will involve magnetic stirrers, ultrasonic devices, autoclaves, ovens, and heat treatment furnaces. These tools and materials shall enable the development of efficient brine lithium extraction and advanced material synthesis.

3. Result and Discussion

The steps for conducting the study are as follows:

1. Collecting data on the most significant lithium silicate mines worldwide, particularly spodumene, petalite, hectorite, and lepidolite.
2. Gathering data on the most important lithium chloride mines globally.
3. Selecting mines that are geologically, environmentally, and climatically similar to Iran and extracting their location and characteristics.
4. Reviewing datasets from ASTER, Sentinel-2, and MODIS sensors and selecting samples of their imagery with minimal environmental interference (e.g., minimal impact of dust, clouds, and vegetation cover) for the selected lithium mines.
5. Performing radiometric and atmospheric corrections on the images obtained from the aforementioned sensors.
6. Extracting the spectral features of the selected lithium mines, comparing, and integrating the results from all sensors and mines.
7. Obtaining Level 2 MODIS sensor images (radiometrically corrected) for the study area, ensuring temporal consistency with the spectral feature extraction timeline.
8. Implementing remote sensing target detection methods based on spectral analysis using spectral features derived in the previous phase, alongside spectral libraries from ASTER and USGS. This step involves applying these methods to MODIS imagery to identify potential areas for lithium extraction.
9. Acquiring imagery from other sensors for the identified potential areas (step 3), ensuring temporal consistency and minimal environmental interference. Preprocessing the imagery, correcting radiometric and atmospheric errors, and reapplying remote sensing target detection methods to validate or exclude potential areas.
10. Examining geological layers around the identified potential zones, including the proximity to volcanic rocks (especially pegmatites), fractures, faults, and digital elevation models. This step concludes with selecting a candidate zone for a lithium chloride mine and a lithium silicate mine.
11. Comparing all outputs and selecting the most effective sensor.
12. Conducting the final lithium mine potential mapping using the most effective sensor and providing a map of the candidate area.
13. Evaluating the ecological capacity of the identified lithium-rich zones to support the development of mineral industries.

3.1. Remote sensing study using SAM method

Once satellite images become available to users, three stages of processes are conducted on them: preprocessing, processing, and post processing. The first stage is that of preprocessing itself, correction, is conducted to deal with radiometric and geometric errors. Such kinds of errors are called internal errors, arising either from the satellite itself or atmospheric and terrestrial influences. Geometric correction tries to accurately place pixels within the image using ground control points (Rayegani, 2019; Rayegani et al., 2020). Atmospheric correction is performed, therefore, to remove the impact of scattering and atmospheric absorption utilizing specific algorithms (Rayegani, 2019). After finishing all the required preprocessing and georeferencing steps of the satellite imagery, start processing (Kheirandish et al., 2014).

The third processing stage involves the application of transformation and classification procedures upon the rectified data. This is the third stage that ends at the validation stage, where data obtained during processing are substantiated through sampling in the research area.

This section focuses on one such algorithm used in the classification of satellite imagery for data extraction, the Spectral Angle Mapper (SAM). Quite a considerable amount of research has been conducted on this algorithm (De Carvalho & Meneses, 2000; Girouard et al., 2004; Kuching, 2007; Pournamdari et al., 2014; Rashmi et al.,). The SAM is of immense significance mainly in the fields of mineralogy and geology. Some of the traditional approaches, such as Maximum Likelihood, Minimum Distance, Mahalanobis Distance, and Support Vector Machine, are employed based on the specific application in use. Satellite image classification is divided into unsupervised and supervised classes, as shown in Figure 4.

The SAM algorithm is based on the theory that each pixel in remote sensing imagery represents a unique ground cover material that can be unambiguously assigned to one land cover class (Rashmi et al., 2014). The method calculates the spectral similarity between two spectra by calculating the angle that remains between them, imagining the spectra as vectors in a multidimensional space with a dimension equal to the number of bands (Kuching, 2007; Rashmi et al., 2014). The Spectral Angle Mapper (SAM) algorithm formula is based on Equation 4.

$$\alpha = Cos^{-1}\frac{\sum_{i=1}^{nb} t_i r_i}{\left(\sum_{i=1}^{nb} t_i^2\right)^{0.5}\left(\sum_{i=1}^{nb} r_i^2\right)^{0.5}} \qquad (4)$$

The SAM algorithm assumes that each pixel in remote sensing images represents a unique land cover class. It measures spectral similarity by calculating the angle between spectra, treating them as vectors in a multi-dimensional space (Rashmi et al., 2014). The method is robust against solar factors since the angle is independent of vector lengths (Girouard et al., 2004). Smaller angles indicate closer alignment with reference spectra, while pixels exceeding a specified angle threshold are not classified. SAM is also insensitive to albedo effects when applied to calibrated reflectance data.

The main advantage of SAM is its efficiency in mapping spectral similarity, while its primary drawback is spectral mixing, particularly in medium-resolution images, such as Landsat TM. This issue can be reduced with high-resolution images but may also be exacerbated by local variations in spectral characteristics (Girouard et al., 2004).

Figure 5 depicts a lithium brine deposit in Chile, utilizing data from the Tier 1 product of Landsat 8, which includes necessary atmospheric and radiometric corrections Geometric corrections were performed, and the study area and database were analyzed using remote sensing studies leveraging the SAM algorithm for sampling the target environment.

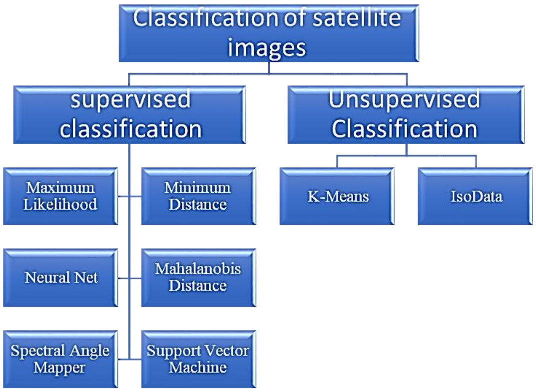

Figure 4. The classification of satellite images.

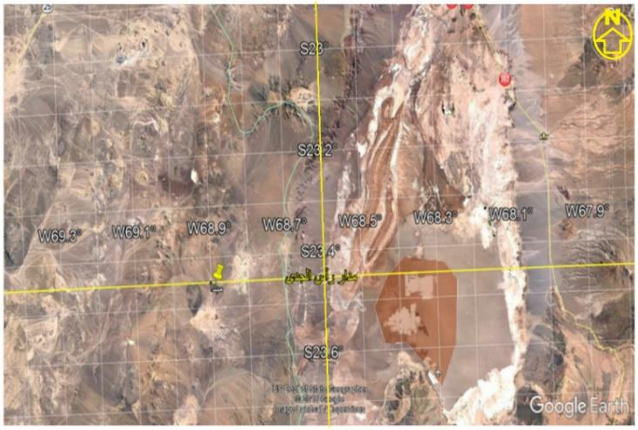

Figure 5. Lithium brine in Chile.

3.2. The Analysis of Sample Devices

All collected samples are prepared for analysis and sent to the laboratory of Zaramaz Mineral Studies Company. The selection of chemical analytical methods depends on the level of exploratory work, the nature of samples, and the detection limits for element analysis (Geochemical Exploration Guidelines for Large-Scale Alluvial Deposits, 2011). Accurate chemical analysis is a prerequisite for obtaining good research results. Higher detection limits are needed for economic grade measurements, whereas lower limits are needed for the identification of elemental potential in exploratory areas.

Inductively Coupled Plasma (ICP) spectrometry offers increased sensitivity and better detection limits compared to other analytical techniques. This method is particularly useful for the determination of trace metallic elements, such as lithium, in matrices, such as brine, rock, industrial soil, and alluvial sediments. Under certain research conditions, other methods, including portable techniques and chromatography, can be employed as well.

Flame spectrometry or atomic absorption methods are suitable for lithium quantification in brines where salinity does not reach 7 grams per liter. However, in naturally occurring brines with a concentration of dissolved salts exceeding 300 grams per liter, the precise measurement of low lithium concentrations through the mentioned methods is often hindered by interference from other salts, unless lithium is selectively separated from the brine (Davari et al., 2017).

3.3. Sample preparation for Inductively coupled plasma Mass Spectrometry (ICP-MS)

Liquid samples should be absolutely clear, and free from solid or undissolved particles in colloidal or emulsion form. Samples with elemental concentrations above 10,000 ppm are usually best diluted, but this should be done by an experienced operator as the purity of the solvent and the accurate measurement of the initial and diluted solution volumes significantly affect the analysis.

Solid samples must be dissolved in a solvent and therefore must undergo a digestion process before analysis. The digestion process either completely dissolves the solid material or selectively dissolves the particular element of interest. The dissolution process is very important and should preferably be carried out by an experienced operator. Two aspects make the digestion important: first, the target element must be taken out entirely from the solid phase into the liquid phase; second, solvent purity is very important since even a small amount of impurities can cause considerable error in measurement. Therefore, ultra-pure solvents should always be used by an operator to ensure effective digestion.

3.4. The Collection of Samples and Analysis in the Study Area

This research focuses on Babak City, part of Kerman Province, Iran. It falls within 53° 26′ to 59° 29′ E longitude and 25° 55′ to 32° N latitude, encompassing the geographical area within the southeastern part of the Iranian plateau. Precipitation in Kerman Province, on average over a long-term period in a year, was 128 mm.

The samples of soil were collected by excavation of pits manually during the autumn season. The samplings were random. The geographical positions of the samples collected from Shahrebabak are shown in Figures 4-6. For the determination of the position of sampling, remote sensing methods, the SAM algorithm, and the use of satellite bands by the satellite Landsat were employed

The depth range of 0.5 to 2 meters was selected based on several considerations. First, this depth represents the near-surface brine layers that are most accessible and cost-effective for sampling and analysis, particularly in exploratory studies. Second, preliminary geological assessments and field investigations indicated that lithium-bearing brines in Shahrebabak are predominantly concentrated within these shallow layers, with deeper layers showing limited evidence of significant lithium enrichment. Additionally, logistical constraints, including the absence of advanced drilling infrastructure in the study area, made deeper sampling less feasible for this phase of research. Future studies should incorporate deeper drilling campaigns and advanced geophysical surveys to comprehensively assess lithium distribution at greater depths, ensuring that the resource potential is fully evaluated.

Table 2 gives the geographic coordinates for all collected soil samples at a depth of 0.5 meters. The first sample is located at 55°09'34.83" east longitude and 29°58'59.64" north latitude. The location of the second sample has the coordinates 55°15'20.51" of east longitude and 30°01'54.87" of north latitude. Moreover, Figure 7 illustrates the location of the first sample, whereas Figure 8 illustrates the location of the second sample.

Figure 9: Spatial distribution of sampling points which have been located about 10 km from each other in the Babak region, Kerman. Sampling of soil was done from a depth of 0.5 meters. Each of the 2-gram samples was put into bags and dispatched to Zarazma Mineral Studies Company Laboratory for analysis. The analysis results of these

samples showed that the soil of the studied area has considerable concentrations of Mg, Ca, K, and Na and trace quantities of Li and B. Tables 3 and 4 show the analytical results of six elements in the collected samples analyzed by ICP-MS technology.

Table 2. The geographic coordinates of the sampling locations for lithium (from 50 cm underground soil).

Sample Number	N (Latitude)	E (Longitude)
Sample 1	29° 58' 59.64"	55° 09' 34.83"
Sample 2	30° 01' 54.87"	55° 15' 20.51"

Table 3. Sample analysis results (first) 98ZR-304 (6-element analysis).

No.	Element	Concentration (ppm)
1	Potassium	4100
2	Magnesium	24000
3	Calcium	16000
4	Sodium	4500
5	Boron	32
6	Lithium	105

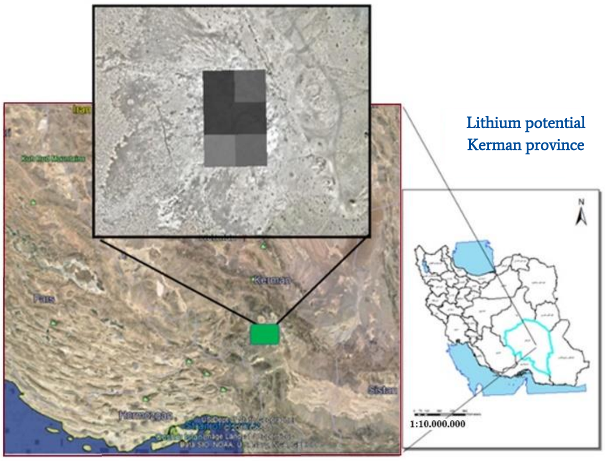

Figure 6. The map of the study area.

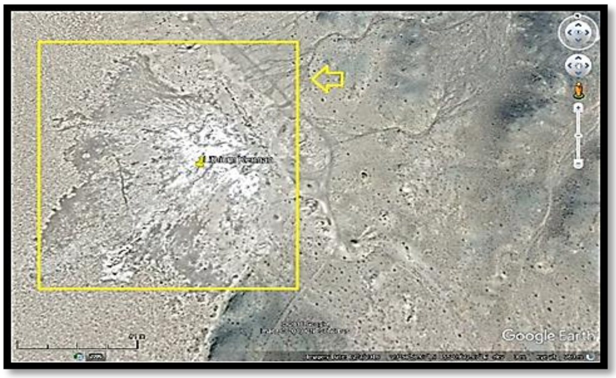

Figure 7. The location of the first sample.

4. Future Directions

A few ways are suggested to improve the overall process efficiency of lithium extraction processes from brine resources in Iran, including efficiency and sustainability. Precipitation processes are not recommended, especially for a magnesium-to-lithium ratio above 3, considering the simultaneous precipitation of both lithium and magnesium. It would rather be effective to put in more effort toward selective extraction methods tailored to specific brine composition in order to improve overall yield and reduce operational complexities.

When the ratio of magnesium to lithium is below 3 in brine, then the precipitation methodology would work effectively for extraction purposes. In reverse, when this is above 3, adsorption techniques stand as suitable as their alternatives. The methodologies ensure not only a better rate of recovery of lithium but also a reduction in environmental risk due to the usage of organic solvents in the cases of extraction by solvents. Future research should be directed at developing and optimizing these extraction techniques with both economic viability and environmental sustainability in mind for further development of clean energy resource development within the region.

Figure 8. The location of the second sample.

Figure 9. The location of the sampling points relative to each other in the city of Babak, Kerman (with an approximate distance of 10 kilometers from each other).

Table 4. The results of the sample analysis (second) 98ZR-305 (6-element analysis).

No.	Element	Concentration (ppm)
1	Potassium	3500
2	Magnesium	17000
3	Calcium	11000
4	Sodium	6200
5	Boron	40
6	Lithium	94

5. Conclusion

This study specifically investigated the lithium potential of brine sources in Shahrebabak, Kerman Province, employing advanced remote sensing techniques (including Landsat 8 and Sentinel-2 imagery) alongside geochemical analyses using ICP-MS. Sampling at depths ranging from 0.5 to 2 meters revealed lithium concentrations between 94 and 105 ppm, with Mg/Li ratios varying from 1.2 to 3.8. While these values suggest the presence of lithium, they also highlight challenges related to its economic extraction.

Emerging technologies, such as direct lithium extraction (DLE) methods, including ion exchange, adsorption, and membrane filtration, offer promising solutions for sites with low lithium concentrations and high Mg/Li ratios. These methods have shown potential for selective lithium recovery while minimizing environmental impacts compared to traditional evaporation techniques. Additionally, advancements in nanomaterials and hybrid processes could further enhance lithium separation efficiency. Incorporating such innovations into future feasibility studies may transform Shahrebabak and similar regions into viable extraction targets, aligning with global priorities for sustainable resource utilization and clean energy development.

The integration of spectral analysis via the Spectral Angle Mapper (SAM) algorithm with satellite imagery identified promising lithium-bearing zones. However, detailed geochemical analysis demonstrated that lithium concentrations in Shahrebabak remain at trace levels, with magnesium, potassium, sodium, and calcium dominating the brine composition. Although this region has some lithium potential, the relatively low economic feasibility suggests that Shahrebabak may not currently be a priority target for large-scale lithium extraction.

Nevertheless, Iran's unique geographical position and the increasing demand for lithium in clean energy applications underscore the importance of continued exploration and resource evaluation. Collaboration between academia, government, and the private sector is crucial for scaling up exploration efforts, developing innovative extraction technologies, and ensuring sustainable resource management. Establishing public-private partnerships could accelerate the deployment of advanced techniques and position Iran as a key player in the global lithium market.

To better understand the country's potential, further investigations are needed to identify other lithium-rich areas, assess extraction methods, and address challenges such as high Mg/Li ratios. Future research should also focus on optimizing techniques for cost-effective and environmentally sustainable lithium extraction from brines, ensuring alignment with global climate goals and sustainable development objectives.

This study provides a foundational framework for lithium exploration in the world and serves as a stepping stone for broader, multidisciplinary research efforts aimed at enhancing Iran's contribution to the global clean energy transition.

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